United States
Department of
Agriculture

Forest Service

Pacific Southwest Forest and Range Experiment Station

Research Paper
PSW-151

Saligna Eucalyptus Growth in a 15-Year-Old Spacing Study in Hawaii

Gerald A. Walters

Author:

GERALD A. WALTERS is assigned to timber and watershed resource development studies at the Station's Institute of Pacific Islands Forestry, Honolulu, Hawaii. He received B.S. (1965) and M.S. (1967) degrees in forestry from the University of Missouri. He joined the Forest Service in 1966.

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

February 1980

Saligna Eucalyptus Growth in a 15-Year-Old Spacing Study in Hawaii

Gerald A. Walters

CONTENTS

IN BRIEF

Walters, Gerald A.
1980. **Saligna eucalyptus growth in a 15-year-old spacing study in Hawaii.** Res. Paper PSW-151, 6 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Retrieval Terms: Eucalyptus saligna, Hawaii, plantation spacing, volume increment

In 1961, a spacing study was begun to test the effects of four different spacings on the growth and development of saligna eucalyptus *(Eucalyptus saligna* Smith) trees. The study site was on the north slope of Mount Haleakala on the island of Maui. Spacings tested were 8 by 8 feet (2.4 m), 10 by 10 feet (3.0 m), 12 by 12 feet (3.7 m), and 14 by 14 feet (4.3 m). Because at the start of this study the only anticipated use of saligna was for sawtimber, these spacings are wider than those used for pulp and fuelwood production.

A randomized block design provided four replications of each of the four spacings tested. A 25-tree measurement plot was established in each spacing in each replicate. Plot trees were measured at ages 1, 2, 5, 10, and 15 years. Measurements included d.b.h., total height, height to a 4- and 9-inch (10.2- and 22.9-cm) top (outside bark), and height to live crown. Board-foot and cubic-foot volumes were determined.

Saligna trees in all trial spacings grew rapidly. Average height of all trees varied by spacing and ranged from 87 to 112 feet (26 to 34 m). Trees attained from 70 to 90 percent of their total height, depending on spacing, by the fifth year after planting. Sawtimber trees (those at least 11 inches [27.9 cm] d.b.h.) averaged about 129 feet (39 m) after 15 years, with no significant differences between spacings. Trees 140 to 150 feet (43 to 46 m) tall were common at all spacings.

Diameter growth in all spacings was rapid, and was most rapid during the first few years. Diameter growth curves indicated that competition became a factor before 5 years. By 15 years, diameter ranged from 8.6 inches (21.8 cm) for trees in the 8-foot spacings to 12.5 inches (31.8 cm) for trees in the 14-foot spacings. Average d.b.h. differences between spacings were statistically significant at the 5 percent level.

Rate of basal area increase was greater for all spacings between 2 and 5 years after planting. After 15 years, basal area ranged from 154 square feet per acre (35 m^2/ha) for the 14-foot plots to 295 square feet per acre (56 m^2/ha) for the 8-foot plots.

Saligna trees in all spacings produced large volumes of wood in just 15 years—about 29,000 board feet per acre. Because the 14-foot spacing requires fewer seedlings to plant and maintain, and because fewer trees need to be harvested than for the narrower spacings, it is probably the best of the spacings tested in terms of economics to use for sawtimber yield. An average of 7600 cubic feet per acre (532 m^3/ha) of pulpwood was produced in 15 years. For pulpwood, the narrower spacings resulted in a larger volume per unit area than the wider spacings. This study, however, did not indicate which spacing is best for pulpwood. Perhaps a spacing narrower than 8 by 8 feet would result in a greater volume per unit area.

Saligna eucalyptus *(Eucalyptus saligna* Smith) is one of the most commonly planted tree species in Hawaii. It thrives on a variety of sites and produces a large volume of wood in short periods (Carlson and Bryan 1959, LeBarron 1962). Trees more than 150 feet tall and 3 feet in diameter are not unusual in Hawaii. Some trees may grow more than 100 feet tall in only 5 years (Walters and Schubert 1969). In a 30-year-old stand, 94,000 board feet (Int. 1/4-inch rule) per acre were tallied (Pickford and LeBarron 1960).

Saligna wood is used locally for general construction lumber, flooring, pallets, and fuel. It is potentially useful for poles and pilings, furniture, and particle board. Some saligna wood chips are exported from Hawaii to Japan for the manufacture of paper.

Presently in Hawaii, seedlings are planted at 10- by 10-foot (3.0-m) spacing, but in the past, tree spacings ranged from 5 by 5 (1.5 m) to 20 by 20 feet (6.1 m). The optimum spacing—one that results in the greatest yield in size, form, and quality of trees required—is not known.

The Forest Service, U.S. Department of Agriculture, and the Hawaii Division of Forestry began a study in 1961 to test the effects of four different spacings on the growth and development of saligna eucalyptus trees. At that time, the anticipated use of saligna was solely for sawtimber. Because small trees were not commercially marketable, the study's only objective was to determine which spacing would result in the largest volume of sawtimber in the least time. The market for both sawtimber and pulpwood is expanding. The spacings tested provide information for sawtimber and for sawtimber and pulpwood production. But they do not provide adequate information on just pulpwood production because all spacings tested were too wide for maximum volume production.

STUDY SITE

The study area lies on the north slope of Mount Haleakala, a 10,000-foot (3050-m) high dormant volcano that forms the eastern portion of the island of Maui. Slopes vary from 10 to 70 percent. Elevation is 500 feet (150 m). Annual rainfall of about 150 inches (3800 mm) is evenly distributed throughout the year. The soil is classified as Kailua silty clay of the thixotropic, isothermic family, Typic Hydrandepts group. It is deep, well drained, depleted of bases, and low in available phosphorus with a strongly acid A horizon and a moderately acid B horizon.

METHODS

Seed was collected from trees growing on the islands of Maui and Hawaii. Seedlings were grown in flats at the Hawaii Division of Forestry nursery at Kahului, Maui. The flats were taken to the site, where only thrifty seedlings of uniform size were planted.

A randomized-block design provided four replications of the four spacings being tested: 8 by 8 (2.4 m) 10 by 10 (3.0 m), 12 by 12 (3.7 m), and 14 by 14 (4.3 m) feet. A measure plot with 25 trees was established in each spacing in each block. Plot trees were measured at ages 1, 2, 5, 10, and 15 years. Measurements included diameter-at-breast-height (d.b.h.), total height, height to a 4-inch (10.2-cm) and 9-inch (22.9-cm) top (outside bark), and height to live crown. Board foot volumes were determined using the International ¼-inch formula. Whole tree volumes were determined using the formula

$$V = D^2 (0.001818\,H + 0.01636)$$

in which

V = volume in cubic feet

D = diameter (outside bark) in inches at 4.5 feet (1.4 m) above ground (d.b.h.)

H = total height in feet

This equation interprets each tree as a cylinder from ground level to breast height and a cone from breast height to tip (Meskimen and Franklin 1978).

The cubic foot volume of the stem above the 9-inch top diameter was determined using Smalian's formula

$$V = L\frac{(b+t)}{2}$$

in which

V = volume in cubic feet

b = area in square feet at large end of log

t = area in square feet at small end of log

L = length of log in feet

Analyses of variance techniques were used to test treatment differences.

Stem Height

Saligna eucalyptus trees in all trial spacings grew taller in 15 years than most United States mainland broad-leaved and coniferous species grow in 80 years. Saligna, like other eucalyptus species, is a "sprinter" —height growth is rapid for about the first 5 years, then slows. Periodic measurements of the trees in this study show this sprinter trend *(fig. 1)*. Trees attained 70 to 90 percent of their present height, depending on spacing, by the fifth year after planting. Annual height growth of trees in all spacings averaged 14 feet (4.3 m) for the first 5 years, 4 feet (1.2 m) for the second 5 years, and about 1 foot (0.3 m) for the third 5 years.

When all trees in the measure plots were included, stem height curves varied by spacing *(fig. 1)*. No significant differences in stem height were found at 2, 5, or 10 years, but were found at 15 years *(table 1)*. Trees in the 12- and 14-foot spacings averaged about 111 feet (33.8 m), significantly taller (5 percent level) than trees in the 10-foot spacing that averaged 96 feet (29.3 m). Trees in the 10-foot spacing, on the average, were significantly taller than trees in the 8-foot spacing. Trees in the 8-foot spacing plots averaged 87 feet (26.5 m) tall—5 feet (1.5 m) shorter than 5 years before. The slower rate of height growth for trees in the 10-foot spacings and the decrease in average stem height for trees in the 8-foot spacings was apparently the result of increased competition. Some of the less vigorous trees became suppressed; some even died back. Sawtimber trees—those at least 11 inches (27.9 cm) d.b.h. in all spacings—averaged 116 feet (35.4 m) at 10 years, and 129 feet (39.3 m) at 15 years after planting. Differences between average height by spacing for sawtimber trees at either measurement time were not significant.

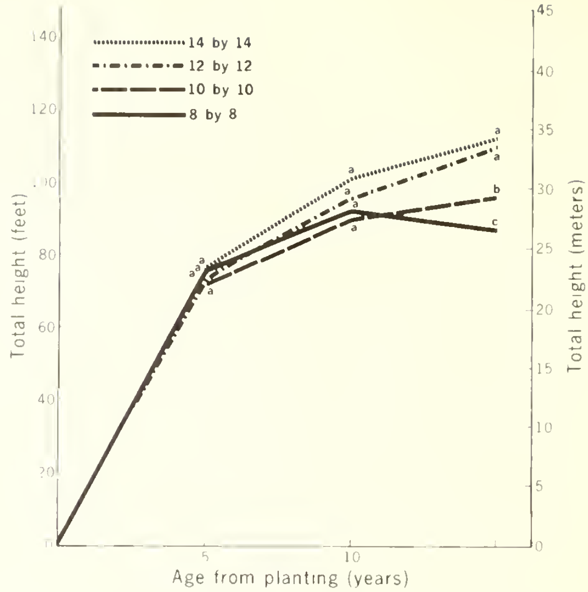


Figure 1—Cumulative height growth of saligna eucalyptus (all trees), by spacing. Means for trees of the same age with the same letter do not differ significantly at the 5 percent level.

The largest tree measured at 15 years was 161 feet (49.1 m) tall and 24.4 inches (61.2 cm) in diameter in the 14-foot spacing. Trees 140 to 150 feet (43 to 46 m) tall were common at all spacings.

Stem Diameter

Diameter growth of trees in all spacings was rapid. Diameter growth curves were similar to the height

Table 1—*Stand density, basal area, diameter, and height of saligna eucalyptus trees 15 years after planting, by spacing*

Spacing *(Feet [m])*	Stand density		Basal area	Diameter-at-breast-height (d.b.h.)		Height	
	All trees	Sawtimber[1]		All trees	Sawtimber[1]	All trees	Sawtimber[1]
	Trees/acre (Trees/ha)		*Ft^2/acre (m^2/ha)*	*Inches (cm)*			*Feet (m)*
8 by 8 (2.4)	524 (1294)	162 (400)	[2]245 a (56)	[2]8.6a (21.8)	13.1 d (33.3)	87 a (26)	126 d (38)
10 by 10 (3.0)	362 (894)	154 (380)	221 ab (50)	9.6 a (24.4)	13.4 d (34.0)	96 b (29)	125 d (38)
12 by 12 (3.7)	242 (598)	136 (336)	189 bc (43)	11.1 b (28.2)	14.4 e (36.6)	110 c (34)	133 d (40)
14 by 14 (4.3)	164 (405)	100 (247)	154 c (35)	12.5 c (31.75)	15.1 f (38.4)	112 c (34)	131 d (40)

[1] Sawtimber trees are those 11.0 inches (27.9 cm) d.b.h. and larger.
[2] Values followed by the same letters are not significantly different at the 5 percent level.

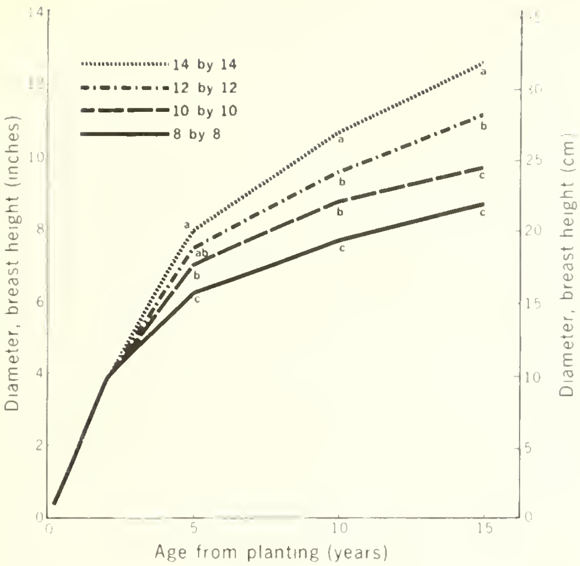


Figure 2—Cumulative diameter growth of saligna eucalyptus (all trees), by spacing. Means for trees of the same age with the same letter do not differ significantly at the 5 percent level.

growth curves; that is, they were rapid for about the first 5 years, then slower *(fig. 2)*. Trees in each spacing averaged 3.8 inches (9.6 cm) in diameter after 2 years. The divergence of the curves after 2 years indicates that competition became a factor before 5 years. The periodic annual diameter increment was less between 2 and 5 years than it was between 0 and 2 years for all spacings. Between 5 and 10 years, the periodic annual increment was only about one-third of what it was between 2 and 5 years for all spacings *(table 2)*. Rate of growth continued to decline between 10 and 15 years.

By 15 years, diameter ranged from 8.6 inches for trees in the 8-foot spacing *(fig. 3)* to 12.5 inches for trees in the 14-foot spacing. Diameter varied significantly (5 percent level) with spacing *(table 1)*. Average diameter of trees in the 14-foot plots was significantly greater than that of trees in the 12-foot plots. Diameters of trees in the 8- and 10-foot spacings were significantly less than those in the 12-foot plots, but any difference between the 8- and 10-foot spacings was not

Table 2—*The periodic annual diameter increment of saligna eucalyptus trees by spacing*

Spacing	Measurement periods (years after planting)			
	0 to 2	2 to 5	5 to 10	10 to 15
Feet (M)	*Inches (Cm)*			
8 by 8 (2.4)	1.9 (4.8)	1.0 (2.5)	0.3 (0.8)	0.2 (0.5)
10 by 10 (3.0)	1.9 (4.8)	1.3 (3.3)	.3 (0.8)	.2 (0.5)
12 by 12 (3.7)	1.9 (4.8)	1.4 (3.6)	.4 (1.0)	.3 (0.8)
14 by 14 (4.3)	1.9 (4.8)	1.6 (4.1)	.5 (1.3)	.4 (1.0)

significant. Significant differences between d.b.h. and spacing were also found when only sawtimber trees were considered. The percentage of sawtimber-size trees increased as spacing increased, from 31 percent for the 8-foot spacings to 61 percent for the 14-foot spacings. The 8-foot spacings, however, contained the largest number of sawtimber-size trees *(table 1)*.

Basal Area

For each measurement, basal area increment was greatest for the 8- by 8-foot plots. The rate of basal area increase was greatest for all spacings between 2 and 5 years after the trees were planted *(fig. 4)*. The rate of increase ranged from 17 square feet per acre per year (4 m^2/ha/yr) for the 14-foot spacing to 33 square feet per acre per year (8 m^2/ha/yr) for the 8-foot spacing. The rate of basal area accumulation for each spacing between 5 and 15 years was about 10 square feet per acre per year (2 m^2/ha/yr). After 15 years, basal area ranged from 154 square feet per acre (35 m^2/ha) for the 14-foot plots to 245 square feet per acre (56 m^2/ha) for the 8-foot plots *(table 1)*.

Stem Quality

After 15 years, sawtimber-size trees in all spacings averaged about 100 feet (30 m) to a 4-inch (10-cm) top. Height to live crown averaged about 75 feet (23 m). Differences among spacings were not significant. Only 2 or 3 percent of the trees in each spacing had severe crooks, sweeps, or other deformities that made them unmerchantable for sawtimber.

Table 3—*Sawtimber volume and cubic foot volume after 15 years, by product and spacing*

Spacing	Product (volume)		
	Sawtimber[1] and pulpwood[2]		Pulpwood only
Feet (M)	*M bd ft/acre*	*Ft^3/acre (m^3/ha)*	*Ft^3/acre (m^3/ha)*
8 by 8 (2.4)	[3]27.3 a	3060 (214)	[3]9759 a (683)
10 by 10 (3.0)	28.3 a	2275 (159)	8930 a (625)
12 by 12 (3.7)	31.3 a	1345 (94)	8672 a (607)
14 by 14 (4.3)	29.9 a	530 (37)	7096 a (496)

[1] Board foot volume—International 1/4 Rule, trees 11.0 inches (27.9 cm) d.b.h. and larger measured to 9-inch (22.9-cm) top diameter, outside bark.

[2] This pulpwood volume consists of trees with d.b.h. ranging from 4.0 to 10.9 inches (10.2 to 27.7 cm) and tops of sawtimber, i.e., the stem above the 9-inch top diameter.

[3] Means followed by the same letter do not differ significantly at the 5 percent level.

Figure 3 — Saligna eucalyptus in an 8- by 8-foot spacing plot 15 years after planting. Trees in the 8-foot plots averaged 8.6 inches (21.8 cm) d.b.h. and 87 feet (26.5 m) tall, and yielded more than 9759 cubic feet per acre (683 m^3/ha).

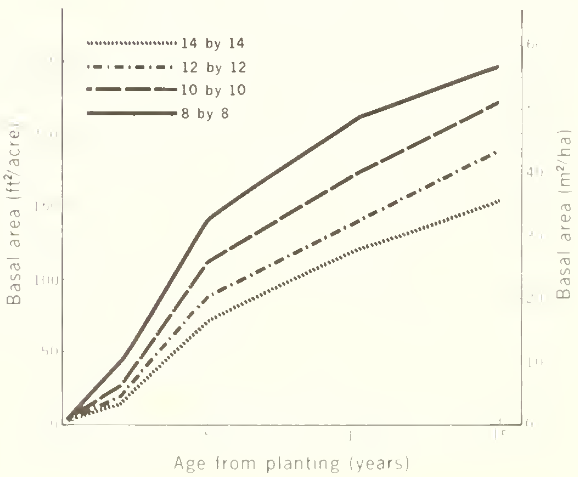


Figure 4 — Cumulative basal area growth of saligna eucalyptus, by spacing.

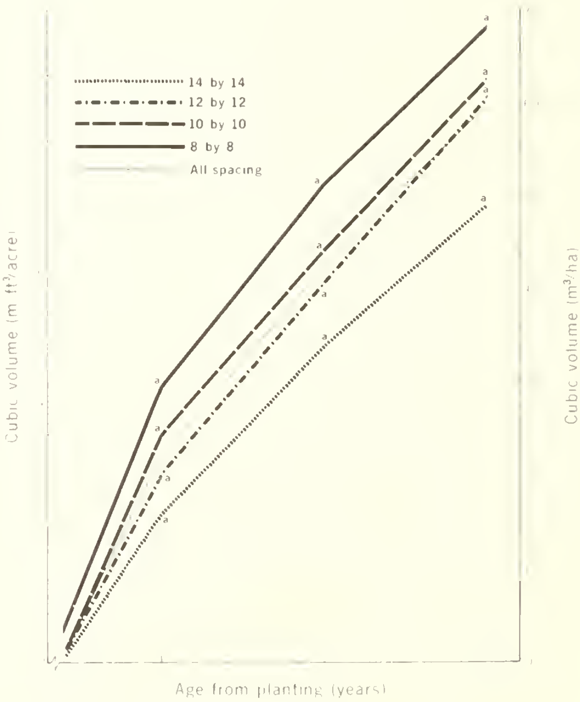


Figure 5 — Mean annual volume increment of saligna eucalyptus, by spacing.

Stem Volume

Trees in all spacings produced large volumes of *sawtimber* in 15 years, ranging from 27,300 board feet per acre for the 8-foot spacing to 31,301 board feet per acre for the 12-foot spacing *(table 3)*. These volumes represent an annual growth rate of 1800 board feet per acre for the 8-foot spacing and 2100 board feet for the 12-foot spacing. The greatest volume produced on a *plot* basis was 41,180 board feet per acre in a 10-foot spacing. Because of variation in replication, differences in mean volume per acre by spacing were not statistically significant at the 5 percent level.

In addition to the sawtimber volume produced per acre, a substantial amount of *pulpwood* volume was produced. Pulpwood in a sawlog-pulpwood operation consists of the upper stems of sawtimber-size trees and of trees between 4 inches (10.2 cm) and 11 inches (27.9 cm) d.b.h. Pulpwood volume decreased as spacing increased, ranging from 3060 cubic feet per acre (214 m^3/ha) for the 8-foot spacings to 530 cubic feet per acre (37 m^3/ha) for the 14-foot spacings *(table 3)*.

The total volume of pulpwood produced ranged from 9759 cubic feet per acre (683 m^3/ha) for the 8-foot spacings to 7096 cubic feet per acre (496 m^3/ha) for the 14-foot spacings. Although mean total volume increased as spacing decreased for each of the measurements *(fig. 5)*, differences in volume per area by spacing were not statistically significant. As with board foot volumes, large variations among replications masked any significant differences between spacings.

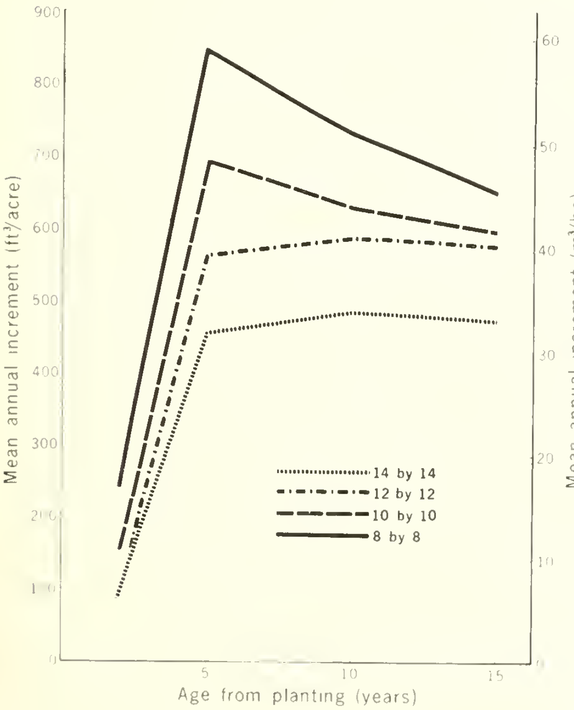


Figure 6 — Mean annual volume increment of saligna eucalyptus, by spacing.

Mean annual volume increment varied with spacing and was greatest for the trees in the 8-foot spacing and least for those in the 14-foot spacing *(fig. 6)*. The mean annual volume increment was greatest at 5 years for trees in the 8- and 10-foot spacings, and then declined. Trees in the 12- and 14-foot spacings reached maximum mean annual increment after about 10 years.

DISCUSSION

This study was begun in 1961 when the only use anticipated for saligna eucalyptus was sawtimber. The objective was to determine which of the spacings tested would result in the greatest yield of sawtimber in the shortest time. Saligna eucalyptus has not proven to be a very good sawtimber tree because of growth stresses that develop in the stem as the tree grows. When older trees are harvested, the effects of growth stress, including log end-splitting, spring in sawing, and the compression failures of brittleheart become serious problems. Wood density within the tree also becomes more variable as age increases. Skolmen (1974) found the effects of growth stress less in younger trees, about 12 years old. Lumber from the young trees is generally of lower grade, but because of its lower density and easier working characteristics, it has a greater potential for use in general construction than wood from older trees.

A pulpwood market also has developed since the study was begun. Available saligna eucalyptus trees are being chipped and sent to Japan for the manufacture of paper. Saligna chips may also be used as a fuel in Hawaii. One ton (oven dry) of saligna chips is about equivalent in Btu's to 2.7 barrels of Bunker c fuel oil (Yang and others 1977).

Sawtimber

Saligna trees in all spacings produced about the same board foot volume in 15 years (differences were not statistically significant)—about 29,000 board feet per acre. This volume yield was from only 100 sawtimber trees per acre at the 14-foot spacing, whereas it was from 162 trees per acre at the 8-foot spacing. More than 61 percent of the trees in the 14-foot spacing were of sawtimber-size as compared with only 31 percent in the 8-foot spacing. Because the 14-foot spacing requires fewer seedlings to plant and maintain, and because fewer trees need to be harvested than for the narrower spacings, it is probably the best of the spacings we tested in terms of economics to use for a sawtimber operation. Because of the problems that result from growth stress in older eucalyptus, trees in the 14-foot spacing should be harvested at 15 years of age. For the 8-foot spacing, it may be best to delay harvesting until a higher percentage of the trees reach sawtimber-size. With the competition that exists in the narrow spacings, however, diameter growth would only be about 0.2 inch per year. This extension of the rotation would, of course, add to the overall costs that the increased yield may or may not cover. Trees smaller than sawtimber-size can be used for pulpwood. Because pulpwood is a product lower in value than sawtimber, it is desirable to use as many trees as possible for sawtimber.

Pulpwood

In a pulpwood operation, it is desirable to fully utilize the site as quickly as is practical and harvest the trees when mean annual cubic volume increment culminates. In this study, mean annual cubic volume increment culminated at about 5 years for trees in both the 8- and 10-foot spacings. By then, the 8-foot spacings contained an average of about 4200 cubic feet per acre (294 m^3/ha) and the 10-foot spacings contained an average of about 3500 cubic feet per acre (245 m^3/ha). Diameter (breast height) of trees in the 8-foot spacings averaged 6.2 (15.8 cm) and in the 10-foot spacings averaged 7.0 inches (17.8 cm). Trees in both spacings averaged about 74 feet tall. The cubic foot volume produced in 5 years in the 8-foot spacing was almost 4 times the volume produced in an 8-foot spacing in a Florida study in 7.4 years (Meskimen and Franklin 1978). The species in the Florida study was *Eucalyptus grandis*, one closely related to *E. saligna*. The annual volume growth rate of 840 cubic feet per acre (59 m^3/ha) for trees in the 8-foot spacing was 2 to 3 times more than the rates reported for eucalyptus growing in Latin America, South Africa, and Australia (Carter 1974). If one cubic foot equals about 28 pounds, then 840 cubic feet equal 23,520 pounds (10,669 kg) or about 11.7 tons (10.4 tonnes) (dry weight). In terms of Btu's, this dry weight is equivalent to about 32 barrels of oil produced per acre per year. For trees in the 12- and 14-foot spacings, mean annual volume increment culminated at about 10 years. At 10 years the cubic foot volume in the 14-foot spacing was 34 percent less than it was in the 8-foot spacing, whereas the cubic foot volume in the 12-foot spacing was 20 percent less. For a pulpwood operation, the narrower spacings result in a larger volume per unit area than the wider spacings. This study does not indicate however, what spacing is best for a pulpwood operation. Perhaps a spacing narrower than 8 by 8 feet should be attempted.

Combination Sawtimber/Pulpwood

In a combination sawlog/pulpwood operation, trees could be planted close, perhaps 6 by 6 feet (1.8 m), and then thinned at the age of 3 to 4 years, depending on the severity of the competition. Thinned material, including deformed or low vigor trees, or both, could be chipped. Thinning could be such that spacing of crop trees of about 12 by 12 feet (3.7 m) or 14 by 14 feet (4.3 m) would result. Crop trees should be harvested at 12 to 15 years. Utilization could be complete—sawlogs and pulpwood. This study does not provide information as to what initial spacing is best, when the thinning(s) should be made, or the volumes of sawlogs or pulpwood produced.

LITERATURE CITED

Carlson, N. K., and L. W. Bryan.
1959. **Hawaiian timber for the coming generations.** Trustees Bernice P. Bishop Estate, Honolulu, Hawaii. 112 p.

Carter, W. G.
1974. **Growing and harvesting eucalyptus on short rotations for pulping.** Aust. For. 36(3): 214–225.

LeBarron, R. K.
1962. **Eucalyptus in Hawaii: a survey of practices and research programs.** U.S. Forest Serv. Pacific Southwest Forest and Range Exp. Stn. Misc. Paper 64, 24 p. Berkeley, Calif.

Meskimen, George, and E. C. Franklin.
1978. **Spacing *Eucalyptus grandis* in southern Florida.** Southern J. Appl. For. 1(1):3–5.

Pickford, G. D., and R. K. LeBarron.
1960. **A study of forest plantations for timber production on the island of Hawaii.** U.S. Forest Serv. Pacific Southwest Forest and Range Exp. Stn. Tech. Paper 52, 17 p. Berkeley, Calif.

Skolmen, R. G.
1974. **Lumber potential of 12-year-old saligna eucalyptus trees in Hawaii.** USDA Forest Serv. Res. Note PSW-288, 7 p. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Walters, G. A. and T. H. Schubert.
1969. **Saligna eucalyptus growth in a 5-year-old spacing study in Hawaii.** J. For. 67: 232–234.

Yang, Christine, Donald Murata, and Curt Beck, eds.
1977. **Biomass energy for Hawaii.** Volume IV, Terrestrial and marine plantations. Chapter 6—Terrestrial plantations, p. 6–1 to 6–155. Inst. for Energy Studies, Stanford University, Stanford, Calif.

Walters, Gerald A.

1980. **Saligna eucalyptus growth in a 15-year-old spacing study in Hawaii.** Res. Paper PSW-151, 6 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

A spacing study was started in 1961 to test the effects of four different spacings on the growth and development of saligna eucalyptus *(Eucalyptus saligna* Smith) trees in Hawaii. Spacings tested were 8 by 8 feet (2.4 m), 10 by 10 feet (3.0 m), 12 by 12 feet (3.7 m), and 14 by 14 feet (4.3 m). Plot trees were measured at ages 1, 2, 5, 10, and 15 years. Measurements included d.b.h., total height, height to a 4- and 9-inch (10.2- and 22.9-cm) top (outside bark), and height to live crown. Board feet and cubic foot volumes were determined. After 15 years, trees 140 to 150 feet tall were common in all spacings. Average d.b.h. ranged from 8.6 inches (21.8 cm) in the 8- by 8-foot spacings to 12.5 inches (31.8 cm) in the 14- by 14-foot spacings. Large volumes of wood were produced, averaging more than 29,000 board feet per acre, or more than 7600 cubic feet per acre (532 m^3/ha).

Retrieval Terms: Eucalyptus saligna, Hawaii, plantation spacing, volume increment.

United States Department of Agriculture

Forest Service

Pacific Southwest Forest and Range Experiment Station

Research Paper PSW-152

Tests of 36 *Eucalyptus* Species in Northern California

James P. King Stanley L. Krugman

The Authors:

JAMES P. KING was in charge of the Station's forest genetics research unit, with headquarters in Berkeley, Calif., at the time of the research reported in this paper. He is now with the Station's timber and watershed management research unit, in Honolulu, Hawaii. He earned degrees at Michigan State University (B.S., in forest management, 1957; Ph.D., in forest genetics, 1964) and Oregon State University (M.F., in forest management, 1958). He joined the Forest Service in 1957. **STANLEY L. KRUGMAN** was formerly head of the Station's forest genetics research unit and is now principal research forest geneticist, Forest Service, U.S. Department of Agriculture, Washington, D.C. He earned degrees at the University of Missouri (B.S., in forestry, 1955) and the University of California, Berkeley (M.S., in plant physiology, 1956; and Ph.D., also in plant physiology, 1961). He joined the Forest Service in 1961.

Acknowledgments:

We thank the heads of the Western Division, Naval Facilities Engineering Command, U.S. Navy, and of the Public Works Office, Concord Naval Weapons Station, for their help in originating and supporting this study; the technical staff of the Institute of Forest Genetics, Pacific Southwest Forest and Range Experiment Station, for work in measuring the test species and maintaining the plantation; and F. T. Ledig, of the Station staff, for providing the photographs.

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

March 1980

Tests of 36 *Eucalyptus* Species in Northern California

James P. King Stanley L. Krugman

CONTENTS

IN BRIEF...

King, James P., and Stanley L. Krugman.
1980. **Tests of 36 *Eucalyptus* species in northern California.** Res. Paper PSW-152, 6 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Retrieval terms: *Eucalyptus*, species trial, California, eucalypts

The purpose of this study was to compare and identify appropriate species of *Eucalyptus* suitable for planting on low-elevation sites in central California.

Australian foresters selected 36 *Eucalyptus* species on the basis of potential cold-hardiness and tree form, and provided us with general area seed collections. Some attempt was made to collect seed from the higher elevations of most species.

A test plantation was established in cooperation with the U.S. Navy near Concord, California, about 20 miles inland from San Francisco Bay. The site is on good agricultural soil and has the hot, dry summer, and cool, moist winters typical of California's central valley. A record-breaking cold spell occurred in the area in the winters of 1972-73, when the oldest trees were still less than 10 years of age.

Thirty-one species were field-planted in 1965, using 10-month-old containerized seedlings. Replanting of fail spots was done in 1966 and a thirty-second species added. In 1968, four additional species were planted.

Of the 36 species tried, 21 were regarded as outright failures. The 21 failure species included all 10 of the species from western Australia and 10 of the 11 *Monocalyptus* species included in the study. In general, the higher elevation collections from eastern Australia were best in terms of survival and growth rate.

The seven highest rated species were: *Eucalyptus camaldulensis*, *E. dalrympleana*, *E. glaucescens*, *E. grandis*, *E. nitens*, *E. ovata*, and *E. viminalis*. These species all had high survival, made good growth, and readily recovered from the record-breaking 1972 freeze.

The study re-emphasized to us the sensitivity of *Eucalyptus* to competition, particularly on this summer-drought site. The interplanted trees, though only 1 year younger than the original planting, were suppressed throughout the entire course of the study and rendered area volume estimates useless.

In 1964, the Forest Service's Pacific Southwest Forest and Range Experiment Station and the Navy's Concord Naval Weapons Station joined in a cooperative study of 36 *Eucalyptus* species. The study was to compare and identify appropriate species that would be suitable for planting on low elevation and similar areas in California. The Navy's interest in such plantation trials stemmed from its desire to better utilize the land under its jurisdiction.

The species tested at Concord, about 20 miles northeast of San Francisco, were to be evaluated primarily for their ability to produce wood products, such as posts, bumper piles, pallets, and timber, and for their potential for wood chips, firewood, and values as wildlife habitat and landscaping. Among the more than 500 *Eucalyptus* species, a number have been tried at numerous sites throughout California, but relatively few have been successful (Metcalf 1961, 1967).

In the first trials, 36 *Eucalyptus* species were selected and obtained from Australia *(table 1)*. Dr. M. R. Jacobs, then Director-General of the Forestry and Timber Bureau of Australia, and the late E. Larsen, of the same organization, made initial recommendations in selecting species and assisted in obtaining the seeds for this study. Species were selected on the basis of potential cold hardiness and tree form. These seed collections usually represented general area collections, although some attempt was made to collect from the highest elevations of most species.

This paper reports results of early survival, growth, flowering and cold resistance.

SITE CHARACTERISTICS

Although the Concord, California, site is within 20 miles of San Francisco Bay, the presence of a range of low hills west of the test site makes the climate more closely related to inland areas. That is, the climate at the site more closely resembles Sacramento than coastal San Francisco.

Mean monthly temperatures range from 43°F (6°C) in January to 73°F (23°C) in July. From 1965 to 1977, temperatures reached over 100°F (38°C) in every summer but one, while the coldest winter temperature reached between 20°F (−7°C) and 25°F (−4°C). A recordbreaking cold spell occurred in December 1972 when temperatures dropped below 32°F (0°C) on nine consecutive nights; the lowest temperature occurred on December 11, when 16°F (−9°C) was recorded. A second cold wave occurred in late December and early January 1973, when the temperature went below freezing on 10 consecutive nights, with a low of 20°F (−7°C) on January 7. Rainfall ranges from 2 inches (51 mm), from April through September, up to 19 inches (508 mm) from October through March. Elevation of the planting site is 204 feet (61.8 m). Soils at the Concord test site are variable but tend to be well-drained sandy loams of excellent agricultural quality.

PROPAGATION AND SURVIVAL

In the initial test series, in May 1964, the seeds of 32 species were sown in flats in the greenhouse at the Station's Institute of Forest Genetics, Placerville, California. Germination was generally good except for *Eucalyptus camaldulensis* and *E. delegatensis*. Once the seedlings had developed two pairs of leaves, they were transplanted into individual plant bands. In later studies, all seeds were stratified for at least 30 days at 41°F (5°C). Such treatment improved both the rate and percentage of seed germination.

Because of differential growth rates between various species, it was necessary to top-prune the faster growing seedlings at least once before field planting. The seedlings (hereafter called the 1964 seedlings) were held in the greenhouse until danger of late spring frost passed in early 1965, after which they were field planted on a prepared site.

The plantation site was disked twice during summer and fall 1964 to reduce weed competition, particularly wild oats and star thistle. The seedlings were planted at 10-foot (3-m) spacing using a soil auger to drill the planting holes. The planting was laid out in three blocks of 32 plots each. Not enough *E. camaldulensis* were available so only 31 plots per block were planted. Each plot contained 16 trees of the same species planted in 4 rows, 4 trees per row. The trees were planted on February 24 and 25. Two months later, April 22, average survival for all species was 72 percent. Irrigation of these seedlings was planned for the first two summers following field planting, but a delay in receiving and installing an irrigation system left the seedlings without water until mid-June. When the second survival count was taken on June 22, survival averaged 33 percent. The third survival count taken on October 11 showed average survival to be 30 percent. By 1968, 15.5 percent of the trees planted were alive. Only four of the 32 species had more than 50 percent survival—*E. melliodora, E. dalrympleana, E. nitens,* and *E. viminalis (table 1).* The seeds of the last three of these species were from elevations above 2900 feet (884 m) in eastern Australia.

In fall 1965, replacement seedlings of 31 species (hereafter called the 1965 seedlings) were grown in the greenhouse at Placerville. They were field planted in April 1966 in the same spots where the 1964 seedlings died. Irrigation was started immedi-

Table 1—*Survival of 36 species of Eucalyptus planted at Concord, California*

Species	Location	Elevation	1964 seedlings: Planted						1965 seedlings: Planted					
			Planted	Alive					Planted	Alive				
			1965	1968	1971	1972	1974	1977	1966	1968	1971	1972	1974	1977
		m												
			Good survival and growth											
E. camaldulensis Dehn.	Victoria	—	0	0	0	0	0	0	48	42	42	42	32	31
E. dalrympleana Maiden	New S. Wales	975	48	31	31	31	31	31	15	14	12	12	10	9
E. glaucescens Maiden and Blakely	Victoria	1067	48	17	17	17	17	17	29	25	23	23	21	21
E. grandis Hill ex Maiden	New S. Wales	—	48	8	8	8	6	6	34	33	33	33	30	31
E. nitens Maiden	Victoria	884	48	29	29	29	26	26	17	17	17	17	17	16
E. ovata Labill.	Tasmania	—	48	18	18	18	14	14	29	14	11	9	7	7
E. viminalis Labill.	New S. Wales	1219	48	41	41	41	41	40	8	8	7	6	6	6
			Good survival											
E. behriana F.v.M.	Victoria	198	32	0	0	0	0	0	48	26	14	14	14	14
E. coccifera Hook	Tasmania	—	48	1	0	0	0	0	47	32	24		19	19
E. fruticetorum F.v.M.	Victoria	—	46	5	[1]6		11	11	35	30	19		13	15
E. melliodora A. Cunn.	New S. Wales	137	48	25	[1]21		28	29	19	21	25		16	16
E. resinifera Sm.	New S. Wales	24	48	11	[1]18	18	16	11	25	21	21		16	15
E. robusta Sm.	New S. Wales	—	48	8	[1]13		11	11	31	31	27		20	20
E. polyanthemos Schau.	Victoria	305	[2]	[2]	[2]	[2]				48			40	40
E. sideroxylon A. Cunn. ex. Woolls.	Victoria	259	[2]	[2]	[2]	[2]				48			35	29
			Failures											
E. andrewsi Maiden	New S. Wales	762	[2]	[2]	[2]	[2]				48			8	4
E. fastigata Deane and Maiden	New S. Wales	—	48	11	8		4	0	28	27	16		9	8
E. niphophila Maiden and Blakely	New S. Wales	—	39	9	8		6	1	37	17	14		10	6
E. obliqua L'Herit.	New S. Wales	61	48	0	0		0	0	47	34	20		18	2
E. pauciflora Sieb. ex Spreng.	Cap. Terr.	1341	48	2	1		0	0	46	16	12		8	4
E. radiata Sieb. ex DC.	New S. Wales	853	[2]	[2]	[2]	[2]				48			14	7
E. regnans F. Muell.	Tasmania	335-549	48	2	2		0	0	43	38	25		8	4
E. stellulata Sieb. ex DC.	Victoria	762	48	13	12		11	5	33	31	17		15	6
E. transcontinentalis Maiden	West. Aust.	—	48	0	0		0	0	48	19	11		5	3
E. oleosa F.v.M.	West. Aust.	—	47	0	0		0	0	47	15	1		2	1
E. robertsoni Blakely	Cap. Terr.	—	47	6	6		0	0	38	18	5		1	0
E. salmonophloia F. Muell.	West. Aust.	—	28	0	0		0	0	48	18	2		2	1
E. brockwayi C. A. Gardn.	West. Aust.	—	48	0	[3]	[3]	[3]		47	9	[3]	[3]	[3]	
E. calophylla R. Br.	West. Aust.	—	48	0	[3]	[3]	[3]							
E. delegatensis R.T. Bak.	Cap. Terr.	—	48	3	[3]	[3]	[3]		27	2	[3]	[3]	[3]	
E. diversicolor F.v.M.	West. Aust.	—	48	0	[3]	[3]	[3]		—		[3]	[3]	[3]	
E. dundasi Maiden	West. Aust.	—	48	0	[3]	[3]	[3]		48		[3]	[3]	[3]	
E. gomphocephala A. DC.	West. Aust.	—	48	0	[3]	[3]	[3]		8	8	[3]	[3]	[3]	
E. polycarpa F.v.M.	North. Terr.	—	48	0	[3]	[3]	[3]		44	0	[3]	[3]	[3]	
E. redunca var. elata Benth.	West. Aust.	—	45	0	[3]	[3]	[3]		30	1	[3]	[3]	[3]	
E. torquata Luehm.	West. Aust.	—	44	0	[3]	[3]	[3]		30	1	[3]	[3]	[3]	

[1] Additional seedlings planted in 1969.
[2] Planted only in 1968.
[3] Discontinued in 1968.

ately after planting, and early survival was very good. Two years following planting, the 1965 seedlings had 50 percent survival. Sixteen of the 31 species had better than 50 percent survival. In June 1966, 82 percent of all the spots in the plantation had living seedlings. In early 1970, four additional *Eucalyptus* species were field planted in plots where other species had failed. In spring 1968, irrigation was stopped on the 3- and 4-year-old eucalypts.

RESULTS

In the discussion of the trials, the differences reported are not necessarily statistically significant. Because of problems in setting up the trials, the tests of significance were not considered reliable.

Of the 36 species planted, nine species had negligible survival at 2 and 3 years *(table 1)*. Most of the mortality among 1964 seedlings was related to drought damage as well as weed competition. For the 1965 seedlings, frost damage appeared to be the most significant factor, but weed competition remained a serious problem. The nine completely unsuccessful species were:

E. brockwayi
E. delegatensis
E. diversicolor
E. dundasi
E. gomphocephala
E. polycarpa
E. redunca var. elata
E. torquata
E. calophylla (tried in 1964 only)

Three other species—*E. oleosa, E. robertsoni,* and *E. salmonophloia*—had very few survivors in the 1964 planting, and some success in the 1965 planting. After five seasons in the field, these species were practically eliminated by repeated frosts.

A third group consisting of nine species had fair to good early survival but has suffered a consistent mortality rate that indicates lack of adaptation to climatic conditions at the site. These species are:

E. andrewsi
E. fastigata
E. niphophila
E. obliqua
E. pauciflora
E. radiata
E. regnans
E. stellulata
E. transcontinentalis

Only one species, *E. regnans,* showed a sharp increase in mortality that could clearly be associated with recordbreaking low temperatures that occurred in December 1972.

Eight species showed good survival, the ability to tolerate drought, and recover from the 1972 freeze, but must be considered too slow-growing for use outside of landscaping:

E. behriana
E. coccifera
E. fruticetorum
E. melliodora
E. polyanthemos
E. resinifera
E. robusta
E. sideroxylon

The seven species showing the most potential in terms of survival and growth rate *(fig. 1)* are:

E. camaldulensis
E. dalrympleana
E. glaucescens
E. grandis
E. nitens
E. ovata
E. viminalis

E. ovata is somewhat borderline. While its growth has been the best in this group, its survival and form are the poorest.

Growth Rate

Of the 11 fastest-growing species, *E. camaldulensis, E. glaucescens, E. grandis, E. nitens,* and *E. ovata* are clearly among the best in terms of height, diameter, and tree volume *(table 2)*. *E. dalrympleana* and *E. viminalis* did well but seem highly inconsistent between the 1964 and 1965 seedlings. This inconsistency can be explained largely by the fact that the 1964 seedlings of *E. dalrympleana* and *E. viminalis* had high survival in 1965. Therefore, the trees planted in 1966 were interplanted in fairly well-stocked plots and were strongly suppressed by the 1964 seedlings.

The large growth variable between the 1964 and 1965 trees of almost all the other species is difficult to explain. The differences between the two plantings are much greater than can be accounted for by a single year's growth. The 1964 planted trees did receive an additional year of irrigation.

Partly because of the additional irrigation in 1964 and therefore faster establishment, and partly because of the suppression effect of the 1964 trees on the 1965 trees, the 1965 trees have less than half

Figure 1 — *Eucalyptus* species that have shown the most potential in terms of survival and growth rate include:

A: *E. camaldulensis* provided good growth, but individual trees varied in form from good to poor.

B: *E. dalrympleana* combined good growth with fair form and good natural pruning.

C: *E. grandis*, in this fully stocked plot, showed exceptionally good form.

D: *E. nitens* combined good to excellent form with above average growth rate in this plot (see *E*).

E: *E. nitens* had particularly stringy and messy bark that could become a serious fire hazard. Other species had clean bark (see *B, G*).

F: *E. ovata* provided good diameter growth, but had only fair survival. Its poor form and exceptionally heavy limbs typical of this species in the test suggest that *E. ovata* may be suitable only for fuelwood.

G: *E. viminalis* showed good growth, survival, and form, making this one of the best plots in the test.

Table 2—*Growth of the 11 fastest growing Eucalyptus species at Concord, California*

Species	1964 seedlings								1965 seedlings							
	1968	1971		1974		1977			1968	1971		1974		1977		
	Ht.	Ht.	D.b.h.	Ht.	D.b.h.	Ht.	D.b.h.	Vol/ tree	Ht.	Ht.	D.b.h.	Ht.	D.b.h.	Ht.	D.b.h.	Vol/ tree
	m	*m*	*Cm*	*m*	*Cm*	*m*	*Cm*	*Cu m*[1]	*m*	*m*	*Cm*	*m*	*Cm*	*m*	*Cm*	*Cu m*[1]
E. camaldulensis									2.74	6.21	6.6	9.08	10.4	10.06	12.4	.06
E. dalrympleana	7.77	14.11	16.5	15.45	20.8	17.22	22.4	.29	1.80	5.40	5.1	7.35	8.4	8.08	8.9	.02
E. glaucescens	3.96	9.45	11.9	12.07	16.8	13.35	17.8	.15	1.59	5.61	5.1	8.63	8.9	9.75	9.9	.03
E. grandis	4.63	8.96	10.7	13.53	17.5	15.33	19.3	.20	2.56	8.14	7.9	10.76	12.2	11.58	12.7	.07
E. nitens	4.88	9.05	13.2	12.80	18.5	13.81	19.8	.19	1.98	7.53	8.4	11.52	13.7	13.17	16.8	.13
E. ovata	6.61	11.46	15.2	14.63	22.9	13.84	24.1	.28	1.62	5.61	7.1	10.58	14.5	11.77	16.0	.10
E. viminalis	5.67	10.45	12.2	13.50	15.7	14.11	17.0	.14	1.71	4.97	4.3	8.38	7.4	9.11	7.9	.02
E. melliodora	2.19	6.10	6.9	8.26	10.4	9.20	11.7	.04	0.91	4.27	4.8	6.37	6.9	7.80	8.4	.02
E. regnans		5.58	4.1						1.19	4.66	3.6	5.94	6.4	10.30	10.9	.04
E. resinifera	2.99	6.16	6.9	6.80	9.9	8.53	11.7	.04	1.40	4.51	4.6	5.79	8.4	6.80	10.4	.03
E. robusta	3.11	6.28	8.6	7.32	12.7	7.65	11.9	.04	1.62	4.54	2.5	5.88	9.4	6.40	9.7	.02

[1] Volume equation derived from data in Metcalf (1924). Stem volume including bark to a 2-inch (15 cm) top. Volume (cubic feet) = 0.00245 (diameter^2 [inches]) (height [feet]) −0.3318. Volume then converted from cubic feet to cubic meters using 1 cubic foot = .02832 m^3.

the volume of the 1964 trees, even after adjusting for age differences. Moreover, the volume differences between 1964 and 1965 trees are getting larger.

Flowering

With the obvious exception of nonsurviving species, all species flowered within 8 years following field planting. Several of the faster-growing species flowered by age 5, including:

E. behriana
E. camaldulensis
E. fruticetorum
E. grandis
E. melliodora
E. resinifera
E. robusta
E. transcontinentalis

Of the 22 species observed at the Concord plantation, variability was evidenced not only in the rate of maturity to first flowering, but also in the time of year when the flowering season occurs *(table 3)*.

1972 Freeze

The very low temperatures that occurred during December and January 1972-73 caused severe damage to many *Eucalyptus* groves in the Bay Area. In the Concord planting, obvious differences between species could be seen in the percent of foliage damaged by the cold. The slower-growing species generally had the most damage. *E. regnans, E. resinifera,* and *E. robusta,* had more than 80 percent of their foliage damaged. *E. camaldulensis, E. dalrympleana, E. glaucescens, E. nitens,* and *E. viminalis* had less than 20 percent of their foliage damaged. *E. grandis* and *E. ovata,* though among

Table 3—*Flowering, fruiting, and seed dispersal seasons of Eucalyptus species*

Species	Seasons		
	Flowering	Fruit ripening	Seed dispersal
E. behriana	Feb-Apr	—	—
E. camaldulensis	Feb-Apr	July-Oct	Commences 8 to 9 months after flowering
E. coccifera	May-June	—	—
E. dalrympleana	June-Aug	Aug-Oct	Oct-Nov
E. delegatensis	Apr-June	Apr-June	May-July
E. fastigata	Apr-May	July-Aug	—
E. fructicetorum	June-Sept	—	—
E. glaucescens	July-Aug	May-Sept	Nov-Feb
E. grandis	Sept-Nov	—	—
E. melliodora	Feb-July	—	—
E. niphophila	Mar-Apr	—	—
E. nitens	Apr-July	May-June	May-June
E. obliqua	Apr-July	May-Aug	—
E. ovata	July-Dec	—	—
E. pauciflora	Mar-May	—	—
E. regnans	Apr-July	June-Sept	—
E. resinifera	Mar-May	—	—
E. robusta	Jan-Mar	—	—
E. sideroxylon	June-Sept	—	—
E. stellulata	July-Nov	—	—
E. transcontinentalis	Jan-Nov	—	—
E. viminalis	All year	12 months after flowering	20 to 22 months after flowering

the faster growing, had moderate (50 to 70 percent) damage to their foliage.

Most of the species showed good ability to recover from the freeze damage. Only *E. regnans* showed an increase in mortality that could be associated with the freeze. Thus, the 1972 freeze provided strong indication that the faster-growing species, when old enough, could withstand even the coldest Bay Area weather.

DISCUSSION

Pryor (1976, p. 76) has pointed out that, with few exceptions, species of the subgenus *Monocalyptus* seldom do well outside Australia. He suggested that such failure by this group could be due to a lack of suitable mycorrhizal fungus in exotic plantations. Pryor (1976, p. 4) also pointed out that a major difference exists in species distribution between southwestern and southeastern Australia that seems independent of climate. A most striking feature of the present data is that the 21 species regarded as failures in this study include all 10 of the western Australian species and 10 of the 11 *Monocalyptus* species. *E. coccifera* was the only *Monocalyptus* that survived well here. No serious damage from disease or insects was noted during the course of this study.

Growth data were not subject to an analysis of variance, for several reasons. To determine that one species was significantly faster-growing than another on the basis of this data would be highly misleading. Most species were represented by general seed collections. Thus, any analysis would have to ignore variation within each species. There might be other seed sources within a slow-growing species that could outgrow the general collections used in this study.

Moreover, the sprouting habit of *Eucalyptus* adds an additional and unquantifiable variation to growth measurements. In a number of instances, individual trees "died" while young but immediately stump-sprouted. The sprouts initially grew much faster than the original stem but eventually slowed to a more "normal" growth rate. Under these circumstances, it is very difficult to define or determine normal volume.

Our experience in this and newer studies has reemphasized the sensitivity of *Eucalyptus* to cultural practices, particularly weed control. Part of a newly planted *E. camaldulensis* provenance study at the Concord site was established on soil that was disked and maintained weed-free for two growing seasons prior to planting. The remaining trees in the test were planted in an adjacent area that was cleared of weeds immediately before planting. All trees were hand watered and maintained free of weed competition for 18 months following planting. The trees in the newly cleared area averaged just under half the height of the trees in the twice-cleared area—2.99 feet to 6.03 feet (0.91 m to 1.84 m). Overall survival was over 92 percent. Thorough weed control is essential in establishing *Eucalyptus* plantations. Interplanting *Eucalyptus* in an established stand, even when very young, is not recommended. The results of this initial trial were confounded by competition between established trees and young seedlings, and suppression of the 1965 seedlings has continued.

In general, the higher elevation collections from eastern Australia did the best in terms of survival and rate of growth, while the lower elevation collections did the poorest. *E. grandis* was an exception. This species is closely related to *E. saligna* and is usually found on lower slopes or alluvial flats (Rodger 1953). Nevertheless, in tests at Canberra, (which is outside its natural range), *E. grandis* has shown resistance to temperatures lower than would occur within its natural range (Rodger 1953).

Greater effort is being taken to ensure that a wider selection of known seed sources be included in future tests. We have begun studies of variation within the faster-growing species. *E. camaldulensis* and *E. grandis* provenance tests are in progress. *E. viminalis, E. dalrympleana,* and *E. globulus* studies are needed.

LITERATURE CITED

Metcalf, Woodbridge.
1924. **Growth of *Eucalyptus* in California plantations.** Univ. Calif., Agric. Exp. Stn., Bull. 380, 61 p. Berkeley, Calif.
Metcalf, Woodbridge.
1961. **Progress with eucalypts in North America, 1956-1961: United States mainland.** *In* National Reports for Second World *Eucalyptus* Conference, [Sau Paulo, Brazil, Aug. 13-26, 1961], p. 1-18.
Metcalf, Woodbridge.
1967. ***Eucalyptus* species for California.** Univ. of Calif., Berkeley, Calif. 23 p.
Pryor, Lindsay D.
1976. **The biology of eucalypts.** Stud. in Biol. 61, 82 p. Edward Arnold (Pub.) Ltd., London.
Rodger, G. J.
1953. **The natural occurrence of the eucalypts.** Leafl. 65, 115 p. Aust. For. and Timber Bur.

King, James P., and Stanley L. Krugman.
1980. **Tests of 36 *Eucalyptus* species in northern California.**
Res. Paper PSW-152, 6 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

A trial of 36 species of *Eucalyptus* near Concord, California, found species of sufficiently rapid growth and good survival to merit further screening. Species from western Australia and of the subgenus *Monocalyptus* all failed on the site. *E. camaldulensis*, *E. dalrympleana*, *E. glaucescens*, *E. grandis*, *E. nitens*, *E. ovata*, and *E. viminalis* were the species with best survival and growth.

Retrieval terms: Eucalyptus, species trial, California, eucalypts

United States
Department of
Agriculture

Forest Service

**Pacific Southwest
Forest and Range
Experiment Station**

Research Paper
PSW-153

Growth of White Firs Defoliated by Modoc Budworm in Northeastern California

George T. Ferrell

Author:

GEORGE T. FERRELL, a research entomologist, is studying the biology, ecology, and control of destructive forest insects, with headquarters in Berkeley, Calif. A native of Klamath Falls, Oreg., he earned three degrees at the University of California, Berkeley: a bachelor's in forestry (1959), a master's in zoology (1965), and a doctorate in entomology (1969). He joined the Station's research staff in 1969.

Acknowledgment:

The study reported in this paper was originated by John R. Pierce, entomologist, Forest Insect and Disease Management Staff, Pacific Southwest Region, Forest Service, U.S. Department of Agriculture, San Francisco, Calif.

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

October 1980

Growth of White Firs Defoliated by Modoc Budworm in Northeastern California

George T. Ferrell

CONTENTS

IN BRIEF . . .

Ferrell, George T.

1980. **Growth of white firs defoliated by Modoc budworm in northeastern California.** Res. Paper PSW-154, 9 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Retrieval Terms: Modoc budworm, *Choristoneura viridis*, white fir, *Abies concolor*, defoliation effects, growth, injury

Outbreaks of Modoc budworm (*Choristoneura viridis*) defoliating white firs (*Abies concolor*) occurred during the years 1959-62 and 1973-75 in the Warner and nearby ranges of northeastern California.

Effects of the outbreaks on fir growth were analyzed by two methods. In 1974, combined totals of 24 firs and 9 nonhost ponderosa pines were sampled from three stands which were defoliated during both outbreaks. Growth of the two species was compared during both outbreak and nonoutbreak periods over the years 1950-74. This method was used because, during the earlier outbreak, defoliation records from individual firs were lacking.

In 1976, a combined total of 36 firs was sampled in four other stands defoliated by the 1973-75 outbreak. Based on defoliation and budworm larval density ratings made in 1974, growth in these firs during the years 1973-76 was compared.

The same growth sampling methods were used in 1974 and 1976. To improve growth comparability, only open-grown, pole-sized trees 40 to 80 years old were sampled. After the trees were felled, height and radial increments (the latter at upper, mid and lower bole levels) for 1950 through the year of sampling were measured. These measurements were converted to growth indexes expressing annual growth as a percentage of increment predicted by fitting a linear regression to each increment series. Growth index analysis, developed by dendrochronologists, eliminated growth patterns due to tree, site, and stand factors in order to isolate growth fluctuations caused by weather and defoliating insects.

Results of fir-pine comparisons for the stands sampled in 1974 indicated that height, but not radial, growth of the two species differed more during outbreak than nonoutbreak periods. Both species had height and radial growth depressions in response to droughts associated with the outbreaks. Compared to pines, however, firs averaged a 14.5 percent or 34.0 cm (1.1 ft) cumulative deficit in height growth over the years during and immediately following the outbreaks. Annually during these periods, the sizes of such deficits were related to the incidence of topkilling in the firs sampled. During the years of the earlier outbreak, both the height growth deficits (0 to 15 percent), and the incidence of topkilling (0 to 3 percent), were low. During the more recent and extensive outbreak, however, both the height growth deficits and the incidence of topkilling increased, rising to 77 and 50 percent, respectively, in 1974—the peak year of the outbreak. Much of the latter height growth deficit, however, was expected to be only temporary because only the current year's growth was killed and, judging from previous topkills, would have been replaced by new tops.

Results of analyzing fir growth in the stands sampled in 1976—1 year after the more recent outbreak had subsided—allowed additional interpretation of the effects of budworm defoliation. Fir growth deficits related to percent crown defoliation during this outbreak were largely limited to 1974. In this year, compared to firs with light (less than 50 percent) defoliation, deficits in firs with medium (50-70 percent) defoliation averaged 33 and 14 percent in height and upper bole radial growth, respectively. These deficits were again related to the incidence of topkilling in these defoliation ratings (10 percent light, 48 percent medium). In 1974, however, results of growth comparisons among firs rated for larval density were largely nonsignificant or contrary to the results expected. Some firs evidencing reduced growth had low larval densities but were heavily defoliated and consequently abandoned by the budworms, resulting in low larval density estimates for these trees.

Host tree effects of the relatively short (3- to 4-year-long) Modoc budworm outbreaks appeared minor compared to the effects on the growth and mortality of conifer hosts by other, more protracted *Choristoneura* budworm outbreaks. Fir mortality associated with Modoc budworm outbreaks was not reported; because topkilling was usually limited to the current year's growth, only a slight crook or fork, and no decay, occurred in the stem in later years. Fir cone crops and Christmas tree values were probably temporarily reduced, but unless future Modoc budworm outbreaks are more protracted or otherwise intensified, this insect can be considered only a marginal pest of firs in California.

Defoliation of white firs (*Abies concolor* [Gord. and Glend.] Lindl.) by feeding green larvae of a tortricid moth has been detected in northeastern California over the last three decades. The defoliation, primarily in the current year's growth and heaviest in the tops of the firs, was formerly attributed to a green form of the spruce budworm (*Choristoneura fumiferana* Clements). Recently, Freeman (1967) recognized this form as a separate species (*C. viridis*) from either the spruce budworm or the western spruce budworm (*C. occidentalis* Free) Although *C. viridis* also infests white fir and grand fir (*A. grandis* [Doug.] Lindl.) in south-central Oregon (Stehr 1967), outbreaks in California have been confined to the Warner Mountains and neighboring ranges in Modoc County; thus, this insect is commonly referred to as the Modoc budworm.

Defoliation in the Warner Mountains has fluctuated from levels characterized in pest detection reports[1] as very light to heavy during the period 1949-76, with considerable local variation within years. From 1949 to 1958, defoliation ranged from very light to light, but in 1959 the infestation enlarged and some topkilling was noted in 1960. By 1961, light to heavy defoliation as well as some topkilling occurred on about 32,000 acres. The infestation subsided the next year and remained at low levels until 1973 when populations again increased. By 1974, the acreage infested was larger than that recorded in any previous outbreak; defoliation ranging from slight to severe was detected on 143,000 acres in the Warner and nearby Manzanita and Knox Mountains. But populations again subsided in 1975, and only 13,000 acres were defoliated. By 1976, Modoc budworm populations were again at an endemic level and no detectable defoliation was expected in 1977.

Serious growth reduction and mortality have been reported in conifer stands defoliated by outbreaks of other *Choristoneura* budworms in both western and northeastern North America (Johnson and Denton 1975, Kulman 1971). The effects of defoliation by Modoc budworm on white fir growth have not, however, been previously studied.

This paper investigates growth patterns and topkilling in white fir stands which were defoliated during the 1959-62 and 1973-75 Modoc budworm outbreaks in northeastern California to determine if this insect is an economic pest justifying control measures.

[1] California Forest Pest Control Action Council. 1949-1976. Annual reports. (Unpublished reports on file, Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.)

METHODS

The use of growth increment patterns to estimate growth reduction in conifers defoliated by species of *Choristoneura* budworms in the western United States has been hampered by the occurrence of other defoliating insects and weather phenomena affecting the growth of both host and nonhost trees (Johnson and Denton 1975). Growth fluctuations due to these other agents frequently mask growth reductions caused by budworm defoliation. Similar difficulties were expected in estimating the effects of defoliation by Modoc budworm, since conifer stands in the Warner Mountains and vicinity have also been subjected to periods of subnormal precipitation and defoliation by other insects during the last three decades. During this period, annual summaries of California weather published by the U.S. Weather Bureau indicate that annual precipitation was below normal at nearby Alturas Ranger Station in the years 1949, 1954-61, 1966-68, and 1972-76. The Modoc budworm outbreaks in 1959-62 and 1973-75 were each associated with periods of 3 years or more when precipitation averaged at least 25 percent below normal (*fig. 1*), although extensive defoliation was not detected following lesser precipitation deficits in other years.

In addition to Modoc budworm, infestations of other insects defoliating white firs have been reported in the Warner Mountains and vicinity over the last three decades. During the 1959-62 Modoc budworm outbreak, larvae of a tortricid moth (*Argrotaenia* sp.) contributed to the defoliation as did the coneworm *Dioryctria renicullela* (Grote). During the 1973-75 outbreak, the fir needleminer *Epinotia meritana* Heinrich ap-

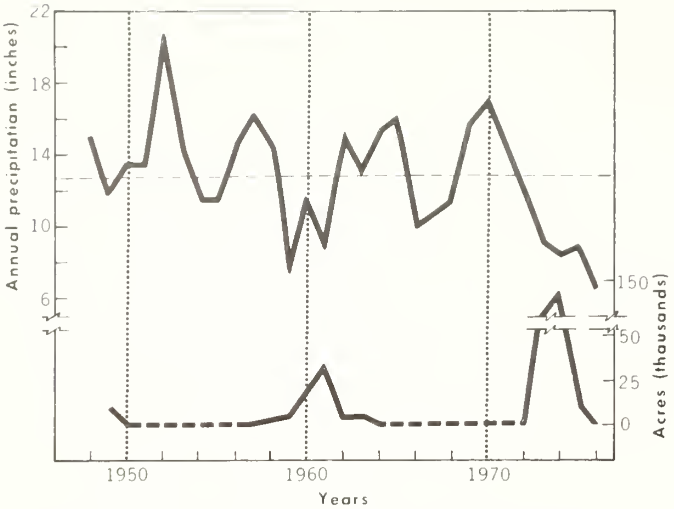


Figure 1—Modoc budworm outbreaks in 1959-62 and 1973-75, depicted as peaks in the acreage defoliated, were each associated with periods of 3 or more years when precipitation was at least 25 percent below normal (horizontal line) at nearby Alturas Ranger Station, in northern California. Dashed lines indicate periods when the infestation was endemic and no acreage estimates were made.

peared in localized areas. An outbreak of the Douglas-fir tussock moth *Orgyia pseudotsugata* McDunnough seriously defoliated limited acreage in the Warner Mountains and vicinity in the period 1964-65. Persistent, localized defoliation of white firs by white fir sawflies (*Neodriprion* sp.) was also reported in these areas during the period studied.

Due to these possibly complicating influences and to the fact that estimates of Modoc budworm population and defoliation on individual sample firs were available only for the year 1974, two different methods were used to try to isolate possible growth reductions in white fir resulting from defoliation by Modoc budworm.

Growth Comparisons Between Host and Nonhost Trees

In the stands sampled in 1974, growth patterns in white firs were compared with those in nonhost ponderosa pines (*Pinus ponderosa* Dougl. ex Laws.). The stands were selected because the fir component was defoliated during the Modoc budworm outbreaks, but no insects or diseases influencing growth of the pines were reported. This approach assumes that growth patterns of host and nonhost trees growing in the same stand should be similar, except during outbreak periods when host trees were defoliated but nonhost trees were not. Any deficits in host, versus nonhost, growth associated with these outbreak periods were then assumed attributable to the effects of the defoliation. Although these assumptions may be subject to error (Kozlowski and Keller 1966, Nairn and others 1962), this method was nevertheless resorted to in the present study because of the absence of individual tree defoliation records from the earlier 1959-62 outbreak. To check the validity of these assumptions, the analysis first compared pine-fir growth differences between outbreak and non-outbreak periods. Commonly, outbreaks of other conifer-feeding budworms have resulted in host tree growth depressions persisting for at least several years after the outbreaks have subsided (Johnson and Denton 1975, Kulman 1971). Therefore, for the 1959-62 Modoc budworm outbreak, fir growth deficits during the period 1959-64 were attributed to the effects of the outbreak. The similar period for the 1973-75 outbreak, however, was only 1973-74, as the trees were felled for sampling in 1974. Further sampling was undertaken in 1976, after the outbreak subsided, to assess more complete growth effects of this outbreak.

For purposes of comparison with the outbreak growth periods, nonoutbreak periods were defined as growth periods during the years 1950-58 and 1965-72, assuming that the very light to light fir defoliation reported during these periods caused little or no growth reduction in the firs.

In 1974, three plots were sampled in mixed white fir-ponderosa pine stands, in which the firs were defoliated by Modoc budworm during the years 1959-62[2] and 1973-75 (no outbreaks of other defoliating insects were reported during the period 1950-74). The plots were located at elevations of 1800 to 2400 m (6000 to 8000 ft) along 64 km (40 mi) of the north-south backbone of the Warner Mountains. The plots were sampled during the period July 22 to August 15 when current height and radial growth were expected to be essentially completed, judging from long-term records for comparable elevations in the Sierra Nevada (Fowells 1941). On each plot eight white firs and three ponderosa pines were sampled. Only young, rapidly growing trees 40 to 80 years old, 15 to 35 cm in dbh, and 8 to 20 m tall, with dominant or open-grown crowns were sampled to avoid the effects of suppression and improve growth comparisons. Study results of other conifer-feeding *Choristoneura* sp. indicated that such firs were also expected to support higher budworm populations (Williams and others 1971) and to suffer larger percentage growth reductions (McLintock 1955) than slower growing firs with less exposed crowns.

At the time of sampling, defoliation of the firs appeared as a reddening of the new growth on the branch tips, concentrated mainly in the tops, giving the fir a scorched appearance. Many of the current year's buds or shoots were killed, as were most of the new needles once they had been partially consumed and loosely webbed together. The budworms also fed on the older needles but to a lesser extent. Foliage of a few top whorls of many firs was sparse and faded (*fig. 2*), contrasting strongly with foliage beneath the top which was often abnormally bushy and clumped, probably due to the growth of adventitious buds and shoots in response to the death of buds during earlier defoliations, as described for other conifer-feeding *Choristoneura* sp. (Schmidt and Fellin 1973, Williams 1967).

The trees were severed 45 cm above ground and the following measurements were taken: *stump*—age by ring count with 6 years arbitrarily added for the tree to reach stump height, diameter outside bark (cm); and *bole*—total tree height (m)

[2] Pacific Northwest Region, Forest Service. 1961-1964. Spruce budworm egg mass biological evaluation. (Unpublished report on file, Pacific Southwest Region, Forest Serv., U.S. Dep. Agric., San Francisco, Calif.)

and the lengths (cm) of internodes for the years 1950-74. Uncertainty over delimitation of internodes was resolved by sectioning the bole and comparing ring counts made above and below the specific internode. Topkill in previous years was visible as a dead terminal issuing from a fork or crook in the bole (*fig. 3*). Both the length of the killed tip (cm) and the year it was killed (by counting the internodes on a regrown leader) were recorded. Because growth reduction in grand firs defoliated by western spruce budworm was found to vary with height in the bole (Williams 1967), a 2-cm-thick cross-sectional disk was sawn from three levels in the bole, defined as midbole (1950 internode); upper bole (midway between the 1950 internode and the top), and lower bole (stump height). Three 2-cm-wide radial sections were then sawn from each disk. On lower bole and midbole sections, the width of each annual ring formed in the years 1950-74 was measured (±0.01 mm). All rings formed in the years 1960-74 were measured on upper bole sections from a region of the stem that was too young to have increments from the 1950's. After cross-checking the sections for false (traumatic) and missing or discontinuous rings, averages of each ring width on the three radial sections from each disk were used in the growth analysis.

Growth index analysis developed by dendrochronologists (Fritts 1966) was used to isolate growth effects attributable to the outbreaks. The indexes were designed to increase comparability of tree growth by isolating growth fluctuation caused by weather and defoliation and eliminating growth patterns attributable to differences in species, age, site, and surrounding stand characteristics. Other methods to separate the effects of these factors on radial growth of trees have been developed but require more complete stem dissections (Duff and Nolan 1953, Mott and others 1957, Stark and Cook 1957) or more elaborate statistical analysis (Williams 1967).

The growth indexes were calculated by fitting a least squares regression line with positive, negative, or zero slope to both height and radial increments formed in each tree in the years 1950-74, or in the upper bole radial increments from the early 1960's through 1974 (*fig. 4*). Linear regression was considered adequate after plotting increment series from a

Figure 2—Recent defoliation by Modoc budworm left fir tops with thin, faded foliage. Bushy, clumped foilage in lower crowns resulted from adventitious growth response of trees to past defoliation.

Figure 3—Topkilling attributed to previous outbreaks of Modoc budworm was limited to the former terminal shoot (central dead twig), which was later replaced by upturned branches forming a forked stem.

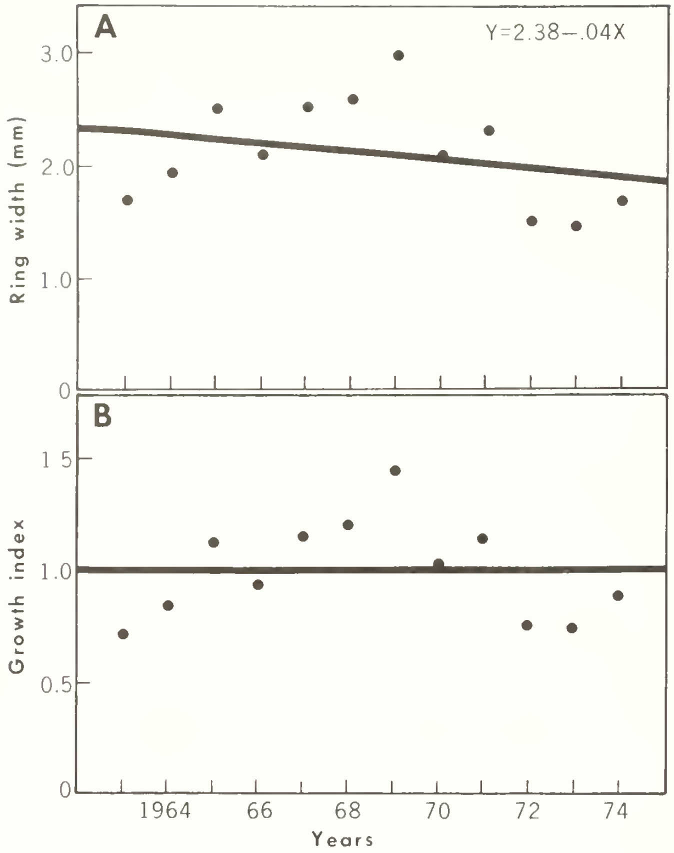


Figure 4—Annual growth indexes calculated for radial increments in the upper bole of white fir for the years 1963-74. The measurements are divided by values predicted by regression line (A) to obtain indexes varying about 1.0, representing predicted or expected growth (B).

subsample of trees, which indicated that curvilinearity could be ignored due to the short length of the series studied. Each year's index was then obtained by dividing the measured increment by that predicted by the regression line. Indexes with a value of 1 represented growth equal to expected growth patterns in the absence of unusual factors such as drought or defoliation. Indexes with a value less than 1 indicated growth below that expected from long-term patterns in the tree, while indexes greater than 1 indicated growth above predicted levels. When multiplied by 100, the indexes expressed annual growth as a percentage of predicted growth based on increments over the entire 1950-74 study period.

Pine-fir growth differences during outbreak periods were compared with those during nonoutbreak periods, as follows. For each year studied, the signed difference between the mean growth index of pines and that of firs (pine-firs) was obtained on each plot. To provide a firm basis for comparison, periods associated with the outbreaks (1959-64, 1973-74) were combined, as were nonoutbreak periods (1950-58 and 1965-72), and data from all three plots were analyzed. Since neither the indexes nor their differences were expected to be normally distributed, the nonparametric Fisher's randomization test (Bradley 1960, Green 1977) was used, although it was realized that the growth differences were not completely independent observations. The probability of randomly obtaining a mean growth difference between periods larger than that observed was calculated and declared significant at the 5 percent level For increments in which signed differences between pines anc firs during outbreak periods significantly exceeded difference: during nonoutbreak periods, the average growth deficit in fir during outbreak periods was obtained as the difference be tween the mean growth index of the two species—expressec as a percentage of predicted increments.

Growth Comparisons Among Host Trees Grouped by Defoliation and Larval Density Ratings

Methods used in 1976 to sample stands and calculate growtl index to search for growth reductions and topkilling attribut able to the 1973-75 outbreak were similar to those methods fo stands sampled in 1974. In 1976, a total of 16 firs was sample from three stands in the Warner Range, and an additional 2 firs were sampled from a single stand at nearby Manzanit Mountain. All four stands were currently being defoliated an had been sprayed with insecticide in late June 1974 whe Modoc budworms were fifth to sixth instar larvae. Both befor and after treatment, budworm population density and crow defoliation were estimated in these trees in order to gauge th efficacy of the insecticide spray. Results of this evaluatio indicated that, although over 90 percent of the larvae wer killed, little or no defoliation was prevented,[3] enabling thes trees to be used for growth impact studies.

Defoliation of each fir was rated as light, medium, or heav by the following method. The crown was visually divided int six horizontal strata. Separate ocular estimates were made o the percentage defoliation of both the new (current year's) an the old (previous years') foliage in each stratum. These esti mates were recorded as defoliation scores. The scores and th percentage defoliation they represented were 0 (none), 1 (les than 50 percent, 2 (50 to 90 percent), and 3 (greater than 9 percent). New and old foliage scores were averaged over a strata. Due to retention of foliage produced in previous years the ratio of old to new foliage in the crown was estimated a about 4:1. Thus, the same score for both old and new foliag was interpreted to indicate that the biomass of old foliage los was about four times that of new foliage. Therefore, averag scores for old and new foliage were weighted by factors of and 1, respectively, when averaged to obtain an overall defoli ation score for the entire crown. A light defoliation rating wa arbitrarily represented by an overall score less than 1.0, indi cating less than 50 percent crown defoliation. Scores of 1.0 t 1.5 represented medium, or about 50-70 percent defoliation. score over 1.5 was rated as heavy, or in excess of 70 percen crown defoliation. It appeared that not all of this defoliatio occurred in 1974; some of the defoliation of old growth prob ably occurred in 1973. Thus, the tree's score was interpreted t represent the cumulative amount of defoliation during th period 1973-74.

[3] Pierce, J.R. 1974. Pilot control project of Dylox on the Modoc budworm (Unpublished report on file, Pacific Southwest Region, Forest Serv., U.S Dep. Agric., San Francisco, Calif.)

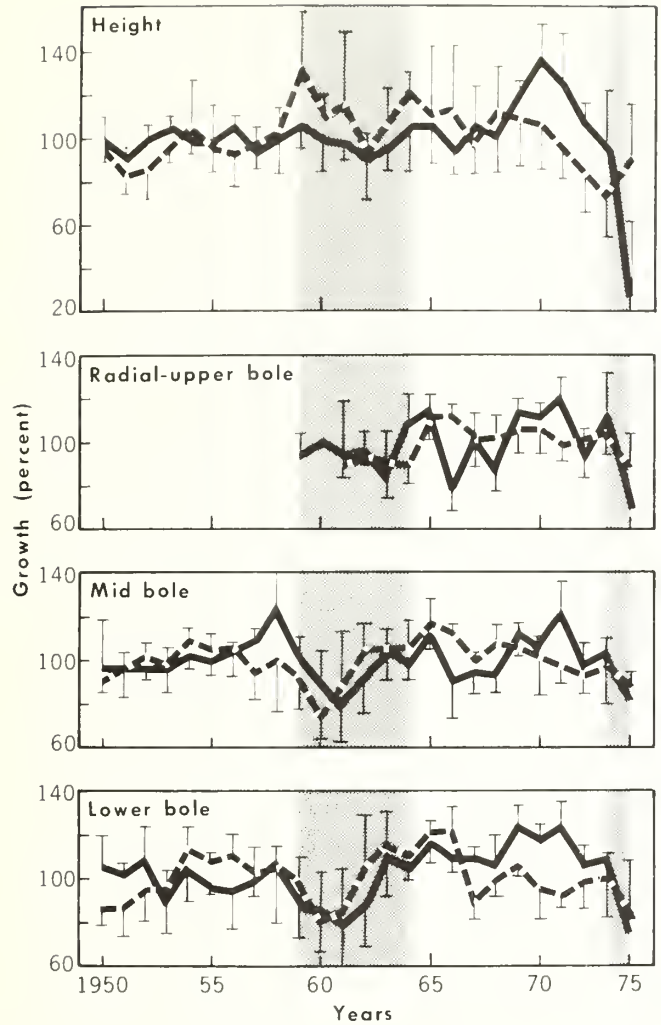


Figure 5—Mean annual height and radial growth as percentages of predicted increments in white firs (solid lines) and ponderosa pines (dashed lines) in three fir stands defoliated by both the 1959-62 and 1973-75 Modoc budworm outbreaks. For growth comparisons, outbreaks (shaded) were compared with nonoutbreak (unshaded) periods. Vertical lines extend one standard deviation from means.

Similarly, the budworm population density on each tree was rated as light, medium, or heavy. Budworm counts were made on four mid-crown branches of each tree. The foliage surface area on each branch was calculated by measuring the maximum dimensions of the foliage, both along and normal to the branch axis. These dimensions were considered to represent the altitude and base, respectively, of a triangular surface area of foliage on each branch.

From the budworm counts and the foliage surface areas on the four branches from each tree, the mean density of budworms per 1000 square inches of foliage surface was calculated for the tree. Budworm densities averaging less than 100 per 1000 square inches foliage were arbitrarily rated as light, 100 to 200 as medium, and over 200 as heavy.

Annual growth indexes for each tree were calculated by measuring annual height and radial increments for the years 1965-76. Increments from earlier years were ignored, since some of the firs in the Manzanita Mountain area were defoliated by tussock moth in 1964-65. Mean and standard deviation were calculated for annual growth indexes of firs in each of the defoliation ratings. For each of the years between 1973-76, variation in the mean annual growth index for firs in the defoliation and larval density ratings was analyzed for significance (5 percent level) by the nonparametric Kruskal-Wallis test (Kruskal and Wallis 1952) and, where significant, used as a basis for paired comparisons between ratings also at the 5 percent level of significance (Miller 1966, p. 166-167).

Table 1—*Mean annual height and radial growth differences between nonhost ponderosa pines and white firs during Modoc budworm outbreak compared with nonoutbreak years during the period 1950-74 on three plots, Warner Mountains, California*

Increments and bole level sampled	Growth as a percentage of predicted increment		
	Outbreak (O)	Nonoutbreak (N)	Differences (O−N)
Height growth:			
Pines	104.4	97.8	6.6
Firs	89.9	104.7	−14.9
Diff.[1]	14.5	−6.9	21.5*
Radial growth:			
Upper bole:			
Pines	92.4	104.0	−11.6
Firs	96.9	101.5	−4.6
Diff.	−4.5	2.5	−7.0†
Midbole:			
Pines	94.4	102.2	−7.8
Firs	93.3	102.8	−9.5
Diff.	1.1	−0.6	1.7†
Lower bole:			
Pines	96.4	101.4	−5.0
Firs	91.3	104.1	−12.8
Diff.	5.1	−2.7	7.8†

[1]Signed difference (pines-firs). Only differences followed by symbols were tested statistically.
*Statistically significant at 5 percent level (Fisher's test).
†Not significant.

RESULTS

Growth Comparisons Between Host and Nonhost Trees

Growth comparisons between firs and pines during outbreak and nonoutbreak periods indicated that the height growth of firs might have been affected by the outbreaks. Trends in mean annual growth as percentages of predicted increments indicated that both height and radial growth of both species was depressed during the outbreaks in response to the associated periods of subnormal annual precipitation (*fig. 5*).

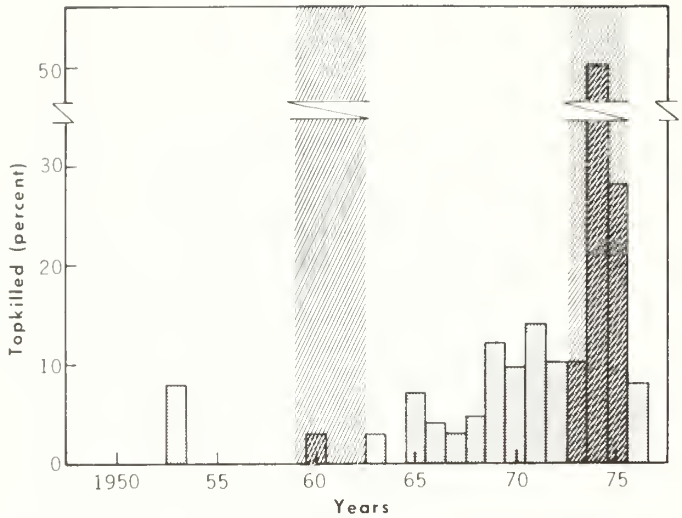


Figure 6—During the outbreaks (hatched periods), the annual percentage of firs topkilled (1974 and 1976 samples combined) had not exceeded 3 percent during the years 1959-62, but increased to 50 percent during the more extensive outbreak in 1973-75.

During outbreak periods, however, differences in height growth between species were significantly greater than during nonoutbreak periods, although such differences in radial growth were not significant at any bole level sampled (*table 1*). During outbreak periods, height growth of firs averaged 89.9 percent of predicted increments, compared with a 104.4 percent growth rate for pines, indicating that the firs had an average annual height growth deficit of 14.5 percent during these periods. The reverse occurred during nonoutbreak periods, however, when the height growth of firs exceeded that of pines by an average of 6.9 percent per year.

Based on these growth percentages and the average height growth of firs during the outbreak periods as predicted by the regressions, the cumulative deficit in height growth of firs compared with pines over these periods can be calculated in centimeters or feet. Predicted height growth of firs over these years should have averaged 236.1 cm (7.8 ft). If, however, the firs had grown at the rate averaged by the pines during these periods, their cumulative height growth should have averaged 104.4 percent of predicted growth, or 246.0 cm (8.1 ft). Instead, fir height growth averaged only 89.9 percent of predicted growth, or 212.0 cm (7.0 ft). Compared to pines, therefore, the firs had an average height growth deficit of 34.0 cm (1.1 ft) attributable to the two outbreaks.

During the years of the outbreaks, height growth deficits in the firs were related to the incidence of topkilling (*fig. 6*). During the 1959-62 outbreak, such deficits ranged from 0 to 15 percent and percentages of topkilled firs varied from 0 to 3 percent. During the more extensive outbreak of 1973-75, both the deficits and percentage of firs topkilled increased to 77 and 50 percent, respectively. During nonoutbreak periods, however, considerable topkilling also occurred, which was only partially related to subnormal precipitation or outbreaks of other defoliating insects.

Host Tree Growth Related to Defoliation and Larval Density Ratings

In firs sampled in 1976, growth reductions related to percentage of crown defoliation during the 1973-75 outbreak were largely limited to 1974—the peak year of the outbreak and the year when the defoliation estimates were made. During the years 1973-76, the height growth of firs in all ratings remained near predicted levels. Radial growth, however, declined at all three bole levels, probably in response to declining annual precipitation during this period. In 1974, however, firs with medium ratings (50-70 percent defoliation) averaged growth deficits of 33 percent in height and 14 percent in upper bole radius, compared to predicted increments in firs with light (less than 50 percent defoliation) ratings (*table 2*). These deficits were related to the percentage of firs in those ratings which were topkilled in 1974, 48 and 10 percent in medium and light ratings, respectively (*table 3*). In two comparisons, only firs rated as having heavy (greater than 70 percent) defoliation had significant growth deficits compared to firs in the other ratings. In 1974, heavily defoliated firs averaged a 16-percent deficit in lower bole radial growth compared to firs with light ratings. Comparable deficits were not found in height and upper bole radial increments for 1974, however, probably because none of the heavily defoliated firs was topkilled in that year. At the upper bole level in 1976, however, these firs averaged a radial growth deficit of 20 percent and had a higher incidence of topkilling (67 percent), compared to firs

Table 2—*Mean annual height and radial growth as percentages of predicted increments for white firs with light, medium and heavy defoliation ratings during the 1973-75 Modoc budworm outbreak, Warner and Manzanita Mountains, California*

Defoliation rating	Mean percentage of predicted growth (standard deviation)[1]			
	1973	1974	1975	1976
		Height		
Light	100.3(33.5)	108.2(42.4)a	113.5(29.9)	105.1(26.8)
Medium	95.8(36.5)	77.5(48.7)b	102.9(29.5)	101.6(49.6)
Heavy	115.9(28.5)	92.0(58.0)ab	132.1(49.9)	117.6(57.1)
		Radial-upper bole		
Light	118.6(23.5)	105.7(17.1)a	82.8(13.7)	85.0(11.3)a
Medium	124.2(19.5)	91.5(19.6)b	80.8(20.4)	95.0(33.3)a
Heavy	130.8(16.1)	104.9(12.7)ab	73.4(15.6)	64.8(14.4)b
		Radial-midbole		
Light	121.5(15.6)	113.0(11.4)	81.9 (8.7)	91.2(13.2)
Medium	120.6(14.3)	109.6(10.7)	84.3(13.5)	79.9(20.1)
Heavy	113.4 (9.9)	105.1 (8.6)	88.2(12.7)	79.9 (5.3)
		Radial-lower bole		
Light	126.0(21.6)	116.4(12.9)a	82.2(15.0)	84.8(17.6)
Medium	114.1 (8.2)	111.9 (9.2)ab	87.6(15.7)	84.4(16.8)
Heavy	112.4 (5.5)	99.7 (8.8)b	91.4(25.5)	87.9(11.2)

[1]Means followed by different letters differ significantly; those means followed by the same letter do not. Variation among unlettered means was not significant at the 5 percent level (Kruskal-Wallis test).

Table 3—*Annual percentages of white firs topkilled in the years 1973-76 compared by defoliation, and larval density, ratings during the 1973-75 Modoc budworm outbreak in northeastern California*

Rating	Trees	1973	1974	1975	1976
		Percentage topkilled			
Defoliation[1]					
Light	10	10.0	10.0	20.0	0.0
Medium	23	17.4	47.8	30.4	4.3
Heavy	3	0.0	0.0	33.3	66.6
Larval density:[2]					
Light	17	23.5	47.1	35.3	11.8
Medium	13	7.7	30.8	23.1	7.7
Heavy	6	0.0	16.6	16.6	0.0

[1]Percent crown defoliation rated as light (less than 50), medium (50-70), or heavy (greater than 70).
[2]Mean number of larvae per 1000 square inches of foliage on four midcrown branches, rated as light (less than 100), medium (100-200), or heavy (greater than 200).

Table 4—*Mean annual height, and radial growth, as a percentage of predicted increments, for white firs with light, medium, and heavy larval density ratings during the 1973-75 Modoc budworm outbreak, Warner and Manzanita Mountains, California*

Defoliation rating	Mean percentage of predicted growth (standard deviation)[1] 1973	1974	1975	1976
	Height			
Light	100.9(39.4)	74.9(51.5)	106.2(39.1)	92.3(53.4)
Medium	96.0(33.0)	88.9(44.6)	115.2(17.8)	117.2(34.2)
Heavy	98.6(28.6)	112.0(44.7)	99.3(32.7)	108.3(26.0)
	Radial-upper bole			
Light	130.1(20.7)a	86.2(19.9)a	72.4(20.4)	91.8(35.8)
Medium	120.2(19.6)a	106.2(12.1)b	87.8(13.1)	85.3(24.0)
Heavy	110.5(11.9)a	108.2(16.3)ab	92.0 (9.5)	94.1(11.7)
	Radial midbole			
Light	115.0(13.2)	105.5 (9.4)	82.6(11.7)a	76.7(17.7)
Medium	122.9 (9.8)	112.9(10.8)	84.1(12.6)a	90.8(18.9)
Heavy	129.4(20.2)	117.4 (9.1)	87.6(13.4)a	84.1(11.3)
	Radial-lower bole			
Light	110.3(10.1)a	107.9(11.0)	87.0(16.5)	81.0(15.3)ab
Medium	121.9(14.9)ab	116.3 (9.1)	85.8(17.7)	93.8(17.2)a
Heavy	127.2(12.8)b	115.3(11.3)	86.3(13.7)	76.4 (6.9)b

[1]Variation among means followed by letters was significant. Means followed by different letters differed significantly in pair-wise tests, while means followed by the same letter were not statistically different. Variation among unlettered means was not significant (Kruskal-Wallis test, 5 percent level).

with light ratings. No comparable deficit was found in that year's height growth, although judging from older topkills, some permanent height growth loss probably resulted from this topkilling. Results from firs with heavy defoliation ratings, however, are somewhat uncertain due to only three trees in this rating.

Agreeing with results from defoliation ratings, only a few fir growth deficits related to budworm larval density in 1974 occurred in years associated with the 1973-75 outbreak. A growth deficit in firs with heavy, versus medium or light, larval density ratings occurred only in 1976 radial increments at the lower bole level (*table 4*). This growth deficit was not related to incidence of topkilling in these ratings (*table 3*). In the only other significant differences found between these ratings, radial growth deficits in firs with light larval densities occurred in 1973 (lower bole level) and 1974 (upper bole level). These results were opposite to those expected as was the incidence of topkilling in the ratings for these years. Underlying these results was an inverse correlation ($r = -0.49$) between defoliation and larval density in these trees, evidently caused by budworms abandoning heavily defoliated firs in favor of less defoliated trees.

CONCLUSIONS

The relatively short, 3- to 4-year-long outbreaks of Modoc budworm during the last 25 years have evidently had less effect on the growth and survival of white firs in northeastern California than the more protracted outbreaks of other budworms (*Choristoneura* sp.) on their coniferous host trees in eastern and western North America. For example, beginning the second year of defoliation of Douglas-fir, spruce, and true fir by western spruce budworm (*C. occidentalis*) in British Columbia, annual increments were reduced 30 to 60 percent over a 4-year period (Silver 1960). In Oregon, depending on the severity of damage from past defoliation and species of host tree, growth during a 10-year outbreak of this budworm was reduced by as much as 40 percent of the growth in the previous decade when no outbreak occurred (Williams 1967). Also, tops of the more severely damaged trees were killed by as much as 6 m (19.8 ft) down the bole, and death of some trees appeared imminent.

In reviewing the effects of severe defoliations of spruce and fir by *C. fumiferana* in northeastern North America, Kulman (1971) found that 30 to 100 percent of the trees died in severely defoliated stands which were subsequently attacked by bark beetles, with most of the surviving trees suffering topkill.

In contrast, the ponderosa pine-white fir growth comparisons estimated that white fir had an average deficit of 14.5 percent or 34.0 cm (1.1 ft) in height increment attributed to outbreaks during both the periods 1959-64 and 1973-74. Included in this average, however, was a 77 percent deficit in 1974, associated with the relatively high incidence of topkilling in that year. But judging from the older topkills examined, much of the 1974 deficit was expected to be only temporary due to subsequent replacement of the dead tops by upturned branches of the uppermost whorl. A more accurate estimate of permanent height growth loss in firs topkilled in 1974 is perhaps obtained from firs sampled in 1976 which had two years to recover from topkilling in 1974. Of these firs, those which had medium defoliation ratings and a 48 percent incidence of topkilling in 1974 had height growth deficits averaging 33 percent, compared with firs with light defoliation ratings and a lower incidence (10 percent) of topkilling.

Radial growth losses associated with the Modoc budworm outbreaks were even more limited than the height growth effects. In stands sampled in 1974, the fir-pine comparisons failed to detect any radial growth deficits attributable to the outbreaks at any of the three bole levels sampled in the firs. In stands sampled in 1976, however, firs with medium-to-heavy defoliation ratings in 1974 had average deficits of 14 percent in that same year and 25 percent in 1976 for radial increments at the upper bole level. Again, these deficits were associated with the high incidence of topkilling in those years. Similar deficits were not detected at the lower and mid-bole levels, except in 1974 when a 13 percent deficit was found at lower bole levels in trees with heavy defoliation. Finding radial growth reductions greater in the upper regions of the bole agreed, however, with the vertical distribution of radial growth effects found in trees defoliated by other *Choristoneura* budworms feeding preferentially on new growth of conifers (McLintock 1955, Williams 1967).

Topkilling was confirmed to be a direct result of defoliation. During the 1973-75 outbreak, the incidence of topkilling increased as the outbreak expanded and declined as the outbreak subsided. In 1974, the peak year of the outbreak, firs with medium to heavy defoliation had a higher incidence of topkilling than firs with light defoliation. The droughts associated with the outbreaks also may have contributed to the topkilling. Considerable topkilling, however, occurred inexplicably in years not associated with either outbreaks or droughts. Growth losses in both height and upper bole radius were strongly associated with topkilling; many of the sample trees were topkilled more than once during the two outbreaks. Because of the small size of killed tops, however, the resulting stem defects were limited to a slight crook or a fork, and no decay was observed.

Host tree mortality resulting from Modoc budworm infestations has not been detected. Increased killing of white firs by the fir engraver bark beetle (*Scolytus ventralis* Lec.) was reported in the Warner Mountains in the years 1960-64, 1967-68, and 1972, and localized mortality of firs infested by needle miner (*Epinotia meritana*) occurred on Manzanita Mountain in 1977. However, in none of these instances was defoliation by Modoc budworm implicated as an important factor contributing to the death of these trees.[4]

Defoliation by Modoc budworm left much of the tree crowns intact. Defoliation estimates made at the peak of the recent outbreak indicated that from 50 to 100 percent of the new or current year's foliage, but less than 50 percent of the old foliage from previous years, was destroyed on most trees. The new foliage, although more heavily fed upon, was estimated to comprise only about 25 percent of the foliage mass of the entire crown due to retention of the old foliage. Consequently, expressed as a percentage of the entire crown, 10 of the 36 white firs rated in 1974 had less than 50 percent of their crowns defoliated. Observations in 1976, after the outbreak subsided, indicated that the trees responded to the defoliation by producing adventitious buds and shoots to compensate for the destroyed foliage. Failure to find growth reductions in trees defoliated to this extent is not uncommon; a recent review of the literature on growth effects in trees defoliated by insects (Mattson and Addy 1975) indicated that trees with less than 40 to 50 percent of their crowns defoliated frequently suffer no detectable growth reductions.

Although not studied, impairment of aesthetic, forage, and watershed values appeared negligible due to the small proportion of the fir canopy which was damaged. Undoubtedly, the value of defoliated firs for Christmas trees was temporarily reduced. Also, cone production, which occurs exclusively in tops of white fir, may have been reduced in fir with heavy upper-crown defoliation and topkilling. Only open-grown pole-sized firs were sampled; but if these results are indicative, unless future outbreaks are of longer duration or otherwise intensify, the Modoc budworm may be considered a marginal economic pest of white fir in California.

[4] California Forest Pest Control Action Council. 1961-1977. Forest pest conditions in California. (Unpublished annual reports on file, Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.)

LITERATURE CITED

Bradley, James V.
1960. **Distribution-free statistical tests.** U.S. Air Force, Wright Air Development Division WADD Tech. Rep. 60-661, 377 p.

Duff, G.H. and Norah J. Nolan.
1953. **Growth and morphogenesis in the Canadian forest species. I. The controls of cambial and apical activity in *Pinus resinosa* Ait.** Can. J. Bot. 31:471-513.

Fowells, H.A.
1941. **The period of seasonal growth of ponderosa pine and associated species.** J. For. 39:601-608.

Freeman, T.N.
1967. **On coniferophagous species of *Choristoneura* (Lepidoptera: Tortricidae) in North America. I. Some new forms of *Choristoneura* allied to *C. fumiferana*.** Can. Entomol. 99:449-455.

Fritts, H.C.
1966. **Growth-rings of trees: their correlation with climate.** Science 154:973-979.

Green, Bert F.
1977. **A practical interactive program for randomization tests of location.** Amer. Stat. 31:37-39.

Johnson, Phillip C., and Robert E. Denton.
1975. **Outbreaks of the western spruce budworm in the American Northern Rocky Mountain area from 1922 through 1971.** USDA Forest Service Gen. Tech. Rep., INT-20, 144 p. Intermountain Forest and Range Exp. Stn., Ogden, Utah.

Kozlowski, T.T., and T. Keller.
1966. **Food relations of woody plants.** Bot. Rev. 32:293-382.

Kruskal, William H., and W. Allan Wallis.
1952. **Use of ranks in one-criterion variance analysis.** J. Amer. Stat. Assoc. 47:583-621.

Kulman, H.M.
1971. **Effects of insect defoliation on growth and mortality of trees.** Annu. Rev. Entomol. 16:289-324.

Mattson, William J., and Norton D. Addy.
1975. **Phytophagous insects as regulators of forest primary production.** Science 190:575-622.

McLintock, T.F.
1955. **How damage to balsam fir develops after a spruce budworm epidemic.** U.S. Forest Service Northeast Forest Exp. Stn. Paper 75, 17 p., Upper Darby, Pa.

Miller, Rupert G., Jr.
1966. **Simultaneous statistical inference.** McGraw-Hill, New York, 272 p.

Mott, D.G., C.D. Navon, and J.A. Cook.
1957. **Radial growth in forest trees and effects of insect defoliation.** For. Sci. 3:286-304.

Nairn, L.D., W.A. Reeks, F.E. Webb, and V. Hildahl.
1962. **History of larch sawfly outbreaks and their effect on tamarack stands in Manitoba and Saskatchewan.** Can. Entomol. 94:242-255.

Schmidt, Wyman C., and David G. Fellin.
1973. **Western spruce budworm damage affects form and height growth of western larch.** Can. J. For. Res. 3:17-26.

Silver, G.T.
1960. **Notes on a spruce budworm infestation in British Columbia.** For Chron. 36:362-374.

Stark, R.W., and J.A. Cook
1957. **The effects of defoliation by the lodgepole pine needle miner.** For. Sci. 3:376-396.

Stehr, G.W.
1967. **On coniferophagous species of *Choristoneura* (Lepidoptera: Tortricidae) in North America. II. Geographic distribution in accordance with forest regions.** Can. Entomol. 99:456-463.

Williams, Carroll B., Jr.
1967. **Spruce budworm damage symptoms related to radial growth of grand fir, Douglas-fir, and Engelmann spruce.** For. Sci. 12:274-285.

Williams, Carroll B., Jr., Patrick J. Shea, and Gerald S. Walton.
1971. **Population density of western spruce budworm as related to stand characteristics in the Bitterroot National Forest.** USDA Forest Serv. Res. Paper PSW-72, 8 p. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

The Forest Service of the U.S. Department of Agriculture

...Conducts forest and range research at more than 75 locations from Puerto Rico to Alaska and Hawaii.

...Participates with all State forestry agencies in cooperative programs to protect and improve the Nation's 395 million acres of State, local, and private forest lands.

...Manages and protects the 187-million-acre National Forest System for sustained yield of its many products and services.

The Pacific Southwest Forest and Range Experiment Station

...Represents the research branch of the Forest Service in California, Hawaii, and the western Pacific.

Ferrell, George T.

1980. **Growth of white firs defoliated by Modoc budworm in northeastern California.** Res. Paper PSW-153, 9 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Open-grown, pole-sized white firs defoliated by Modoc budworm (*Choristoneura viridis*) in northeastern California in the years 1959-62 and 1973-75 suffered only minor growth reductions and topkilling compared with the effects that more protracted budworm outbreaks have had elsewhere on their conifer hosts. Growth index analysis indicated that the firs averaged a cumulative height growth deficit of 14.5 percent, or 34 cm (1.1 ft), over both outbreaks. Firs heavily defoliated during the 1973-75 outbreak were more frequently topkilled and consequently suffered larger height growth deficits. Topkilling during both outbreaks, however, was limited to the terminal shoot, resulting in slight crooks or forks, but no decay, in the stems. Radial growth deficits attributable to the outbreaks were not found and, unless future outbreaks are more protracted or otherwise intensify, the Modoc budworm can be considered only a marginal economic pest of firs in California.

Retrieval Terms: Modoc budworm, *Choristoneura viridis*, white fir, *Abies concolor*, defoliation effects, growth, injury.

ted States
partment of
riculture

est Service

cific Southwest
rest and Range
periment Station

search Paper
W-154

Improving Plantation Establishment by Optimizing Growth Capacity and Planting Time of Western Yellow Pines

James L. Jenkinson

Author:

JAMES L. JENKINSON is a plant physiologist with the Station's research unit studying the genetics of western forest trees, with headquarters in Berkeley and field facilities at the Institute of Forest Genetics, near Placerville, California. His investigations are concerned with how diverse seed sources of pines and firs interact with the nursery environment to control seedling growth and survival potentials, and with the field environment to control tree growth in plantations. He earned degrees in forestry (B.S., 1957) and plant physiology (Ph.D., 1966) at the University of California, Berkeley, before joining the Station staff in 1966.

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

November 1980

nproving Plantation Establishment 'y Optimizing Growth Capacity and 'lanting Time of Western Yellow Pines

mes L. Jenkinson

CONTENTS

IN BRIEF...

Jenkinson, James L.

1980. **Improving plantation establishment by optimizing growth capacity and planting time of western yellow pines.** Res. Paper PSW-154, 22 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Retrieval terms: Pinus ponderosa, P. washoensis, P. jeffreyi, genetic variation, genotype-environment interaction, progeny tests, seedling growth, seedling survival, artificial regeneration

Spring plantations are readily established on cleared sites in the California forests if the planted seedlings are dormant and have the capacity to resume rapid growth. Because California's commercial conifers range through several climatic regions, seedlings of different seed sources in the same nursery may vary markedly in their fall and winter development of dormancy and growth capacity. These innate seasonal patterns must be defined and exploited if nurserymen are to consistently deliver seedlings with highest survival potentials.

This paper describes research to define the seasonal patterns of growth capacity for seedlings of 27 sources of western yellow pines raised in a nursery in the western Sierra Nevada, at the Forest Service Institute of Forest Genetics near Placerville. Coincident research explored the relation of field survival to planting time and site environment. The effect of planting time was assessed for sources from five western states by transplanting seedlings in winter and in spring to a cleared site below snow line. The effect of site environment was evaluated for selected sources from the northern Sierra Nevada by planting seedlings in spring on an elevational array of cleared sites, three west and one east of the Sierra crest. The findings apply directly to lifting schedules in the Forest Service Placerville Nursery and to planting schedules on the National Forests that the nursery serves.

In this survey of the western yellow pines, typical populations of California ponderosa, Jeffrey, and Washoe pines were sampled in four climatic regions—coastal California, western Sierra Nevada, eastern Sierra-Cascade, and southern California. Typical ponderosa pine was also sampled in continental climates in southern Oregon, eastern Nevada, central Arizona, and southeastern Wyoming.

Over a 4-year period, seeds of 6 to 9 of the 27 sources were sown in the nursery each spring. Three sources were sown twice to provide a base for comparing sources tested in different years. To monitor top and root growth capacity of each source through the winter season, first-year seedlings were sampled monthly and measured for new growth after 21 days in a standard warm environment. In the field survival tests, first-year seedlings were outplanted from the first and second sowings, and final survivals were recorded the next winter or spring.

There were large differences among sources in seedling root growth capacity (RGC), and the seasonal patterns of RGC were of four distinct types: fall-peak, winter-peak, plateau, and bimodal. That is, depending on source, seedling RGC peaked in fall only, in midwinter only, continuously from fall through winter, or in fall and again in winter. All four patterns were found in ponderosa pine from both outside and inside California, while bimodal patterns characterized Washoe pine and Jeffrey pine.

Midwinter-peak patterns typified ponderosa pine from coastal California, western Sierra Nevada, and eastern Sierra-Cascade regions, and Jeffrey pine from ultramafic soil in the western Sierra Nevada. Plateau patterns characterized ponderosa pine from the western Sierra foothills, Lake Tahoe Basin, and central Arizona. Fall-peak patterns were evident in ponderosa pine from the western Sierra pine belt and eastern Nevada. Bimodal patterns typified both ponderosa pine and Jeffrey pine from southern California, Washoe pine and Jeffrey pine from east of the Sierra crest, and ponderosa pine from southeastern Wyoming.

Within regions, shifts in the pattern for ponderosa pine apparently reflected elevational or latitudinal gradients in temperature and moisture regimes. In two regions, plateau and winter-peak patterns anchored the ends of the gradients. Along the slope of the western Sierra Nevada, the time needed to develop peak RGC increased with elevation of the parent stand, and duration of peak level decreased. East of the Sierra-Cascade crest, the time needed to reach peak RGC increased with latitude of the parent stand, and duration of peak level again decreased. In the San Gabriel Mountains of southern California, the pattern shifted from typically bimodal toward a late-winter peak with increasing elevation of the parent stand.

Apart from these environmental gradients, the seasonal pattern bore little apparent relation to the climate at seed origin. Each pattern type appeared in seedlings from two to four climatic regions, and three patterns appeared in each of two regions.

The seasonal pattern of seedling top growth capacity was a sigmoid curve, and for every source the chilling requirements for renewed top growth were met by midwinter. To enable bud swell, ponderosa pine from west of the Sierra crest required the least chilling, while Washoe pine and Jeffrey pine required the most. For rapid shoot extension, Washoe pine and ponderosa pine from continental climates required the least chilling, while ponderosa and Jeffrey pines from southern California required the most.

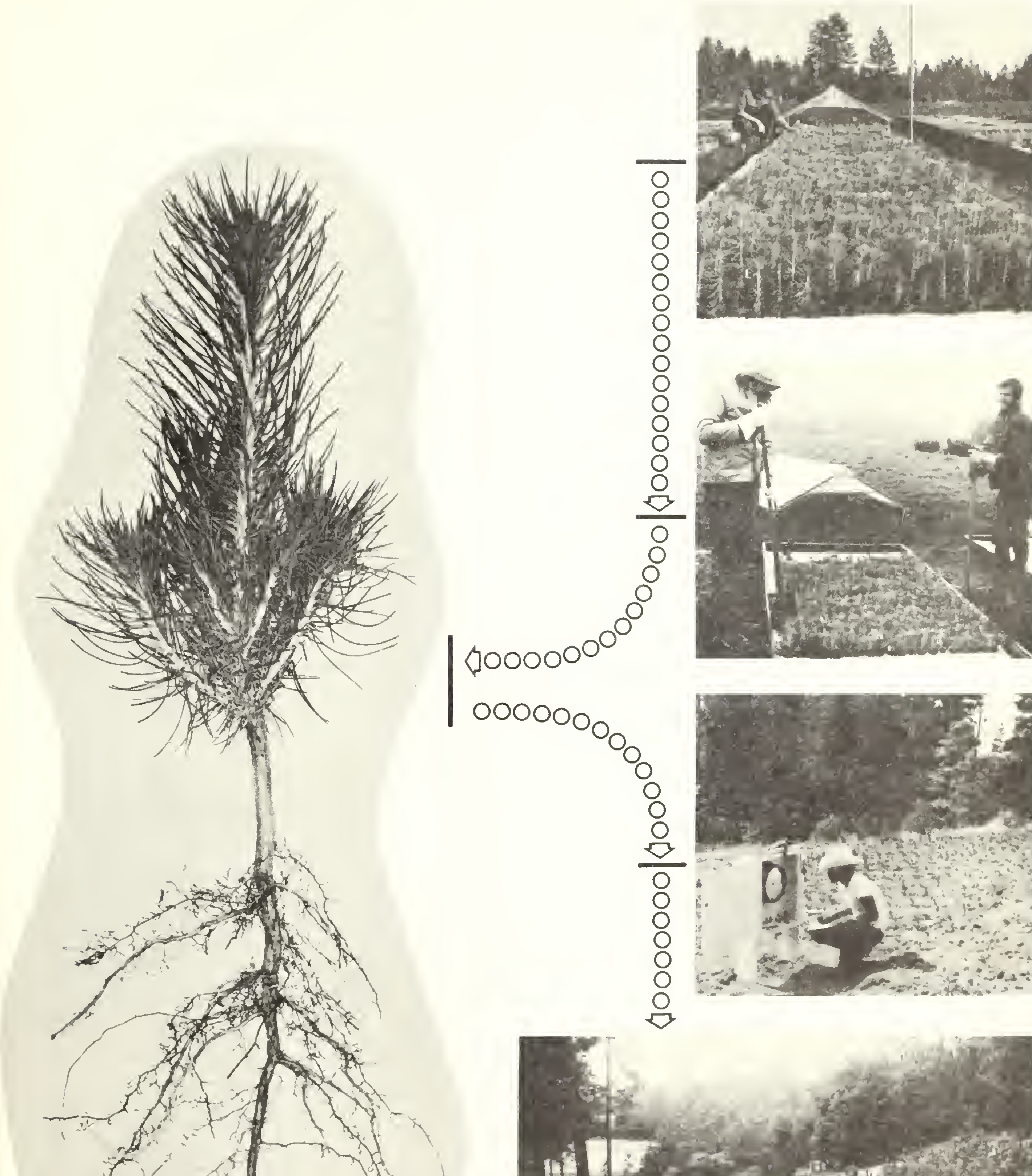
Both seed source and planting time affected seedling survival. Survival was significantly less in midwinter than in spring plantings, and consistently higher for California than for Arizona and Wyoming sources. California sources are adapted to summer drought, and thus survived better than the continental sources which normally receive summer rains. Seedlings planted in midwinter had root growth capacities two to three times higher than seedlings planted in spring, but in cold soil planted seedlings do not elongate roots, do undergo high water stress, and continually expend stored reserves. The expected results are large decreases in RGC before the soil warms in spring, and high seedling mortality during the summer drought.

Site environment and seed source had little or no influence on seedling survivals in spring plantations. Survivals of California ponderosa and Jeffrey pines, from parent stands at 500 to 8200 ft of elevation, were uniformly high on sites ranging from 1900 to 6600 ft. Evidently, plantation establishment is assured on cleared sites if dormant seedlings are lifted with moderate to high RGC, are properly stored, and are planted when the soils are warming sufficiently to enable water uptake and root elongation.

The innate seasonal patterns of RGC indicated optimum lifting schedules for particular sources of seedlings raised in the Placerville Nursery. The data were sufficient to identify specific lifting times for most sources from the northern Sierra Nevada, Cascade Range, Modoc Plateau, and southern California, but were insufficient or lacking for the Klamath Mountains, Coast Ranges, and southern Sierra Nevada.

High survivals in the elevational array of field tests identified planting times that enhance seedling establishment. Using these data, and recognizing that cold soil and evaporative stress limit the spring period when seedlings can be safely planted on a particular site, a planting schedule was prescribed for elevations ranging from 500 to 7000 ft in the central Sierra Nevada. Similar prescriptions, but different in calendar dates, may apply throughout California.

In essence, the key to plantation establishment for a particular seed source is knowing when to lift the seedlings in the nursery and when to plant them in the field.



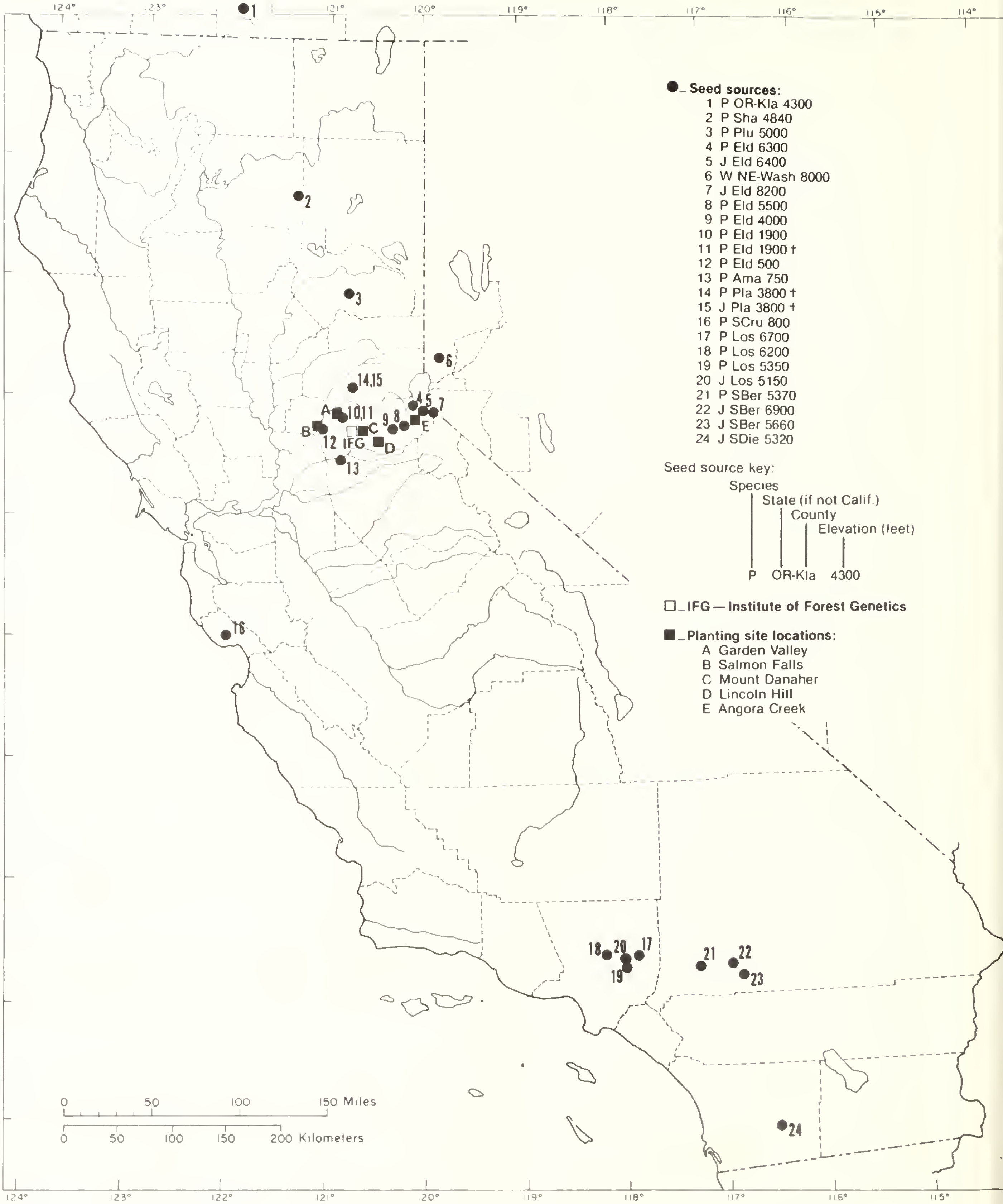


Figure 1—To investigate seedling growth capacity and field survival, 27 sources of ponderosa (P), Washoe (W), and Jeffrey (J) pines were grown in the Institute of Forest Genetics nursery, on Fruit Ridge in the western Sierra Nevada. For seed source description, see *table 1*. Three sources not shown were in Nevada, Arizona, and Wyoming.

Eight of California's commercially important conifers are commonly regenerated by planting bare-root seedlings: ponderosa, Jeffrey, and sugar pines (*Pinus ponderosa* Laws., *P. jeffreyi* Grev. & Balf., *P. lambertiana* Dougl.), Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), white and red firs (*Abies concolor* [Gord. & Glend.] Lindl., *A. magnifica* A. Murr.), incense cedar (*Libocedrus decurrens* Torr.), and big tree (*Sequoiadendron giganteum* [Lindl.] Buchholz). Plantation establishment of every species has varied widely, and it still ranges from mostly failure to routine success. The recent congressional directives to reforest unstocked timberland, i.e., the Supplemental National Forest Reforestation Fund Act and National Forest Management Act of 1976 (USDA Forest Serv. 1978), and yearly increases in regeneration cutting are now requiring the National Forests to triple the acreage that is planted annually. To secure plantation establishment quickly and consistently, foresters must understand the seedling responses to both the nursery and planting site environments.

Universally, bare-root seedlings that survive and grow best sort into the average and large sizes. They have top-to-root ratios under 1.5, and they are free of disease. To produce such "plantable" seedlings, nurserymen must successfully integrate soil management, seed treatment and sowing, mycorrhizal inoculation, irrigation, fertilization, undercutting, and pathogen control. However, optimum cultural regimes and morphological grades alone do not guarantee field survival. To insure plantation establishment, the physiological conditioning requirements of the seedlings must be met at the nursery, the planted seedlings must have adequate growth capacities, and the planting site environments must support seedling function and growth (Tinus 1974).

In most of the California forests, spring is the accepted time to plant bare-root seedlings. To survive in the field, newly planted seedlings must be dormant to minimize transpirational losses of water, and cold-hardy to endure frosts. Further, they must grow roots to reach enough available water to sustain top growth, form terminal buds, and avoid lethal stress during the summer drought.

In California's forest tree nurseries, it is largely the fall and winter climate that develops the seedlings' requisite physiological condition for spring outplanting (Stone and others 1963). Both seedling dormancy in the nursery and the amounts of growth that lifted seedlings can produce in a warm environment are closely related to the seedlings' prior exposure to cold (Krugman and Stone 1966, Stone and Jenkinson 1971).

Nurserymen fix the state of dormancy and the root and top growth capacity of the seedlings they harvest by their choice of the particular dates when those seedlings are lifted and stored. Silviculturists select the planting dates, and thereby determine the soil and air temperature-moisture regimes that planted seedlings encounter during the first critical weeks in the field. The initial field environment may decisively control the expression of growth capacity, and consequently seedling survival (Stone and Jenkinson 1970, Stone and Schubert 1959, Stone and others 1962, Ursic and others 1966).

California's conspicuous diversity of forest climate, physiography, and vegetation warns of large differences between species and between seed sources in how the nursery environment affects seedling dormancy and growth capacity. In the western yellow pines—ponderosa, Washoe (*P. washoensis* Mason & Stockwell), and Jeffrey—and in Douglas-fir, the seed source response to nursery environment creates major variation in the growth capacity of dormant seedlings (Jenkinson 1976, 1978).

This paper reports the inherent seasonal patterns of seedling growth capacity for the western yellow pines, and describes the influences of seed source, planting time and site environment on seedling survival in the field. The findings apply directly to the Forest Service Placerville Nursery, and to the planting operations of its clientele, the National Forests of California.

METHODS AND MATERIALS

Seed sources were deliberately chosen to sample a wide range of yellow pine environments in the Western United States, and especially California *(fig. 1)*. During the period from 1972 to 1976, seedlings of 27 sources were raised in a nursery in the western Sierra Nevada and lifted for specific studies after one growing season.

To evaluate the development of growth capacity, seedlings of every source were sampled periodically during their first winter season, and tested for growth in a warm standard environment (growth capacity study). To determine the effect of planting time on field survival, seedlings of 13 sources were outplanted in winter and in spring on a cleared site below snow line in the western Sierra Nevada (planting time study). To assess the effect of planting site environment on survival, seedlings of 7 local sources were planted in spring on cleared sites west and east of the Sierra Nevada crest (site environment study).

All studies were conducted by staff at the Institute of Forest Genetics, Pacific Southwest Forest and Range Experiment Station, near Placerville *(fig. 1)*. The Institute nursery and the Placerville Nursery are both located on Fruit Ridge, at an elevation of about 2750 ft (840 m). They are 1 mile (1.6 km) apart and have identical climates and soils.

Seed Sources

The seed sources were selected between latitudes 32° and 43°N, in forests that typify the species ranges (Critchfield and Little 1966, Griffin and Critchfield 1976) and vegetational associations in seven climatic regions *(table 1, fig. 1)*. Selection of ponderosa pine was also guided by geographic variation in the monoterpene composition of standing trees; sources were chosen in four of five type regions and two of four transition zones (Smith 1977, Sturgeon 1976).

To represent major climatic regions outside California, ponderosa pine was selected in southeastern Wyoming, central Arizona, and eastern Nevada. The Wyoming and Arizona sources are in continental climates with no drought and with spring drought, respectively (Beschta 1976; U.S. Dep. Comm. 1954, 1959, 1964a, 1965c). The Nevada source gets scattered thundershowers and is largely riparian (U.S. Dep. Comm. 1960, 1965a).

To provide a latitudinal transect in continental climates with summer drought, ponderosa pine was selected in four separate areas east of the Cascade Range and Sierra Nevada crests, from southern Oregon to Lake Tahoe (U.S. Dep. Comm. 1963; 1964b,c; 1965b). Jeffrey pine at the south end of the transect and both Washoe and Jeffrey pines in the adjacent Carson Range were chosen for comparison with ponderosa pine.

To sample a temperature-moisture gradient associated with elevation, ponderosa pine was selected at 500, 1900, 4000, and 5500 ft along or near South Fork of the American River, in the western Sierra Nevada (U.S. Dep. Comm. 1964b,c). Stands were also sampled on unusual and typically xeric sites, including ponderosa pine on an island of infertile, ultramafic soil in the pine phase of mixed conifer forest, ponderosa pine in the foothill woodland of the Cosumnes River drainage, and a mixed stand of ponderosa and Jeffrey pines in a large area of ultramafic soil surrounded by typical mixed conifer forest.

For a maritime climate, ponderosa pine was selected in the Santa Cruz Mountains of coastal California. Except for the frequent ocean fogs, the summer drought there resembles that in the western Sierra foothills (Griffin 1964; U.S. Dep. Comm. 1964b,c).

Finally, in southern California, a region where arid climates severely challenge regeneration (U.S. Dep. Comm. 1964b,c), ponderosa pine was selected at three elevations in the San Gabriel Mountains and in one area in the San Bernardino Mountains. Jeffrey pine was selected in the San Gabriel Mountains, in two areas in the San Bernardino Mountains, and in the Laguna Mountains of the southern Peninsular Ranges.

Cones were collected from the upper crown of 10 or more well-distributed trees of every source.[1] The collection from each parent tree, hereafter termed a family, was handled separately. The seeds were extracted from sun-dried cones, cleaned to eliminate the hollow and incompletely filled seeds, air-dried at ambient room temperatures, and stored at 1°C (34°F) or at −18°C (0°F).

Nursery Procedures

Seeds were stratified 60 days at 1°C (34°F). The treated seeds were sown in early May, in beds measuring 50 ft (15 m) long and 5 ft (1.5 m) wide. Families were sown in plots across the bed, in spots set 2.4 inches (6 cm) apart within rows spaced 6 inches (15 cm) apart. After sowing, the beds were mulched with a thin layer of perlite and drenched with a Captan suspension to control damping-off fungi.

Germination was uniformly rapid, and seedling emergence ranged from 95 to 100 percent for most families. The seedlings were thinned to 20/ft^2 in August, and were watered twice weekly until heavy rains in the fall. To prevent seedling deficiencies in nitrogen and phosphorus, the nursery soil, an Aiken clay loam, was fertilized during bed preparation and in midsummer with a pelletized ammonium phosphate sulfate (NP, 16-20) at rates of 100 lb N/acre (112 kg N/ha).

To define the natural periods of seedling growth and dormancy, the times when visible top and root

---

[1]The Wyoming, Arizona, Nevada, and Oregon collections were supplied by Ralph A. Read, Rocky Mountain Forest and Range Experiment Station, Lincoln, Nebraska; John A. Pitcher, formerly of the Southwestern Region, Forest Service, Albuquerque, New Mexico, and now with the Southeastern Forest Experiment Station, Starkville, Mississippi; Richard H. Smith, Pacific Southwest Forest and Range Experiment Station, Berkeley, California; and Brian D. Cleary, formerly of Weyerhaeuser Co. and now with Oregon State University, Corvallis. The Modoc Plateau and southern California collections were supplied by John Alden, formerly of the Pacific Southwest Region, Forest Service, Yreka, California, and Bureau of Land Management, U.S. Department of Interior,Portland, Oregon; and Gaylord K. Parks, Pacific Southwest Region, Forest Service, Placerville, California.

Table 1—*Seed sources of ponderosa (P), Washoe (W), and Jeffrey (J) pines selected in seven climatic regions in the western United States*

Forest area and seed source[1]	Stand locality and county	Tree seed zone[2]	Elevation		Local arborescent associates[3]
			Feet	*Meters*	
	East Continental Divide				
Laramie Range, Wyoming					
P WY-Lar 7700	Pole Mountain-Buford, Laramie	—	7700	2347	F
	Colorado Plateau				
Mogollon Mesa, Arizona					
P AR-Coco 7000	Chevelon Ranger Stn., Coconino	150	7000	2134	JuSc,JuDe,QuGa
	Basin and Range				
Snake Range, Nevada					
P NE-Whi 7500	Lehman Creek, White Pine	—	7500	2286	AC,PiEn,PsMz,M,JuOs, JuSc
	Eastern Sierra-Cascade				
Cascade Range, Oregon					
P OR-Kla 4300	Aspen Lake, Klamath	701	4300	1311	AC
Modoc Plateau					
P Sha 4840	Hat Creek Rim, Shasta	732	4840	1475	JuOc,AC,LiDe,L
Northern Sierra Nevada					
P Plu 5000	Spring Garden, Plumas	523	5000	1524	L,LiDe,PsMz,QuKe
Lake Tahoe Basin					
P Eld 6300	Emerald Bay, El Dorado	772	6300	1920	LiDe,L,AC,QuKe,J
J Eld 6400	South Lake Tahoe, El Dorado	772	6400	1951	AC,L,LiDe,My
Carson Range					
W NE-Wash 8000	Galena Creek, Washoe	772	8000	2438	J,My,Mt,AM
J Eld 8200	High Meadows, El Dorado	881	8200	2499	My,AM,Mt,Al,JuOc
	Western Sierra Nevada				
Western Sierra Nevada					
P Eld 5500	Wrights Lake Road, El Dorado	526	5500	1676	LiDe,L,AC,PsMz,QuKe,J
P Eld 4000	Sugarloaf, El Dorado	526	4000	1219	L,PsMz,QuKe,LiDe,AC
P Eld 1900	Garden Valley, El Dorado	526	1900	579	L,LiDe,QuKe,QuCh
P Eld 1900†	Johntown Creek, El Dorado	526	1900	579	S,LiDe
P Eld 500	Salmon Falls, El Dorado	526	500	152	S,QuWi,QuDo,QuKe
P Ama 750	Plymouth-Purcell, Amador	526	750	229	S,QuWi,QuDo
P Pla 3800†	Sugar Pine Stn., Placer	525	3800	1158	J,LiDe,L
J Pla 3800†	Sugar Pine Stn., Placer	525	3800	1158	P,LiDe,L
	Coastal California				
Santa Cruz Mountains					
P SCru 800	Mount Hermon, Santa Cruz	097	800	244	QuAg,ArMz
	Southern California				
San Gabriel Mountains					
P Los 6700	Islip Saddle, Los Angeles	993	6700	2042	J,L,AC
P Los 6200	Mount Gleason, Los Angeles	993	6200	1890	J,L,AC
P Los 5350	Charlton Flat, Los Angeles	993	5350	1631	J,Cl
J Los 5150	Chilao Creek, Los Angeles	993	5150	1570	P,Cl
San Bernardino Mountains					
P SBer 5370	Lake Arrowhead, San Bernardino	994	5370	1637	L,QuKe,AC,LiDe
J SBer 6900	Big Bear Lake, San Bernardino	994	6900	2103	L,AC
J SBer 5660	Santa Ana River, San Bernardino	994	5660	1725	P,Cl
Peninsular Ranges					
J SDie 5320	Laguna Mountains, San Diego	998	5320	1622	QuKe,Cl,LiDe

[1]For source designation, see *figure 1;* † indicates source is native on infertile, ultramafic soil.

[2]Forest tree seed collection zones (Schubert and Pitcher 1973; USDA Forest Serv. 1966, 1969).

[3]
P: *Pinus ponderosa* Laws.
J: *P. jeffreyi* Grev. & Balf.
S: *P. sabiniana* Dougl.
Cl: *P. coulteri* D. Don
L: *P. lambertiana* Dougl.
My: *P. contorta* Dougl.
Mt: *P. monticola* Dougl.
Al: *P. albicaulis* Engelm.
M: *P. monophylla* Torr. & Frem.
W: *P. washoensis* Mason & Stockwell
F: *P. flexilis* James
QuGa: *Quercus gambelii* Nutt.
QuKe: *Q. kelloggii* Newb.
QuDo: *Q. douglasii* Hook. & Arn.
QuWi: *Quercus wislizenii* A. DC.
QuAg: *Q. agrifolia* Nee
QuCh: *Q. chrysolepis* Liebm.
JuOc: *Juniperus occidentalis* Hook.
JuSc: *J. scopulorum* Sarg.
JuOs: *J. osteosperma* (Torr.) Little
JuDe: *J. deppeana* Steud.
AM: *Abies magnifica* A. Murr.
AC: *A. concolor* (Gord. & Glend.) Lindl.
PsMz: *Pseudotsuga menziesii* (Mirb.) Franco
LiDe: *Libocedrus decurrens* Torr.
ArMz: *Arbutus menziesii* Pursh
PiEn: *Picea engelmannii* Parry

growth ceased in the fall and resumed in spring were noted. To relate seedling growth, dormancy, and growth capacity to nursery climate, soil and air temperatures were recorded continuously from September to May. A hygrothermograph and min-max thermometers were housed in a standard weather shelter, and soil thermograph probes were set at 3 and 6 inches (7.5 and 15 cm) below the bed surface to sense the zone where seedling roots were concentrated.

Growth Capacity and Planting Time Studies

Seeds of six to nine different sources were sown in 1972, 1973, 1974, and 1975. Sources in the first two sowings represented ponderosa pine from six climatic regions (southern California excepted) and all three species of western yellow pines from the central Sierra Nevada and Carson Range. Sources in the last two sowings were ponderosa and Jeffrey pines from the western Sierra Nevada and southern California. To compare sources tested in different years, three sources were sown twice: P AR-Coco 7000 in 1972 and 1973, P Eld 1900 in 1973 and 1974, and P Eld 4000 in 1974 and 1975 (see *fig. 1* for the key to source designations).

The annual sowing design was a randomized block with eight replications. Ten families per source were sown in separate, quarter-row family plots, and the seedlings were thinned to 10 per plot.

Site Environment Study

Seeds of seven to eight sources from the western Sierra Nevada and Lake Tahoe Basin, representing ponderosa pine from 500 to 6300 ft and Jeffrey pine from 3800 to 8200 ft, were sown in 1972 and 1973. Five of these sources were also included in the planting time study: P Eld 500, 1900, 6300; J Eld 6400, 8200.

The annual sowing design was a randomized block with four replications. Ten families per source were sown in separate, full-row family plots, and the seedlings were thinned to 48 per plot.

Growth Capacity Evaluation

Seedlings in the current nursery crop were sampled five or six times from October to March. A randomly selected block was lifted each time, and the roots of the lifted seedlings were pruned 9 inches (23 cm) below the cotyledon nodes, roughly 8 inches (20 cm) below ground line *(fig. 2)*.

For every source, three sets of 10 typical seedlings, each from a different family, were planted in separate, stainless steel containers measuring 3 by 15 by 12 inches deep (7.5 by 37.5 by 30.5 cm). The seedlings were planted with a moist soil mix of 1:1:1:1 Aiken clay loam, sand, perlite, and finely shredded redwood bark, and were thoroughly watered once. To retain soil and speed irrigation, the container drainports were capped inside with 10-mesh brass screen bent to form an inverted channel 1 inch wide and 0.8 inch deep (2.5 by 2 cm). After watering, the containers were drained overnight, sealed with rubber stoppers, and mulched with white sand.

The watertight containers were immersed to the rim in a row of five thermostatically controlled stainless steel water baths housed in an airconditioned greenhouse. Every source was positioned in three different baths, in a randomized block design with three replications.

The soil temperature was maintained at 20°C (68°F). Air in the greenhouse was circulated continuously, and was held below 27°C (81°F) during the day and near 15°C (59°F) at night. The natural photoperiod was extended to 16 hours with an overhead bank of mercury-phosphor lights (Bickford and Dunn 1972, Veen and Meijer 1962). The lights were on from 6 to 8 a.m. and from 4 to 10 p.m., and gave 35 w/m^2 at the seedling level. To compensate for seasonal differences in sunlight and heat load, the greenhouse was shaded with a 53 percent shade screen for tests started in October and March.

After 21 days, or 24 days (1972-1973 only), the seedlings were washed free of soil, and the following data were promptly recorded for each seedling:

- Length of every new root elongation of 1.5 cm or more (to the nearest 0.5 cm).
- Number of roots with new growth between 0.2 and 1.5 cm.
- Growth activity of the top, using a top growth index:

  1 = leader (terminal bud) and fascicle buds dormant
  2 = fascicle buds swelling
  3 = 2 with color change in the terminal centimeter of leader
  4 = 2 with leader elongating
  5 = leader and needles elongating

- Length of the zone of leader elongation, to the nearest millimeter.
- Stem diameter at 1 cm below the cotyledon node.

Differences in root growth between sources and between lifting dates for every source were established by least significant difference procedures, and by Duncan's new multiple range test (p = 0.05, Steel and Torrie 1960).

Field Survival Evaluation

Typical pine sites, four west and one east of the Sierra Nevada crest, were chosen for testing seedling survival *(table 2)*. All of the sites are in El Dorado County *(fig. 1)*, in forest areas that were

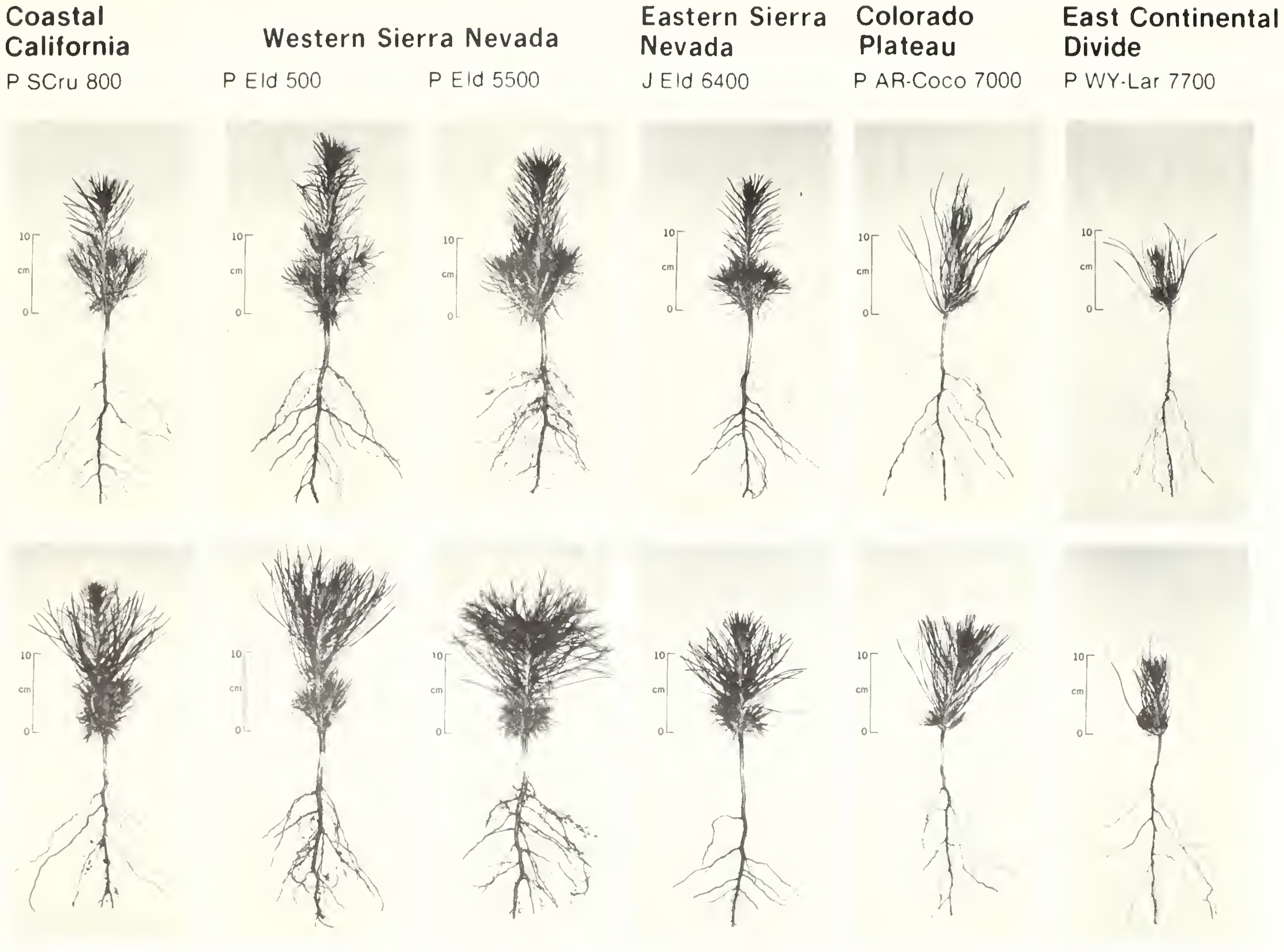


Figure 2—Typical seedlings of western yellow pines, lifted in the nursery and root-pruned 23 centimeters below the foliage, were tested for growth capacity and field survival.

either clearcut, cleared for agriculture, or burned by wildfire many years ago.

Site preparation at Salmon Falls was done by hand in spring; the thick grass sod was scalped to bare mineral soil, to make planting spots about 1 yd^2 ($1\ m^2$). In contrast, the other sites were cleared by tractor in fall, and site preparation was thorough and complete. At Garden Valley and Angora Creek, the slash, small stumps, and brush root crowns were pushed and raked off the site, and the soil was leveled by back-blading. At Garden Valley and Mt. Danaher, which once was in pear orchards, the soil was disked and rotovated. At Lincoln Hill, the regrowth of mountain misery and brush after herbicide treatment was bladed to mineral soil in strips 8 ft wide along slope contours roughly 10 ft (3 m) apart.

Planting Time Study

The test seedlings were lifted on January 23 and March 14, 1973, and on February 27 and March 28, 1974. One randomly selected block was lifted on each date, and the roots were pruned 9 inches (23 cm) below the cotyledon nodes. The same day or the next, 50 typical seedlings of every source—five from each of the 10 families—were planted at Garden Valley. The planting design was a randomized block with 10 replications, and seedlings were spaced 1 ft (0.3 m) apart in family-plot rows spaced 2 ft apart. Because of the close spacing, the seedlings were planted with planting bars.

The Garden Valley site was chosen because the summer is always hot and the drought normally extends from April to November. To monitor the site environment, a soil thermograph and two rain gages were installed with the first planting. The probes were set at depths of 3 and 6 inches (7.5 and 15 cm), and the gages were read after every storm. To conserve the available soil water, competing vegetation was removed whenever it appeared.

Seedling condition and mortality were scored monthly, and the final checks were made after heavy rains in November. The 1973 plantings were cleared to accommodate the 1974 plantings.

Site Environment Study

The test seedlings were lifted on February 24, 1973, and on March 11, 1974. Seedlings of all blocks were grouped by source and family, culled to eliminate those damaged or atypical, pruned 9 inches below the cotyledon nodes, sorted into planting replications, and stored at 1 °C (34 °F) in sealed polyethylene bags.

The 1973 seedlings were planted at Salmon Falls on March 5 to 9, at Mt. Danaher on March 29 to April 2, and at Angora Creek on May 15 to 17. For each source, 480 seedlings—48 per family—were planted on each site. At Salmon Falls and Angora Creek, the planting design was a randomized block with six replications. Source plots were randomized within the block and family plots were randomized within the source. Seedlings were planted two per

Table 2—*Planting sites selected for testing field survival of western yellow pines in the central Sierra Nevada*

Name of study and planting site	Tree seed zone	Elevation		Aspect and slope (pct.)	Soil series and parent rock[1]	Local arborescent associates[2]
		Feet	*Meters*			
Planting time study						
Garden Valley	526	1900	579	South 9 to 15	Boomer-Sites gravelly loam Marine	P,L,PsMz,LiDe,QuWi, QuKe,QuCh
Site environment study						
Salmon Falls	526	500	152	North 9 to 30	Auburn very rocky silt loam Metavolcanic	P,S,QuWi,QuDo,QuKe
Mount Danaher	526	3400	1036	Northwest 3 to 15	Aiken loam Pyroclastic	P,L,PsMz,AC,LiDe, QuKe,ArMz
Lincoln Hill	526	4500	1372	South 9 to 30	Josephine gravelly loam Marine	P,L,PsMz,AC,LiDe, QuKe
Angora Creek	772	6600	2012	Northwest 0 to 5	Meeks stony loamy coarse sand Granitic	J,AM,My,AC

[1] Calif. Div. Mines and Geol. 1971; Rodgers 1974a,b.

[2]
P: *Pinus ponderosa* Laws.
J: *P. jeffreyi* Grev. & Balf.
S: *P. sabiniana* Dougl.
L: *P. lambertiana* Dougl.
My: *P. contorta* Dougl.
AM: *Abies magnifica* A. Murr.
AC: *A. concolor* (Gord. & Glend.) Lindl.
QuKe: *Quercus kelloggii* Newb.
QuDo: *Q. douglasii* Hook.& Arn.
QuWi: *Q. wislizenii* A. DC.
QuCh: *Q. chrysolepis* Liebm.
LiDe: *Libocedrus decurrens* Torr.
ArMz: *Arbutus menziesii* Pursh
PsMz: *Pseudotsuga menziesii* (Mirb.) Franco

spot in four-spot family rows, in spots spaced 6 by 6 ft (1.8 m). At Mt. Danaher, the design was a randomized block with 24 replications. Seedlings again were planted two per spot, but in single-spot family plots spaced 8 by 8 ft (2.4 m).

The 1974 seedlings were planted at Lincoln Hill on April 17 to 19. There, 320 seedlings—32 per family—were planted for each source. The design was a randomized block with eight replications. Source rows were centered in the bladed strips, with seedlings planted two per spot in two-spot family rows. Spacing was 5 ft (1.5 m) within and 10 ft (3 m) between rows.

At Salmon Falls, the soil was very rocky and the planting had to be done with planting bars. Soils were less rocky on the other sites, and the planting holes were easily made with powered soil augers.

During the first summer, competing vegetation was allowed to develop only at Salmon Falls. There, new grasses soon formed a dense stand, and the scalped spots were not treated until the following spring. Pocket gophers invaded every planting, but were controlled by trapping whenever fresh activity was found.

Seedlings on every site had high survival and good growth to midsummer. Seedlings on the best site, at Mt. Danaher, were basin-watered once in late July to sustain their rapid growth, as further mortality there was judged unlikely.

All of the plantings were scored at frequent intervals until the winter storms, and were scored again in spring and fall of the second year.

RESULTS

In the nursery, seedlings always ceased visible top growth by the middle of October and visible root growth by late November *(fig. 3)*. The first traces of renewed root growth appeared in late February, and roots were elongating on every seedling of every source by mid-March. Bud swell consistently began in late March, after new root growth was extensive on all seedlings. The period of natural seedling dormancy generally coincided with the time when soil temperature was below 10°C (50°F). Although the winter temperature and rainfall regimes varied from year to year, they were typical of the Fruit Ridge locality.

Root Growth Capacity (RGC)

The seed source and the nursery lifting date always affected the amount of root growth on seedlings planted in the standard environment *(table 3)*. The seed source differences in root growth capacity were large and significant in every winter season.

The seasonal patterns of RGC in the first seedling crop *(table 3A)*, representing sources from five climatic regions *(table 1)*, illustrate the range of interaction between seed source and the Fruit Ridge environment:

- Beginning November 1, after growth had ceased in the nursery, RGC was already at or near peak level in Wyoming and Arizona ponderosa pine, and in Jeffrey pine. By comparison, RGC was low to very low in California ponderosa pine.

- Between November 1 and 27, RGC in Wyoming ponderosa pine decreased by more than 60 percent and that of Jeffrey pine by more than 30 percent. RGC in Arizona ponderosa pine increased 20 percent, while RGC in the California sources increased twofold (P Eld 5500), sixfold (P SCru 800), and tenfold (P Eld 500).

- To December 21, RGC continued to increase only in P Eld 5500, seemingly decreased in the P Eld 500 and Arizona sources, and held constant in P SCru 800, Wyoming ponderosa pine, and Jeffrey pine.

- To January 24, RGC peaked a second time in Wyoming ponderosa pine and in Jeffrey pine, finally peaked in P Eld 5500 and P SCru 800, and returned to peak level in P Eld 500 and Arizona ponderosa pine.

- To March 13, RGC decreased to a moderate or low level in every source. This was two weeks after root growth began in the nursery and two weeks before bud swell *(fig. 3)*. In P SCru 800, a significant increase in the rate of root elongation partly compensated for a large decrease in the number of roots elongating, a result detected in no other source.

The apparent December depression of RGC in Arizona ponderosa pine, P Eld 500, and P SCru 800, probably reflected root damage caused by lifting the seedlings when the nursery soil was too wet. Rainfall totalled 3.4 inches (8.6 cm) for the 3 days before lifting *(fig. 3)*, and soil water contents were still at saturation. The consequent damage to small roots was evident in 17 to 27 percent decreases in the number of roots that elongated, compared to the late-November test. Thereafter, if rain was either falling or predicted, the selected block was covered with a transparent shelter for 3 days before lifting (the time the nursery soil takes to drain to field capacity at the 8-inch [20-cm] depth). The RGC of Arizona ponderosa pine showed no trace of a depression in the following winter, so values for the sources noted were adjusted upward accordingly.

Unusually intense cold did not explain the depression. In the period December 6 to 19, when air temperature was below 0°C (32°F) for 80 hours and hit a record −10°C (14°F), the seedlings were insulated under snow and soil temperature ranged from 3° to 7°C (38° to 45°F), values commonly recorded throughout the winter season. Further, seedlings lifted in January—when RGC was high and soil water content was no problem—had been fully exposed during equally cold and colder periods *(fig. 3).*

Seasonal Patterns of RGC

As described in an earlier paper (Jenkinson 1976), four distinct types of inherent seasonal pattern of root growth capacity were found in ponderosa pine: fall-peak, winter-peak, plateau, and bimodal. Depending on the seed source *(fig. 1, table 1),* RGC peaked in the fall only, in midwinter only, continuously from late fall through winter, or in fall and again in winter *(table 3).* Every pattern type occurred in ponderosa pine from both outside and inside California *(fig. 4, 5),* and two types occurred in Jeffrey pine *(fig. 5).*

Table 3—*Seedling growth capacities for 27 sources of western yellow pines raised in a nursery in the western Sierra Nevada*

Seed source[1]	Growth capacity by nursery lifting date and cumulative cold exposure (hours below 10° and 5°C)				
A. 1972-73 winter season	Nov 1 (168, 2)	Nov 27 (648, 48)	Dec 21 (1148, 360)	Jan 24 (1864, 720)	Mar 13 (2824, 962)
	Root growth capacity, *cm/seedling*[2]				
P AR-Coco 7000[3]	82 b	107 b	73 c	98 c	55 ab
P WY-Lar 7700	74 bc	23 c	22 d	54 c	25 b
P SCru 800	9 d	100 b	88 abc	215 a	76 a
P Eld 500	27 cd	168 a	122 a	171 ab	51 ab
P Eld 5500	46 bcd	88 b	110 ab	160 b	59 ab
J Eld 6400	137 a	92 b	86 bc	163 b	92 a
	Top growth capacity, *index and range*[4,5]				
P AR-Coco 7000[3]	1	1	2.2 (1-4)	4.9 (3-5)	5
P WY-Lar 7700	1	1	2.3 (1-4)	4.7 (2-5)	5
P SCru 800	1	1.1 (1-2)	2 (1-3)	3.6 (1-5)	4.5 (4-5)
P Eld 500	1	1.3 (1-2)	1.8 (1-3)	3 (1-5)	4.3 (4-5)
P Eld 5500	1	1	1.8 (1-3)	3.8 (1-5)	4.2 (4-5)
J Eld 6400	1	1	1	2.8 (1-5)	4.7 (1-5)

Seed source[1]	Oct 17 (0, 0)	Nov 14 (240, 22)	Dec 6 (744, 310)	Jan 21 (1680, 670)	Feb 26 (2394, 984)	Mar 26 (2858, 1164)
B. 1973-74 winter season						
	Root growth capacity, *cm/seedling*[2]					
P AR-Coco 7000[3]	20 b	75 a	75 a	73 cd	30 cd	14 a
P NE-Whi 7500	23 b	57 ab	47 b	37 e	27 d	3 b
P OR-Kla 4300	40 a	70 a	80 a	123 a	91 ab	6 b
P Plu 5000	7 c	56 ab	84 a	113 ab	113 a	15 a
W NE-Wash 8000	46 a	51 b	36 b	80 bcd	82 b	7 b
J Eld 8200	27 b	52 b	35 b	94 abc	52 c	15 a
P Eld 6300	2 c	76 a	79 a	86 bcd	95 ab	7 b
P Eld 1900[3]	3 c	49 b	82 a	57 de	51 c	7 b
	Top growth capacity, *index and range*[4,5]					
P AR-Coco 7000[3]	1	1	1.6 (1-4)	4.4 (4-5)	4.4 (4-5)	5
P NE-Whi 7500	1	1	1.6 (1-4)	4.4 (4-5)	4.4 (4-5)	4.9 (4-5)
P OR-Kla 4300	1	1	1.1 (1-2)	4.6 (2-5)	4.9 (4-5)	5
P Plu 5000	1	1	1.3 (1-2)	4.2 (3-5)	4.9 (4-5)	5
W NE-Wash 8000	1	1	1	4.7 (1-5)	4.9 (3-5)	5 (4-5)
J Eld 8200	1	1	1	3.1 (1-5)	3.5 (2-5)	4.9 (4-5)
P Eld 6300	1	1	1.3 (1-2)	4.2 (2-5)	4.9 (4-5)	5
P Eld 1900[3]	3	1	1.2 (1-2)	3.8 (2-5)	4.4 (4-5)	5 (4-5)

Table 3—*(Continued)*

Seed source[1]	Growth capacity by nursery lifting date and cumulative cold exposure (hours below 10° and 5°C)				
C. 1974-75 winter season	Oct 31 (81, 2)	Dec 4 (593, 39)	Jan 21 (1492, 348)	Feb 19 (2085, 659)	Mar 19 (2587, 827)
	Root growth capacity, *cm/seedling*[2]				
P Eld 4000[3]	55 a	97 a	172 a	108 ab	55 ab
P Eld 1900[3]	35 b	95 a	147 a	97 b	48 bc
P Eld 1900†	54 a	82 a	160 a	79 bc	43 bc
P Ama 750	32 b	47 bc	134 ab	67 c	28 c
P Pla 3800†	65 a	69 b	149 a	109 ab	56 ab
J Pla 3800†	31 b	39 c	118 b	70 c	39 c
P Sha 4840	56 a	84 a	171 a	130 a	68 a
	Top growth capacity, *index and range*[4,5]				
P Eld 4000[3]	1	1	3.8 (2-5)	4.3 (4-5)	4.6 (4-5)
P Eld 1900[3]	1	1	4.3 (3-5)	4.4 (4-5)	4.7 (4-5)
P Eld 1900†	1	1	3.8 (1-5)	4.2 (4-5)	4.4 (4-5)
P Ama 750	1	1	3.8 (1-5)	4.4 (4-5)	4.7 (4-5)
P Pla 3800†	1	1	3.8 (1-5)	4.1 (4-5)	4.6 (4-5)
J Pla 3800†	1	1	1.2 (1-5)	3.0 (1-5)	3.4 (1-4)
P Sha 4840	1	1	3.9 (1-5)	4.4 (1-5)	4.8 (1-5)

D. 1975-76 winter season	Oct 24 (0, 0)	Nov 13 (486, 24)	Dec 8 (901, 158)	Jan 6 (1468, 390)	Feb 3 (1815, 493)	Mar 2 (2355, 675)
	Root growth capacity, *cm/seedling*[2]					
P Eld 4000[3]	3	69 a	129 ab	122 a	162 a	125 a
P Los 6700	1	63 a	100 bc	91 a	157 a	108 a
P Los 6200	1	73 a	124 b	90 a	162 a	112 a
P Los 5350	6	51 ab	137 ab	58 b	145 a	71 b
J Los 5150	1	33 b	61 c	13 d	44 bc	30 c
P SBer 5370	4	70 a	157 a	97 a	150 a	105 a
J SBer 6900	8	19 b	76 c	44 bc	66 b	49 b
J SBer 5660	3	27 b	57 c	30 c	32 c	52 b
J SDie 5320	2	23 b	62 c	27 cd	70 b	44 bc
	Top growth capacity, *index and range*[4,5]					
P Eld 4000[3]	1	1	1.3 (1-2)	2.5 (1-3)	3.8 (3-5)	4.6 (4-5)
P Los 6700	1	1	1.2 (1-2)	1.5 (1-3)	3.3 (3-4)	4.5 (3-5)
P Los 6200	1	1	1.2 (1-2)	1.6 (1-3)	3.1 (2-4)	4.4 (3-5)
P Los 5350	1	1	1.3 (1-2)	1.6 (1-2)	2.5 (1-4)	4.6 (4-5)
J Los 5150	1	1	1	1	1.7 (1-4)	2.6 (1-4)
P SBer 5370	1	1	1	1.9 (1-3)	3.9 (2-5)	4.8 (4-5)
J SBer 6900	1	1	1	1	2.0 (1-4)	3.1 (2-5)
J SBer 5660	1	1	1	1.1 (1-2)	1.4 (1-2)	3.1 (2-5)
J SDie 5320	1	1	1	1.3 (1-2)	2.1 (1-4)	3.1 (2-5)

[1]For source designation, see *figure 1;* † indicates source is native on infertile, ultramafic soil.
[2]Within columns, means followed by unlike letters differ significantly ($p = 0.05$).
[3]Source tested in consecutive years.
[4]An index value of 1 = top dormant, 2 = fascicle buds swelling, 3 = 2 and color change in apical centimeter of stem, 4 = 2 and leader elongating, 5 = leader and needles elongating.
[5]In the March tests, the zone of leader elongation, by year and source, reached these lengths (mm):
1973. 56, 74, 70, 50, 53, and 53
1974. 92, 75, 26, 68, 47, 52, 69, and 79
1975. 51, 65, 62, 65, 54, 22, and 54
1976. 55, 46, 56, 58, 21, 67, 24, 31, and 22

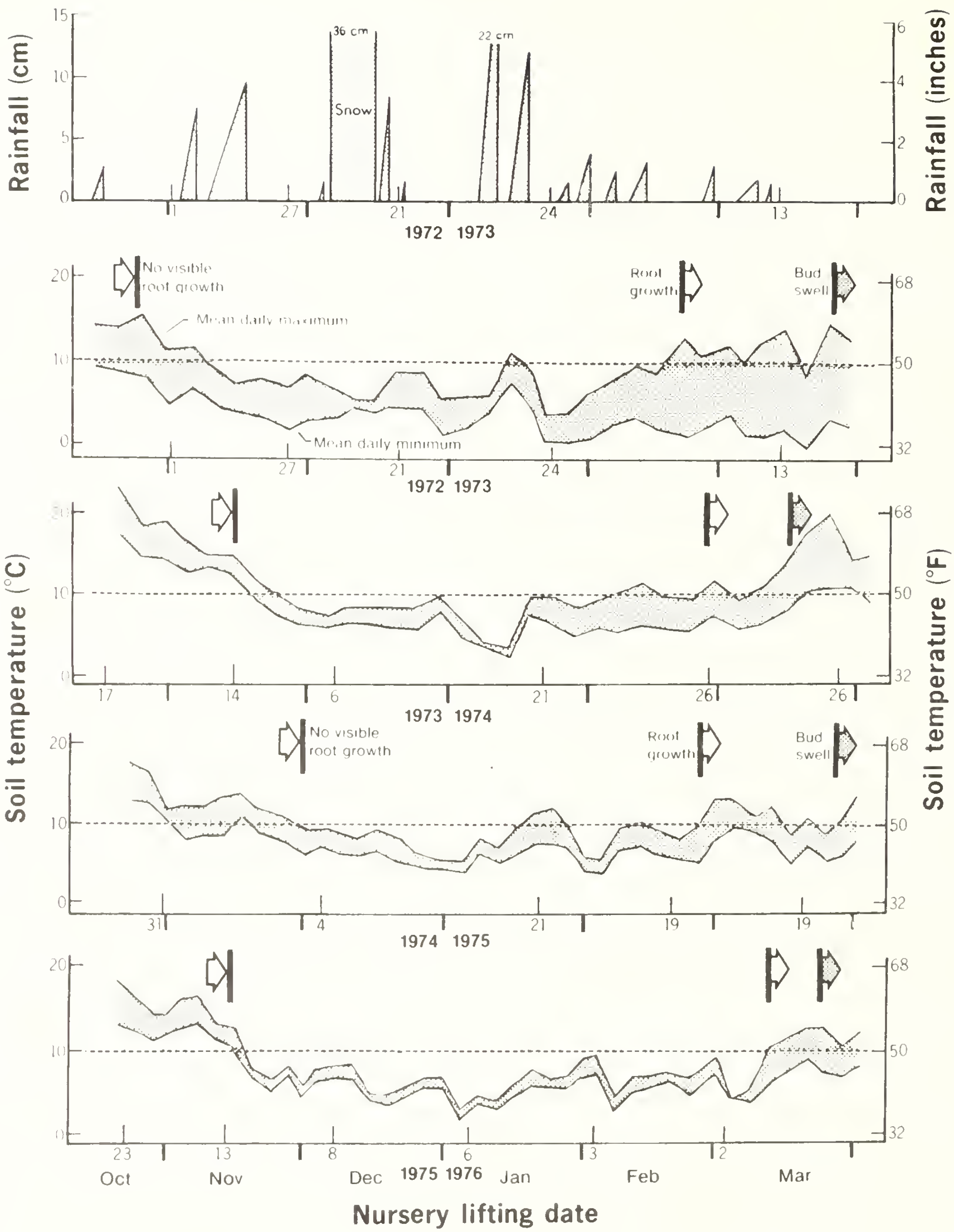


Figure 3—Under rainfall and temperature regimes typical of the winter season on Fruit Ridge, seedlings of western yellow pines in the nursery cease root growth in fall when soil cools below 10° C, resume it in spring when soil warms above 10° C, and begin top growth 2 to 5 weeks after root growth. Through each winter season, seedlings in the nursery beds were periodically sampled for tests of growth capacity.

Fall-peak

A unimodal pattern with a fall peak characterizes ponderosa pine from the Basin and Range region (P NE-Whi 7500). In the same winter season, a similar fall-peak pattern appeared in ponderosa pine from the pine phase of mixed conifer forest in the western Sierra Nevada (P Eld 1900). In the next season, however, five of those families and five others from a nearby stand on ultramafic soil (P Eld 1900†) produced patterns with a midwinter peak, suggesting either large variability among the seed parents or yearly differences in nursery climate.

Winter-peak

Unimodal patterns with a midwinter peak characterize ponderosa pine from east of the Cascade Range (P OR-Kla 4300, P Sha 4840), from coastal California (P SCru 800), and from the western Sierra Nevada. In the latter region, sources from granitic soils in the mixed phase of mixed conifer forest (P Eld 4000, 5500) produced patterns conforming to earlier experience (Stone and Schubert 1959). Ponderosa pine from P Eld 4000 repeated this winter-peak pattern in consecutive years, and similar patterns appeared in sundry other sources from the western Sierra, including ponderosa and Jeffrey pines from ultramafic soil (P, J Pla 3800†) and ponderosa pine from a foothill woodland (P Ama 750).

Plateau

A plateau type of pattern characterizes ponderosa pine from the center of the most extensive forest on the Colorado Plateau. Root growth capacity in Arizona ponderosa pine (P AR-Coco 7000), evaluated in consecutive years, was consistently at peak levels from October to February. Plateau patterns also appeared in California ponderosa pine from the western Sierra foothills (P Eld 500) and from Lake Tahoe Basin in the eastern Sierra Nevada (P Eld 6300).

Bimodal

Bimodal patterns typify ponderosa pine from east of the Continental Divide and both Washoe pine and Jeffrey pine from east of the Sierra crest. The patterns for Wyoming ponderosa pine (P WY-Lar 7700) and Tahoe Basin Jeffrey pine (J Eld 6400) were clearly bimodal because two lifting

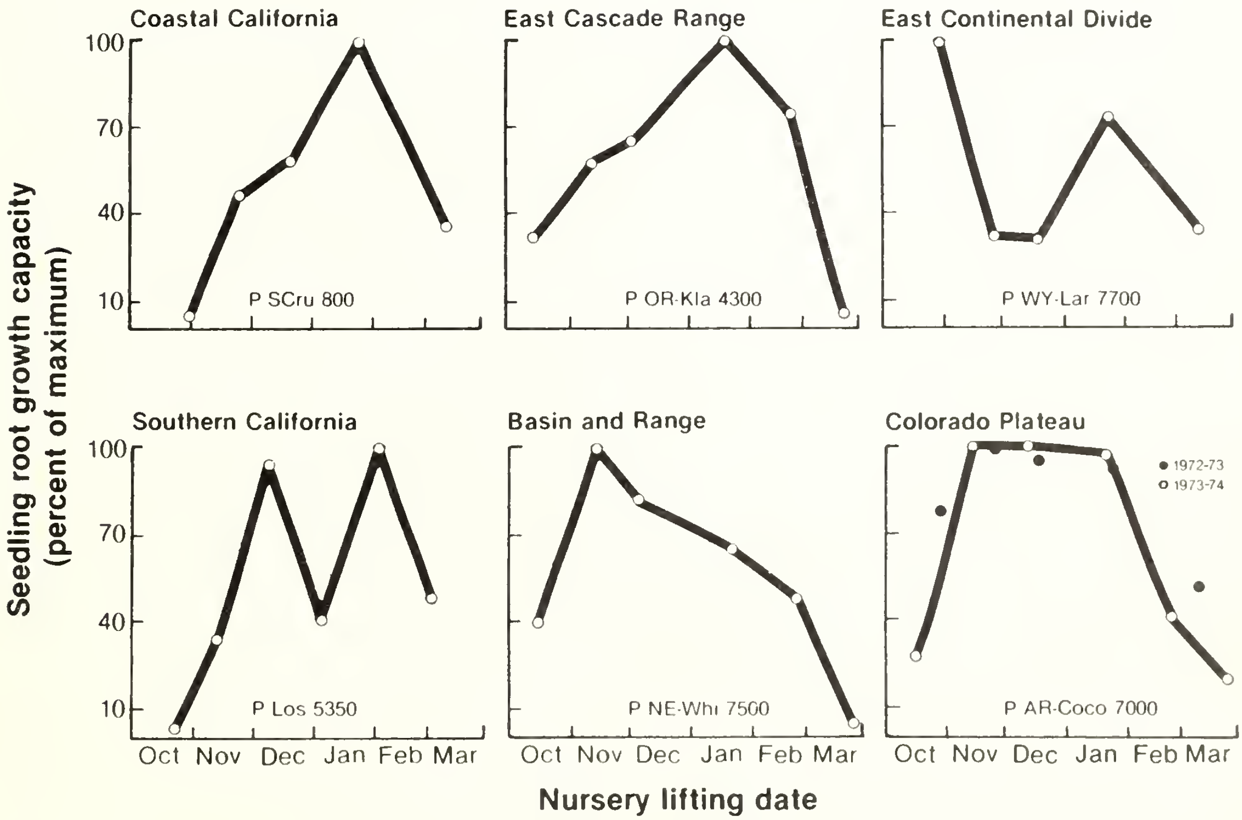


Figure 4—In ponderosa pine from diverse climatic regions, changes in seedling root growth capacity define four distinct types of seasonal pattern: winter-peak (northern California and Oregon), bimodal (Wyoming and southern California), fall-peak (Nevada), and plateau (Arizona).

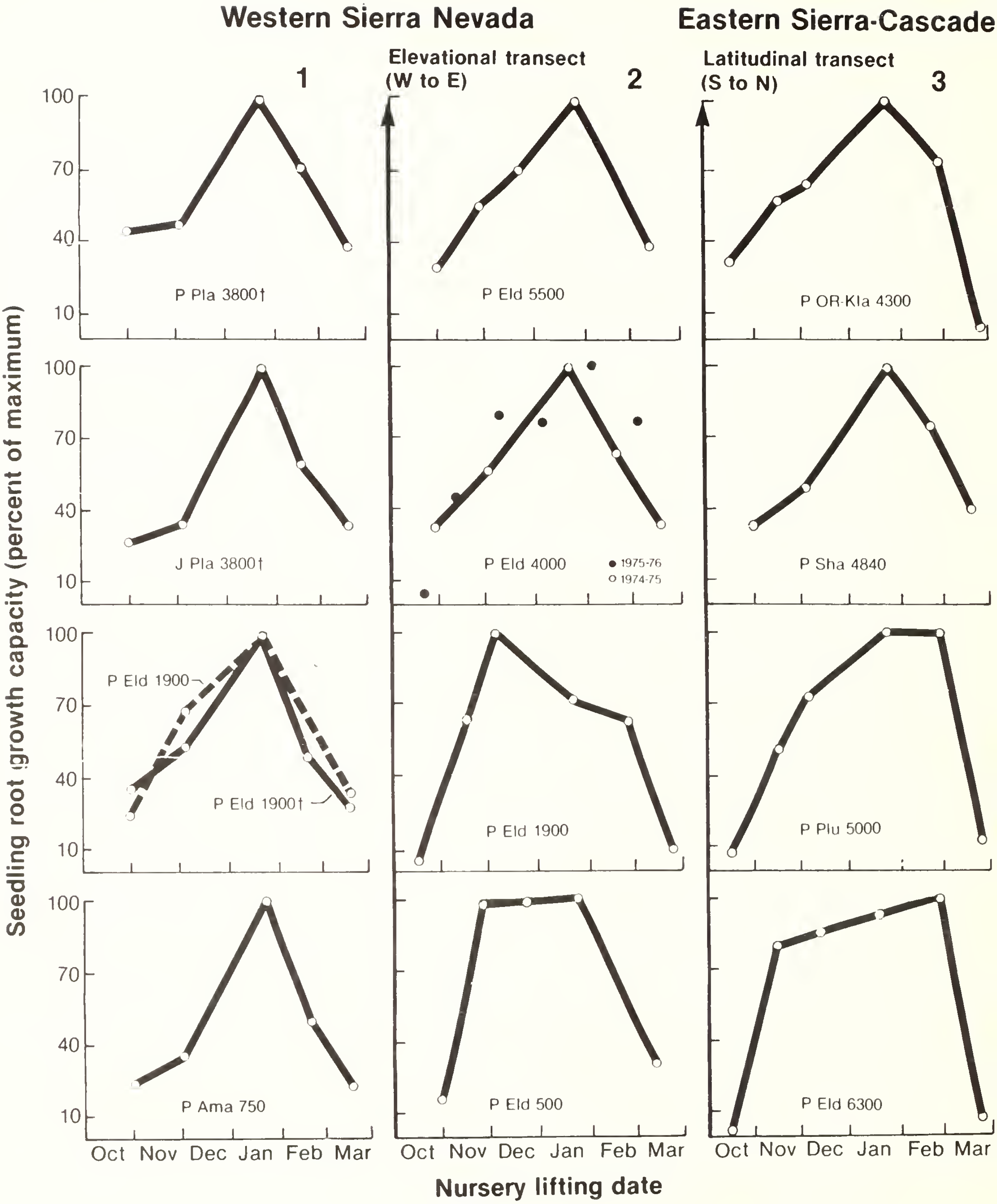
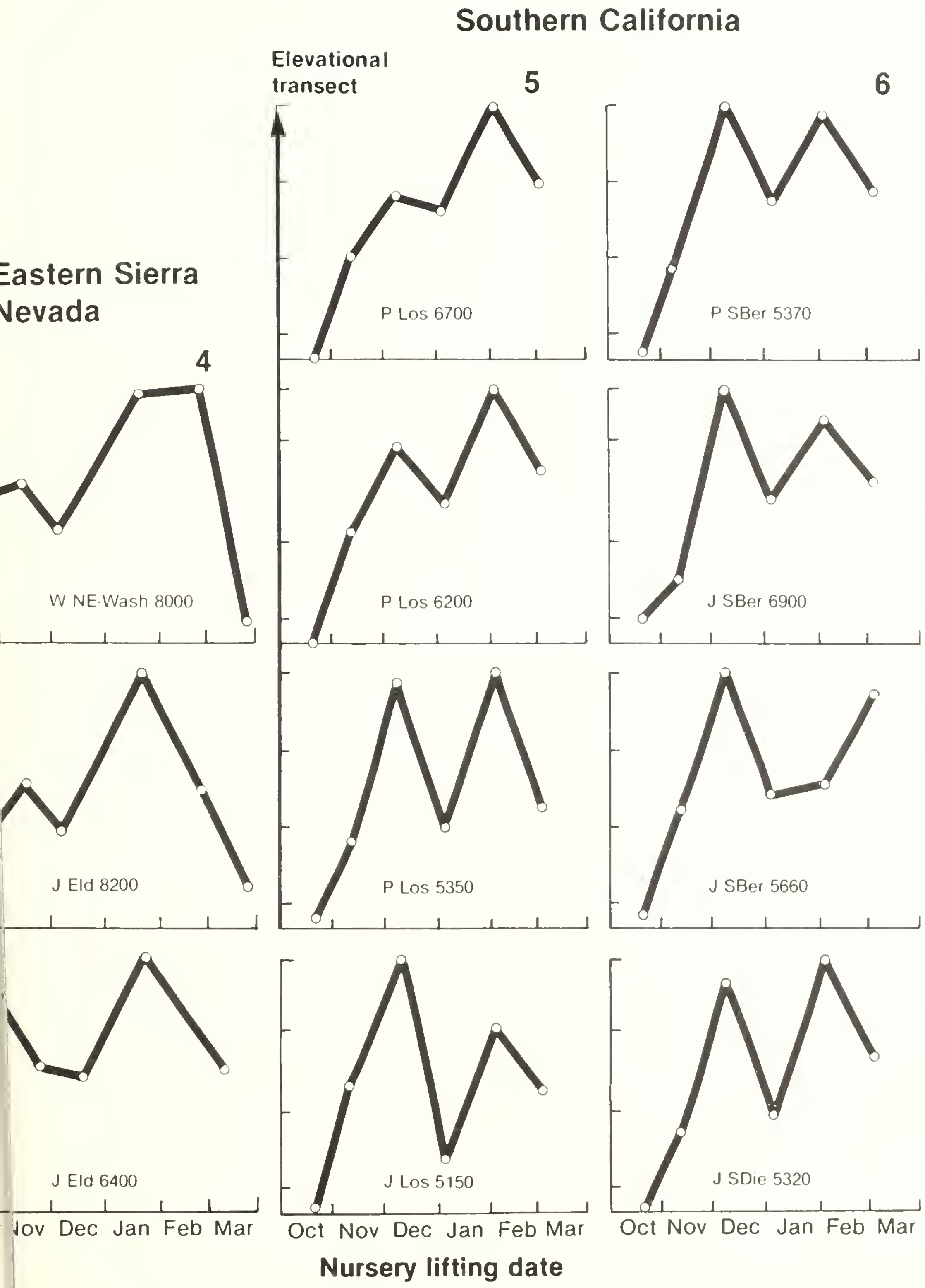


Figure 5—In California ponderosa and Jeffrey pines, the seasonal pattern of seedling root growth capacity varies with climatic region, latitude *(panel 3)*, and elevation of the parent stand *(panels 2, 5)*. In Washoe pine (W NE-Wash 8000), the pattern resembles that of the local region Jeffrey pine (J Eld 8200) in October-December and ponderosa pine (P Plu 5000, P Eld 6300) in January-March.



Southern California
Elevational transect
5
6
Eastern Sierra
Nevada
4
P Los 6700
P SBer 5370
W NE-Wash 8000
P Los 6200
J SBer 6900
J Eld 8200
P Los 5350
J SBer 5660
J Eld 6400
J Los 5150
J SDie 5320
Nov Dec Jan Feb Mar
Oct Nov Dec Jan Feb Mar
Oct Nov Dec Jan Feb Mar
Nursery lifting date

dates defined the December low between peaks.

Bimodal patterns also characterize both ponderosa pine and Jeffrey pine from southern California, but for this region the low between peaks appeared in January. In Jeffrey pine from the Santa Ana River watershed (J SBer 5660), two lifting dates defined the low between peaks, and the second peak was later than in other sources. In ponderosa pine from the San Gabriel Mountains, the pattern varied from strongly bimodal (P Los 5350) to obscurely so (P Los 6700), suggesting a shift toward a winter-peak pattern with increase in elevation of the parent stand *(fig. 5, panel 5).*

Environmental Gradients

For seed sources in the same climatic region, shifts in pattern type apparently reflect gradients in the regional temperature and moisture regime. Patterns from the transect of ponderosa pine within the American River drainage of the western Sierra Nevada suggest an elevational gradient of root growth capacity *(fig. 5, panel 2).* In sources from 500 to 5500 ft (P Eld 500, 1900, 4000, 5500), the time needed to reach peak RGC increased with increasing elevation of the parent stand. Simultaneously, the duration of peak level decreased.

Contrasting patterns typify sources from opposite sides of the Sierra Nevada crest, the topographic barrier separating two major climatic regions. In ponderosa pine from similar granitic soils and south slopes, and from the same mixed conifer association except for Douglas-fir, the pattern type changed from one of slow increase and a midwinter peak of short duration (P Eld 5500) to one of rapid increase and a peak level spanning more than 3 months (P Eld 6300). In Jeffrey pine, the patterns were bimodal types in sources from east of the crest (J Eld 6400, 8200) and a winter-peak type from the western slope (J Pla 3800†).

Patterns from the transect of ponderosa pine east of the Sierra-Cascade crest suggest a latitudinal gradient of root growth capacity *(fig. 5, panel 3).* In sources from the west shore of Lake Tahoe (P Eld 6300), the northern Sierra Nevada (P Plu 5000), northeastern California (P Sha 4840) and southern Oregon (P OR-Kla 4300), the time needed to reach peak RGC increased with increasing latitude of the parent stand, and the duration of peak level decreased.

Apart from the elevational and latitudinal shifts, variation in the seasonal pattern is not readily related to climate at the seed source. The same pattern type was commonly associated with diverse native climates: every type appeared in at least two climatic regions, and three appeared in three regions *(fig. 4, 5).*

Top Growth Capacity

Unlike root growth capacity, top growth capacity in every source displayed a sigmoid seasonal pattern *(fig. 6).* The pattern is like that of leader elongation on western white pine seedlings (*P. monticola* Dougl.) chilled at 5°C (41°F) for periods varying from 8 to 20 weeks (Steinhoff and Hoff 1972), and of bud burst and shoot growth on Douglas-fir periodically sampled in a nursery and tested in standard environments through a winter season (Lavender and Hermann 1970).

The amount of natural cold exposure that dormant seedlings needed to break buds and flush rapidly was least in Washoe pine and ponderosa pine from continental climates, and greatest in Jeffrey pine. In California ponderosa pine and Jeffrey pine, the exposure required apparently was least in sources from the eastern Sierra-Cascade region, intermediate in sources from the western Sierra Nevada and coastal California, and greatest in sources from southern California *(table 3, fig. 6).*

Differences in the development of top growth capacity during a single winter season *(table 3B),* in yellow pines from four climatic regions *(table 1),* illustrate the range of interaction between seed source and the Fruit Ridge climate:

- In October, before air temperature dipped below 10°C (50°F), ponderosa pines from continental climates, Washoe pine, and Jeffrey pine remained dormant in the standard environment. In contrast, ponderosa pine from the western Sierra Nevada (P Eld 1900) resumed leader growth under the 16-hour photoperiod.

- In November, after 200 hours of cold exposure, every source remained dormant.

- In early December, after 700 hours of cold, the ponderosa pines produced small amounts of top growth, with Arizona and Nevada sources showing the most. There was no trace of top growth in Washoe pine and Jeffrey pine.

- In January, after 1600 hours of cold, top growth was greatest on Washoe pine and Oregon ponderosa pine, with both leaders and needle fascicles elongating rapidly. Leader growth was clearly greater in Arizona, Nevada, and California ponderosa pines from east of the Sierra Nevada crest (P Plu 5000, P Eld 6300) than in ponderosa pine from the western Sierra (P Eld 1900). Top growth was least in Jeffrey pine, with terminal and fascicle buds swelling but not elongating.

- In February, after 2400 hours of cold, top growth exceeded that for January in every source except Arizona and Nevada ponderosa pines, which remained the same. Top growth was greatest in Washoe pine and ponderosa pine from the eastern

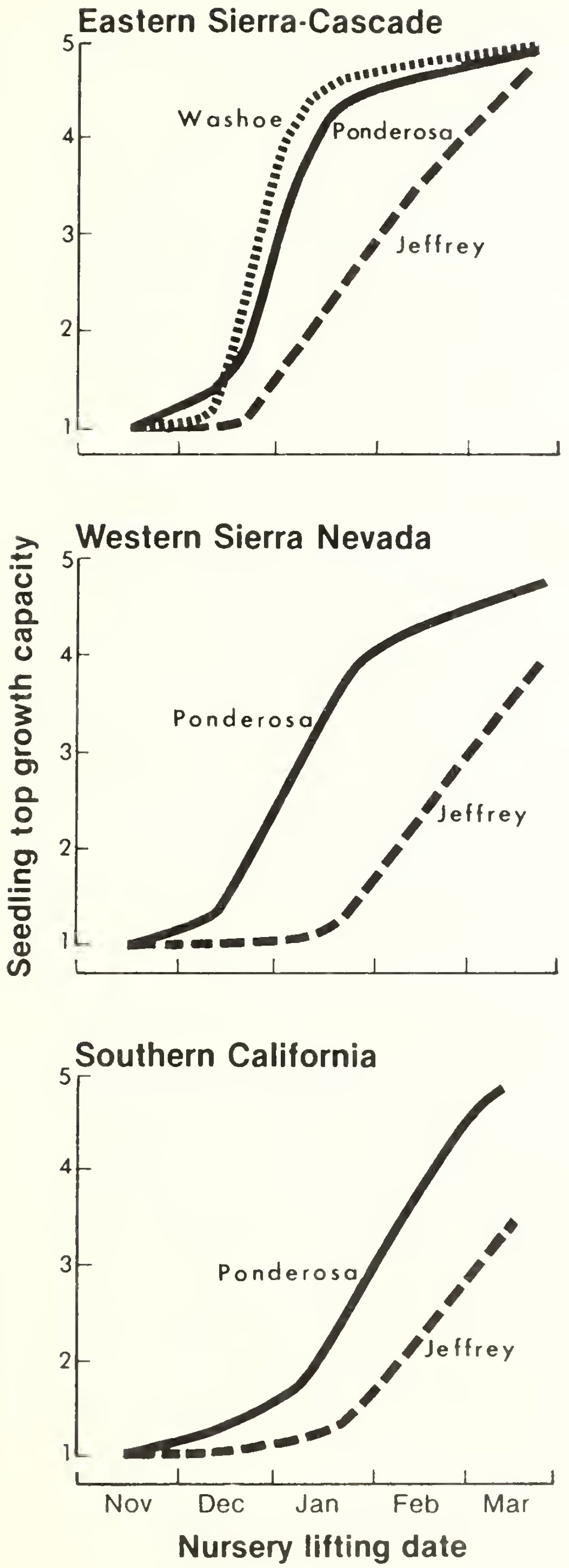


Figure 6—Seedlings of ponderosa and Washoe pines develop top growth capacity earlier and faster than Jeffrey pine, and sources from the eastern Sierra-Cascade region develop it sooner than sources from southern California. A value of 1 on the scale indicates dormancy; 5 indicates rapid elongation of leader and needles.

Sierra-Cascade region (P OR-Kla 4300, P Plu 5000, P Eld 6300), and least in Jeffrey pine.

• In late March, needle elongation was exceptional in every source because top growth had begun in the nursery. The top growth index already was 3.9 for Washoe pine, 3.5 to 3.9 for ponderosa pine, and 2.4 for Jeffrey pine.

Field Survival

Large differences in seedling survival were associated with planting time, seed source, and site environment.

Planting Time Study

In 1973, field survival was 20 to 78 percent greater for the seedlings planted in March, even though root growth capacity was 2 to 3 times higher in the seedlings planted in January *(table 4)*. Survival was also greater for the California than for the Wyoming and Arizona sources, averaging 79 against 27 and 37 percent in the January planting, and 98 against 46 and 66 percent in the March planting.

Most seedlings in both plantings had elongated leaders by early May. By June, however, some were curtailing needle growth, suggesting high plant water stress. In July, mortality appeared in every source in the January planting, and in the Wyoming source in the March planting. Mortality continued until October, when rains ended the summer drought.

In 1974, planting time had no effect and survivals were uniformly high *(table 4)*. Survivals ranged from 88 to 100 percent in the February planting, and from 92 to 100 percent in the March planting, even though top growth was well underway when the March seedlings were lifted. Heavy rains fell in April, and in early July over 3 inches (8 cm) recharged the soil profile and eliminated lethal plant water stress for the rest of the summer season.

Site Environment Study

In November, field survivals of all sources ranged from 85 to 95 percent at Mt. Danaher, 94 to 99 percent at Angora Creek, and 82 to 91 percent at Lincoln Hill *(table 5)*. Differences between sources were not significant on any of those three sites. Gophers caused 80 percent of the mortality at Mt. Danaher, and 87 percent at Lincoln Hill. Mortality was light and random in the second year, and did not alter the first year's results.

At Salmon Falls, survivals were 87 to 93 percent in June, but ranged from 39 to 59 percent in late August. Severe grass competition for soil water accounted for 91 percent of the midsummer mortality. Survivals of ponderosa pine from the western

Table 4—*Root growth capacity (RGC) and field survival of western yellow pines planted in winter and in spring, below snow line in the western Sierra Nevada (planting time study)*[1]

Test year and seed source[2]	Winter planting		Spring planting	
	RGC when planted	Field survival	RGC when planted	Field survival
	Cm/seedling	*Percent*	*Cm/seedling*	*Percent*
1973				
P AR-Coco 7000[3]	98	37	55	66
P WY-Lar 7700	54	27	25	46
P SCru 800	215	80	76	96
P Eld 500	171	81	51	98
P Eld 5500	160	79	59	98
J Eld 6400	163	75	92	98
1974				
P AR-Coco 7000[3]	30	96	14	98
P NE-Whi 7500	26	88	3	96
P OR-Kla 4300	91	94	6	98
P Plu 5000	113	98	15	100
W NE-Wash 8000	81	96	7	96
J Eld 8200	52	100	15	100
P Eld 6300	94	98	7	98
P Eld 1900[4]	51	100	7	92

[1]Seedlings were transplanted from Fruit Ridge to Garden Valley *(table 2)* on January 23 and March 14, 1973; February 27 and March 28, 1974.
[2]For source designation, see *figure 1*.
[3]Source tested in consecutive years.
[4]Source native to Garden Valley locality.

Table 5—*Field survival of ponderosa and Jeffrey pines planted west and east of the Sierra Nevada crest (site environment study)*[1]

Seed source[2]	Seedling survival					
	Western Sierra Nevada					Eastern Sierra Nevada
	Salmon Falls			Mt. Danaher	Lincoln Hill	Angora Creek
	Jun 13, 1973	*Aug 23, 1973*	*Mar 6, 1974*	*Nov 1973*	*Nov 1974*	*Nov 1973*
	Percent					
Western Sierra						
P Eld 500[3,4]	92.5	57.6	46.7	88.7	84.1	97.5
P Eld 1900[3]	—	—	—	—	82.5	—
P Eld 4000	93.6	57.6	55.0	91.6	88.1	99.4
P Pla 3800†	91.6	59.4	55.4	93.2	84.4	97.8
J Pla 3800†	88.5	47.1	43.5	92.7	90.3	94.7
Eastern Sierra[3]						
P Eld 6300	89.6	40.8	39.2	85.6	90.9	97.8
J Eld 6400	93.6	43.3	37.7	95.3	88.1	97.8
J Eld 8200	87.2	39.1	31.0	87.9	88.7	95.2

[1]Seedlings lifted in late winter and held in cold storage were outplanted in spring, 1973 (Salmon Falls, March 5-9; Mt. Danaher, March 29-April 2; and Angora Creek, May 17-19) and 1974 (Lincoln Hill, April 17-19).
[2]For source designation, see *figure 1*; † indicates source is native on infertile, ultramafic soil.
[3]Source tested at Garden Valley *(table 4)*.
[4]Source native to Salmon Falls locality.

Sierra Nevada (P Eld 4000, P Pla 3800†, and P Eld 500—the "home team") were significantly higher than those of ponderosa pine (P Eld 6300) and Jeffrey pine (J Eld 6400, 8200) from east of the Sierra crest, that is, 57 to 59 percent as against 39 to 43 percent. Midsummer survival of Jeffrey pine from the western Sierra (J Pla 3800†) was intermediate at 47 percent. In the following year, survivals still ranged from 31 to 55 percent, with no change in rank for any source.

DISCUSSION

Seedlings of western yellow pines vary widely in root growth capacity. For most seed sources, this latent capacity changes continuously through the fall and winter, even while the seedlings are fully dormant and show no visible growth in the nursery bed. The inherent seasonal pattern of RGC is revealed when the seedlings are periodically sampled and tested for growth in a standard environment. For the 27 sources investigated *(fig. 1)*, specific interactions with the nursery climate on Fruit Ridge generate four distinct types of seasonal pattern in ponderosa pine and two distinct types in Jeffrey pine *(fig. 4, 5)*.

In the Fruit Ridge climate, seedlings consistently develop a root growth capacity that ensures high survival in the field. As demonstrated in the elevational array of test plantings across the central Sierra Nevada *(tables 4, 5)*, high survival is routine if dormant seedlings with just moderate capacity are planted shortly before or during the local onset of spring conditions. *In essence, the key to plantation establishment for a particular seed source is knowing when to lift the seedlings in the nursery and when to plant them in the field.*

Seed Source, Nursery Environment, and RGC

The seed source and the climatic conditioning that seedlings receive in the nursery determine the ability of lifted seedlings to produce new root growth. With identical conditioning, the typical sources of western yellow pines increase in root growth capacity at very different times and at very different rates.

Most of the California sources of ponderosa pine apparently require large amounts of cold exposure to trigger increase in RGC, but the Wyoming, Arizona, Nevada and Oregon sources, along with Washoe pine and Jeffrey pine from east of the Sierra Nevada crest, clearly do not *(table 3A, B)*. With little or no cold exposure, RGC in Washoe pine and Jeffrey pine (J Eld 8200) from the Carson Range was moderately high and 4 to 20 times greater than RGC in ponderosa pine from either the eastern or western Sierra Nevada (P Plu 5000, P Eld 6300, P Eld 1900). After less than 170 hours of exposure, RGC in Tahoe Basin Jeffrey pine (J Eld 6400) peaked and was 3 to 15 times greater than RGC in ponderosa pine from the western Sierra (P Eld 5500, 500) and coastal California (P SCru 800). In a controlled-environment study of ponderosa pine from the western Sierra, RGC increased rapidly and in direct proportion to cold exposure, but only after 540 hours—60 nights—at 6°C (43°F, Krugman and Stone 1966).

Annual evaluations of ponderosa pine in the Ben Lomond Nursery, in the Santa Cruz Mountains of coastal California, showed that RGC peaked 5 to 9 weeks earlier in the colder winter seasons, suggesting that more intense cold exposure speeds the development of RGC (Stone and Jenkinson 1971). And so it may. However, those evaluations necessarily covered a single source from coastal California in the warm winter, and a different source from southern California in each of the cold winters.

Present evidence shows that the seed source exerts major control over the time that RGC takes to peak. For example, in the same winter season, RGC in a foothill source from the western Sierra Nevada (P Eld 500) peaked in less than 1 month, while RGC in typical sources from the higher western Sierra (P Eld 5500) and coastal California (P SCru 800) peaked in 3 months *(table 3A)*. The RGC in one source from the eastern Sierra (P Eld 6300) also peaked in 1 month, while RGC in another (P Plu 5000) took 3 months *(table 3B)*. Finally, RGC in ponderosa and Jeffrey pines from southern California (P Los 5350, P SBer 5370, J Los 5150, J SBer 5660, J SDie 5320) reached the first peak within 2 months, while RGC in ponderosa and Jeffrey pines from the western Sierra (P Eld 4000; P,J Pla 3800†) peaked after 3 months *(table 3C, D)*. Equally large differences are also obvious among ponderosa pines from the Western United States *(fig. 4)*.

Such frequent differences between sources in both onset and rate of increase in RGC clearly restrict application of the simple cold-exposure mechanism hypothesized for ponderosa pine with a winter-peak pattern (Stone and Jenkinson 1970). In any source with a fall-peak or bimodal pattern, changes in RGC are difficult to explain solely in terms of seedling response to cold in the nursery. Most of these sources are typified by short native growing seasons, the result of prolonged summer droughts in southern California and of long, subfreezing winters in the continental regions.

In the continental sources (P WY-Lar 7700, P AR-Coco 7000, P NE-Whi 7500, P OR-Kla 4300, W NE-Wash 8000, P Eld 6300; J Eld 6400, 8200), both top dormancy and high RGC develop in the fall, before the seedlings experience natural cold exposure. This early condition is probably induced by the seasonal decrease in day length, but might also be part of a genetically fixed pattern of annual growth. In ponderosa pine from latitudes 43°N in Nebraska and 33°N in New Mexico, both shoot elongation and weight increase depend on photoperiod (Tinus 1977). In Douglas-fir from latitudes 48°N in Montana and 33°N in New Mexico, seedlings grown under an 18-hour photoperiod enter dormancy independently of the soil and air temperature regime (Lavender and Overton 1972). Whether induced by decreasing photoperiod or inherent pattern, growth cessation and dormancy apparently channel current photosynthate into carbohydrate reserves for future growth (Kreuger and Trappe 1967, Stone and Jenkinson 1970).

In sources with a bimodal pattern, the winter lows of RGC might also be genetically fixed, or might be caused by cold exposure. If the seedlings respond to cold by shifting into deep dormancy, they could require extended time in the standard environment before root growth can commence. This hypothetical delay of growth is suggested by two physiological responses of Scots pine seedlings *(P. sylvestris L.)* hardened by winter cold and transferred to a warm environment. The photosynthesis of hardened seedlings is sharply reduced, and takes 7 to 9 days to recover to high rates (Zelawski and Kucharska 1967). Similarly, the transpiration of hardened seedlings is cut by half and takes 10 to 14 days to reach maximum rates (Christersson 1972).

On Fruit Ridge, the western yellow pines begin root growth within a week when soil at the 3-inch depth consistently warms above 10°C (50°F). In a few sources (P Plu 5000, P Eld 6300, W NE-Wash 8000), a precipitous drop in seedling root growth capacity coincides with the start of spring root growth. In other sources, however, significant declines in RGC start 4 to 15 weeks before root growth resumes. Once root growth does resume, the seedlings' translocatable reserves are rapidly spent in the nursery bed, and elongating roots invariably are damaged during lifting. The consequent losses of food reserves and root tips reduce RGC in every source.

The reduced RGC of most sources in March is also partly explained by the seedlings' rapid top growth in the standard environment. Root growth is naturally reduced once top growth is underway (Cannell and Willett 1976, Eliasson 1971, Lathrop and Mecklenburg 1971). Bud break markedly curtails translocation to elongating roots, and expanding shoots effectively compete for translocatable reserves and current photosynthate (Gordon and Larson 1968, Shiroya and others 1966, Zeimer 1971). In the January or February tests, however, root growth apparently hit peak levels regardless of the coincident top growth.

Inherent variation in the chilling required to break top dormancy had no discernible effect on field growth and survival. The chilling requirements of ponderosa and Washoe pines were essentially satisfied by January, before seedlings were lifted for outplanting. The chilling of Jeffrey pine transplanted in midwinter to Garden Valley apparently was completed on site. Abundant experience with yellow pines, Douglas-fir, and true firs grown on Fruit Ridge has shown that chilling is effectively completed in storage at 1°C (34°F), even for seedlings lifted in December, 6 to 12 weeks before natural cold exposure ensures normal spring top growth.

Planting Time and Field Survival

To select planting time is to choose—consciously or not—the initial climatic environment of planted seedlings. Seedlings in the best physiological condition are endangered when outplanted far in advance of site conditions that enable them to maintain a favorable water balance and begin root growth. In cold soils, planted seedlings cannot grow roots, will undergo high water stress, and will expend stored reserves. The consequent loss of seedling root growth capacity means seedling mortality during the summer drought.

Thus, field survivals in my January and March outplantings were just the reverse of those forecast by root growth capacity *(table 4)*. The January seedlings were lifted at peak RGC, but were planted long before root growth could start. Observations of the time when root growth resumed in the nursery and of soil temperatures there *(fig. 3)* and at Garden Valley show that the planting site was too cold to support root growth until March. Apparently, the seedlings planted in January had their roots in cold soil for about 6 weeks. Seedling roots of western yellow pines elongate very slowly at 10°C (50°F),[2] if they grow at all (Stone and Schubert 1959, Stone and Norberg 1979.)

Besides preventing root growth, a cold soil will cause physiological drought in newly planted pines, even though their stomatal control of transpiration is efficient (Lopushinsky 1969, Lopushinsky and Klock 1974). Because soil temperatures below 10°C increase the viscosity of water and sharply increase

[2]Jenkinson, James L. Data filed 1973. Pacific Southwest Forest and Range Experiment Station, Berkeley, California.

root resistance to water flow (Kaufmann 1975, 1977), the water uptake of pine is reduced 50 to 70 percent in soil at 5°C (41°F) and 85 percent in soil near freezing (Kramer 1942). This reduction in uptake typically produces large increases in plant water stress. With soil water contents near field capacity, soil temperatures below 7°C (45°F) cause daytime stress to exceed 16 bars (atm) in orange (*Citrus* spp.)—even 35 bars below 2°C (36°F), and delay recovery to predawn values until well after sunset (Elfving and others 1972). In Engelmann spruce (*Picea engelmannii* Parry), daytime stress is consistently in the 15- to 20-bar range when soil temperatures are below 7°C; below 5°C (41° to 32°F), stress increases rapidly and exceeds 15 bars even at slow rates of transpiration (Kaufmann 1975). For planted seedlings of Monterey pine (*Pinus radiata* D. Don), maintaining the soil at 5°C can hold daytime stress above 20 bars (Nambiar and others 1978). Cold soil undoubtedly affects the western yellow pines, and especially bare-root seedlings, just as it does orange and spruce.

When daytime stresses are chronically high, the planted seedlings may starve. Respiration of drought-stressed plants often exceeds their photosynthesis, resulting in net losses of reserve carbohydrates (Levitt 1972). In pine, respiration at 10 to 15 bars may be 60 percent of the rate without stress and may climb to 140 percent above 25 bars (Brix 1962). By contrast, photosynthesis plummets when daytime stress tops 5 or 10 bars, and ceases between 10 and 20 bars (Brix 1962, Cleary 1971). Any loss of reserves on the planting site probably diminishes RGC, since seedlings lifted at the peak may lose RGC even in polybags at 1°C (34°F), under zero stress and respiring at minimal rate (Stone and Jenkinson 1971).

Root growth capacity of the seedlings outplanted in March was far below that in January, but still ranged from 0.5 to 0.9 m in the California sources *(table 4)*. The soil warmed enough for rapid root growth in March, and the availability of soil water remained high through April. This favorable environment enabled adequate water uptake and immediate root elongation, thereby compensating for the lower RGC of the March seedlings. Bud swell—triggered by soil temperature (Lavender and others 1973, Paton and others 1979) and regulated by air temperature (Sorensen and Campbell 1978)—began on all seedlings in April, so top growth initially was not competing with root growth in either of the plantings.

In both plantings, Wyoming ponderosa pine had the lowest RGC and the poorest survival. But survival also reflected the degree to which sources in different climatic regions are adapted to drought. California ponderosa pine and Jeffrey pine were superior to Arizona ponderosa pine, which in turn was superior to Wyoming ponderosa pine. The California sources are adapted to summer drought, but the Arizona and Wyoming sources are not. Heavy rains are normal in July and August in central Arizona, and fall throughout the growing season in southeastern Wyoming.

In the following year, planting time had no effect on seedling survival because soil temperature immediately supported root function and growth in both plantings *(table 4)*. Further, timely spring and summer rains ensured the continued availability of water even to seedlings nearly incapable of root elongation. The heavy July rain, totally atypical of California summers, was simply "normal" for Arizona and Nevada ponderosa pines. One year later, however, those sources and Washoe pine had significant mortality and the California sources did not, a result consistent with that in the earlier test.

Improving Plantation Establishment

California sources of ponderosa and Jeffrey pines are readily established in the field, provided that seedlings are lifted at the right time in winter, stored properly (Jenkinson 1975), planted at the right time in spring, and protected against both competing vegetation and animal damage. The same provisions ensure establishment of Douglas-fir in western Oregon and California (Jenkinson and Nelson 1978), and of true firs in the Siskiyou Mountains, Shasta Cascades and western Sierra Nevada[3] (Jenkinson 1978, Stone and Norberg 1979).

In the Fruit Ridge climate, every source of yellow pine develops a moderate or high root growth capacity sometime between November and March, when nursery soil and air temperatures prevent the growth of pine. Lifted and stored at the right time, seedlings delivered to the planting sites are fully dormant and have an RGC greater than the minimums associated with high survival in my field tests.

On every planting site, cold soil fixes the earliest date and excessive evaporative stress fixes the latest date that seedlings can be planted safely. Planted at the right time, seedlings enter the site when daily soil temperatures are warming above 5°C (41°F)—warm enough for water uptake, and will soon exceed 10°C (50°F)—warm enough for root elongation. Within this "planting window", soil water contents remain at or near field capacity. Typical spring rains on most sites will settle the soil in planting holes, sealing in the seedling roots and replenishing available soil water.

---

[3]Jenkinson, James L. Data filed 1979. Pacific Southwest Forest and Range Experiment Station, Berkeley, Calif.

When planted within the planting window, properly conditioned seedlings of both local and nonlocal sources will survive equally well *(table 4),* even in diverse climatic regions *(table 5).* Although first-year mortality may be rare in such offsite plantings, other evidence decisively shows that good growth and survival to harvest age are never achieved when planted seedlings are genetically out of tune with the local climate. For example, in some older wildfire plantations in northern California, genetically maladapted ponderosa pine grew poorly, froze severely, and had to be cleared for replanting. In the altitudinal races test of ponderosa pine in the western Sierra Nevada, high-elevation sources planted at low and middle elevations were still growing poorly after 29 years, but at high elevation were more than equalling the rapid growth of middle-elevation sources; low-elevation sources at the high elevation had significant mortality, lean and breakage after 20 years (Conkle 1973, Echols and Conkle 1971). Similarly, in the earliest of provenance trials in the Pacific Northwest, maladapted sources of Douglas-fir initially survived well, but grew slowly, showed freeze damage, and ultimately finished with high mortality 30 to 50 years after planting (Campbell 1975, Silen 1978).

The planting times for established seedlings, on sites sampling 7000 ft of elevation in the Sierra Nevada, illustrate the dependence of the planting window on local climate *(table 6).* Near the toe of the western slope, the planting window may span up to 10 weeks in the calendar period of January to March. With increasing elevation, the window narrows and opens later. From 2000 ft to snow line near 3500 ft, the window is open for 6 to 8 weeks in February-March. From snow line to 4500 ft, it is 4 to 6 weeks in March-April. To 6000 ft, it is 2 to 4 weeks in April-May. At the highest elevations and anywhere else that snow melts late, the window is 2 weeks and less in May-June. South slopes usually warm 2 or 3 weeks earlier than north slopes, and the windows open accordingly.

Table 6—*Planting times and field survivals of western yellow pines in the Sierra Nevada*

Site		Seedling survival[1]		
Locality	Elevation	Ponderosa pine	Jeffrey pine	Planting time
	Feet	*Percent*		
Beale AFB[2]	200	89	97	Early February
Salmon Falls	500	92	90	Early March
Garden Valley	1900	98	99	Late February, mid-March
Fruit Ridge[3]	3000	95	95	Mid-February, mid-March
Mt. Danaher	3400	97	98	Late March
Lincoln Hill	4500	96	99	Mid-April
Angora Creek	6600	98	96	Mid-May

[1]Average of several sources, adjusted for mortality caused by gophers and grass.
[2]Personal communication from G. K. Parks, Pacific Southwest Region, Forest Service, Placerville, Calif.
[3]Unpublished data on file at Pacific Southwest Forest and Range Experiment Station, Berkeley, Calif.

For sites below snow line in the western Sierra Nevada, late-winter lifting and immediate planting of seedlings grown on Fruit Ridge can ensure excellent survival. Even in early March, the root growth capacity of most sources is still enough to justify outplanting, but only if climate at the site enhances root growth. With root elongation underway, RGC plummeting, and bud break incipient, no lifting is acceptable beyond mid-March.

For sites above snow line, seedlings must be held in cold storage until the snowpack has melted. For any site buried under snow, seedlings lifted in midwinter and held at 1°C (34°F) are safer than seedlings lifted in early spring when RGC of every source is decreasing. When lifted and stored just before RGC peaks, ponderosa pine from the western Sierra will retain high RGC through at least 3 months (Stone and Jenkinson 1971).

For most sources of ponderosa and Jeffrey pine from northern California, RGC peaks in late January on Fruit Ridge, so seedlings for spring planting are best lifted in the period from early December to February. When planting is synchronized with warming soil trends, sources from both sides of the Sierra Nevada can be lifted through late February—right to the time that roots resume growth in the nursery bed. In my tests, such seedlings were quickly established at 500, 3400, 4500, and 6600 ft of elevation, after 2, 6, 5, and 12 weeks of cold storage, respectively.

For sources from southern California, the second peak of RGC typically occurs in early February, suggesting late January-early February as the best time to lift seedlings destined for the southern forests. For the one exception (J SBer 5660), late February-early March is the indicated timc. Whether the first peak is maintained in storage, and whether storage increases RGC from the winter low, has not been determined for any source with a bimodal type of seasonal pattern.

Sources that have a bimodal or plateau pattern suggest that some seedlings grown in the Fruit Ridge climate could be outplanted in fall. Although sources from east of the Sierra crest show high RGC in November (P Eld 6300; J Eld 6400, 8200; W NE-Wash 8000), fall planting is still contingent on sufficient rain to break the summer drought and return soil water contents to field capacity. Further, survival depends on early snows to cover the seedlings and prevent physiological drought. The fall planting window is narrow at best, and in some years it may never open.

REFERENCES

Beschta, Robert L.
1976. **Climatology of the ponderosa pine type in central Arizona.** Univ. Arizona Agric. Exp. Stn. Tech. Bull. 228. 24 p., illus. Tucson, Ariz.

Bickford, Elwood D., and Stuart Dunn.
1972. **Lighting for plant growth.** 221 p. Kent State Univ. Press.

Brix, H.
1962. **The effect of water stress on the rates of photosynthesis and respiration in tomato plants and loblolly pine seedlings.** Physiol. Plant. 15:10-20.

California Division of Mines and Geology.
1971. **Geologic map of California, Sacramento sheet.** Scale 1:250,000. Sacramento, Calif.

Campbell, Robert K.
1975. **Adaptational requirements of planting stock.** *In* Global forestry and the western role. 1975 Permanent Assoc. Committees Proc., p. 103-107. Western For. and Conserv. Assoc., Portland, Oregon.

Cannell, M.G.R., and S.C. Willet.
1976. **Shoot growth phenology, dry matter distribution and root:shoot ratios of provenances of *Populus trichocarpa*, *Picea sitchensis* and *Pinus contorta* growing in Scotland.** Silvae Genetica 25:49-59.

Christersson, Lars.
1972. **The transpiration of unhardened, hardened, and dehardened seedlings of spruce and pine.** Physiol. Plant. 26:258-263.

Cleary, Brian D.
1971. **The effect of plant moisture stress on the physiology and establishment of planted Douglas-fir and ponderosa pine seedlings.** Ph.D. Thesis, Oregon State Univ., Corvallis.

Conkle, M. Thompson.
1973. **Growth data for 29 years from the California elevational transect study of ponderosa pine.** Forest Sci. 19:31-39.

Critchfield, William B., and Elbert L. Little, Jr.
1966. **The geographic distribution of the pines of the world.** USDA Forest Serv. Misc. Publ. 991. 97 p., illus. U.S. Gov. Print. Office, Washington, D.C.

Echols, R.M., and M.T. Conkle.
1971. **The influence of plantation and seed source elevation on wood specific gravity of 29-year-old ponderosa pines.** Forest Sci. 17:388-394.

Elfving, Don C., Merrill R. Kaufmann, and Anthony E. Hall.
1972. **Interpreting leaf water potential measurements with a model of the soil-plant-atmosphere continuum.** Physiol. Plant. 27:161-168.

Eliasson, Lennhart.
1971. **Adverse effect of shoot growth on root growth in rooted cuttings of aspen.** Physiol. Plant. 25:268-272.

Gordon, J.C., and P.R. Larson.
1968. **Seasonal course of photosynthesis, respiration, and distribution of ^{14}C in young *Pinus resinosa* trees as related to wood formation.** Plant Physiol. 43:1617-1624.

Griffin, James R.
1964. **Isolated *Pinus ponderosa* forests on sandy soils near Santa Cruz, California.** Ecology 45:410-412.

Griffin, James R., and William B. Critchfield.
1976. **The distribution of forest trees in California.** USDA Forest Serv. Res. Pap. PSW-82. 118 p., illus. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Jenkinson, James L.
1975. **Cold storage of bare-root planting stock.** *In* Proc. Servicewide Conf. on Plant. Stock Prod. (Coeur d'Alene, Idaho, Sept. 16-18, 1975), p. 80-95. USDA Forest Serv., Div. Timber Manage., Washington, D.C.

Jenkinson, James L.
1976. **Seasonal patterns of root growth capacity in western yellow pines.** *In* America's renewable resource potential—1975: the turning point. Proc. National Convention (Washington, D.C., Sept. 28-Oct. 2) Soc. Amer. Foresters 1975:445-453.

Jenkinson, James L.
1978. **Effect of nursery conditioning and storage on root growth capacity and early survival of selected geographic sources of Douglas-fir, true firs, and ponderosa pine.** Humboldt Nursery Admin. Study 1976-77 Rep. 30 p. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Jenkinson, James L., and James A. Nelson.
1978. **Seed source lifting windows for Douglas-fir in the Humboldt Nursery.** *In* Proc. Western Forest Nursery Council and Intermountain Nurserymen's Assoc. combined Conf. and Seed Processing Workshop (Eureka, Calif., Aug. 7-11, 1978), p. B77-95. Pacific Southwest Region, Forest Serv., U.S. Dep. Agric., San Francisco, Calif.

Kaufmann, Merrill R.
1975. **Leaf water stress in Engelmann spruce: influence of the shoot and root environments.** Plant Physiol. 56:841-844.

Kaufmann, Merrill R.
1977. **Soil temperature and drying cycle effects on water relations of *Pinus radiata*.** Can. J. Bot. 55:2413-2418.

Kramer, Paul J.
1942. **Species differences with respect to water absorption at low soil temperatures.** Amer. J. Bot. 29:828-832.

Kreuger, K.W., and J.M. Trappe.
1967. **Food reserves and seasonal growth of Douglas-fir seedlings.** Forest Sci. 13:192-202.

Krugman, S.L., and E.C. Stone.
1966. **The effect of cold nights on the root-regenerating potential of ponderosa pine seedlings.** Forest Sci. 12:451-459.

Lathrop, J.K., and R.A. Mecklenburg.
1971. **Root regeneration and root dormancy in *Taxus* spp.** J. Amer. Soc. Hort. Sci. 96:111-114.

Lavender, D.P., G.B. Sweet, J.B. Zaerr, and R.K. Hermann.
1973. **Spring shoot growth in Douglas-fir may be initiated by gibberellins exported from the roots.** Science 182:838-839.

Lavender, D.P., and R.K. Hermann.
1970. **Regulation of the growth potential of Douglas-fir seedlings during dormancy.** New Phytol. 69:675-694.

Lavender, Denis P., and W. Scott Overton.
1972. **Thermoperiods and soil temperatures as they affect growth and dormancy of Douglas-fir seedlings of different geographic origin.** Forest Res. Lab. Res. Pap. 13. 26 p., illus. Oregon State Univ., Corvallis.

Levitt, J.
1972. **Responses of plants to environmental stresses.** 697 p. Academic Press, Inc. New York.

Lopushinsky, W.
1969. **Stomatal closure in conifer seedlings in response to leaf moisture stress.** Bot. Gaz. 130:258-263.

Lopushinksy, W., and G.O. Klock.
1974. **Transpiration of conifer seedlings in relation to soil water potential.** Forest Sci. 20:181-186.

Nambiar, E.K.S., D.G. Bowen, and R. Sands.
1978. **Soil temperature and root regeneration of *Pinus radiata*.** CSIRO Div. Forest Res. Ann. Rep. 1976-77:35-36. Canberra A.C.T., Australia.

Paton, D.M., H.D. Slattery, and R.R. Willing.
1979. **Low root temperature delays dehardening of frost resistant *Eucalyptus* shoots.** Ann. Bot. 43:123-124.

Rodgers, John H.
1974a. **Soil survey of the Tahoe Basin area, California and Nevada.** USDA Soil Conserv. Serv. and Forest Serv. in cooperation with Univ. Calif. Agric. Exp. Stn. and Nevada Agric. Exp. Stn. 84 p., illus. U.S. Gov. Print. Office, Washington, D.C.

Rodgers, John H.
1974b. **Soil survey of El Dorado area, California.** USDA Soil Conserv. Serv. and Forest Serv. in cooperation with Univ. Calif. Agric. Exp. Stn. 89 p., illus. U.S. Gov. Print. Office, Washington, D.C.

Schubert, Gilbert H., and John A. Pitcher.
1973. **A provisional tree seed-zone and cone-crop rating system for Arizona and New Mexico.** USDA Forest Serv. Res. Pap. RM-105. 8 p., illus. Rocky Mountain Forest and Range Exp. Stn., Fort Collins, Colorado.

Shiroya, T., G.R. Lister, V. Slankis, and others.
1966. **Seasonal changes in respiration, photosynthesis, and translocation of the ^{14}C labelled products of photosynthesis in young *Pinus strobus* L. plants.** Ann. Bot. 30:81-91.

Silen, Roy R.
1978. **Genetics of Douglas-fir.** USDA Forest Serv. Res. Paper WO-35. 34 p., illus. U.S. Gov. Print. Office, Washington, D.C.

Smith, Richard H.
1977. **Monoterpenes of ponderosa pine xylem resin in Western United States.** USDA Forest Serv. Tech. Bull. 1532. 48 p., illus. U.S. Gov. Print. Office, Washington, D.C.

Sorensen, Frank C., and Robert K. Campbell.
1978. **Comparative roles of soil and air temperatures in the timing of spring bud flush in seedling Douglas-fir.** Can. J. Bot. 56:2307-2308.

Steinhoff, R.J., and R.J. Hoff.
1972. **Chilling requirements for breaking bud dormancy of western white pine seedlings.** USDA Forest Serv. Res. Note INT-153. 6 p., illus. Intermountain Forest and Range Exp. Stn., Ogden, Utah.

Stone, E.C., and J.L. Jenkinson.
1971. **Physiological grading of ponderosa pine nursery stock.** J. Forest. 69:31-33.

Stone, Edward C., and James L. Jenkinson.
1970. **Influence of soil water on root growth capacity of ponderosa pine transplants.** Forest Sci. 16:230-239.

Stone, Edward C., James L. Jenkinson, and Stanley L. Krugman.
1962. **Root-regenerating potential of Douglas-fir seedlings lifted at different times of the year.** Forest Sci. 8:288-297.

Stone, Edward C., and Edward A. Norberg.
1979. **Use of root growth capacity in developing propagation regimes, storage criteria, and nursery stock certification.** Paper presented at True Fir Manage. Coop. Symposium on Regeneration and Management of Young True Fir Stands (Redding, Calif., May 31, 1979). 35 p., illus.

Stone, Edward C., and Gilbert H. Schubert.
1959. **Root regeneration by ponderosa pine seedlings lifted at different times of the year.** Forest Sci. 5:322-332.

Stone, Edward C., Gilbert H. Schubert, Rolf W. Benseler, and others.
1963. **Variation in the root regenerating potentials of ponderosa pine from four California nurseries.** Forest Sci. 9:217-225.

Sturgeon, Kareen B.
1976. **Geographic variation in monoterpenes of *Pinus ponderosa* xylem resin in northern California and southern Oregon and its relation to predation by *Dendroctonus brevicomis*.** MA thesis, California State Univ., Hayward.

Tinus, Richard W.
1974. **Characteristics of seedlings with high survival potential.** *In* Proc. North American Containerized Forest Tree Seedling Symposium (Denver, Colorado, August 26-29, 1974), p. 276-282. Great Plains Agric. Council Publ. 68.

Tinus, Richard W.
1977. **Operating a greenhouse container nursery.** Paper presented at Western Gulf Industrial Tree Impr. Assoc. Meeting (Alexandria, Louisiana, June 1-2, 1977). 27 p.

Ursic, S.J., H.L. Williston, and R.M. Burns.
1966. **Late planting improves loblolly survival.** USDA Forest Serv. Res. Pap. SO-24. 12 p., illus. Southern Forest Exp. Stn., Oxford, Mississippi.

USDA Forest Service.
1969. **California tree seed zone map.** Scale 1:1,000,000. Pacific Southwest Region, San Francisco, Calif.

USDA Forest Service.
1966. **Oregon tree seed zone map.** Scale 1:500,000. Pacific Northwest Region, Portland, Oregon.

USDA Forest Service.
1978. **The principal laws relating to Forest Service activities.** USDA Agric. Handb. 453. 359 p. U.S. Gov. Print. Office, Washington, D.C.

U.S. Department of Commerce.
1954. **Climatography of the United States, No. 42, Wyoming.** 44 p.
1959. **Climatography of the United States, No. 11-2, Arizona.** 59 p.
1960. **Climatography of the United States, No. 11-22, Nevada.** 27 p.
1963. **Climatography of the United States, No. 11-31, Oregon.** 70 p.
1964a. **Climatography of the United States, No. 86-2, Arizona.** 96 p.
1964b. **Climatography of the United States, No. 11-4, California.** 156 p.
1964c. **Climatography of the United States, No. 86-4, California.** 216 p.
1965a. **Climatography of the United States, No. 86-22, Nevada.** 42 p.
1965b. **Climatography of the United States, No. 86-31, Oregon.** 96 p.
1965c. **Climatography of the United States, No. 86-42, Wyoming.** 77 p. U.S. Gov. Print. Office, Washington, D.C.

Veen, R. van der, and G. Meijer.
1962. **Light and plant growth.** 161 p., illus. The Macmillan Co., New York.

Zelawski, W., and J. Kucharska.
1967. **Winter depression of photosynthetic activity in seedlings of Scots pine (*Pinus silvestris* L.).** Photosynthetica 1:207-213.

Ziemer, Robert R.
1971. **Translocation of ^{14}C in ponderosa pine seedlings.** Can. J. Bot. 49:167-171.

☆ U S GOVERNMENT PRINTING OFFICE 1981 – 790 - 089/128

Jenkinson, James L.

1980. **Improving plantation establishment by optimizing growth capacity and planting time of western yellow pines.** Res. Paper PSW-154, 22 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Seedlings of 27 sources of western yellow pines, selected in climates typical of the species, were raised in a nursery in the western Sierra Nevada. Seedling top and root growth capacities were periodically assessed during fall and winter, and field survivals of outplanted seedlings were evaluated in different climates with summer drought. In the nursery, four distinct, innate seasonal patterns of root growth capacity were defined in ponderosa pine from within and outside California, and two distinct patterns were defined in Jeffrey pine. Below snow line in the western Sierra Nevada, seedling survivals were higher in spring plantings than in a winter one, and for California sources than for others. In spring plantings above snow line, survivals for diverse local sources of ponderosa and Jeffrey pines were uniformly high, both on the western slope and east of the Sierra Nevada crest. The results demonstrate that seedlings of any source will have adequate growth capacity and will survive the first year on any well-prepared site if they are lifted at the right time, stored properly, and planted in phase with warming soil trends.

Retrieval terms: Pinus ponderosa, P. washoensis, P. jeffreyi, genetic variation, genotype-environment interaction, progeny tests, seedling growth, seedling survival, artificial regeneration

United States
Department of
Agriculture

Forest Service

**Pacific Southwest
Forest and Range
Experiment Station**

Research Paper
PSW-155

Elytroderma Disease Reduces Growth and Vigor, Increases Mortality of Jeffrey Pines at Lake Tahoe Basin, California

Robert F. Scharpf   Robert V. Bega

Authors:

ROBERT F. SCHARPF, a plant pathologist, is studying problems in forest diseases and their control, with headquarters in Berkeley, Calif. He earned a forestry degree (1954) at the University of Missouri, and a master's degree in forestry (1957) and a doctorate in plant pathology (1963) at the University of California, Berkeley. He joined the Forest Service in 1960, and has been with the Station's research staff since then. **ROBERT V. BEGA** is in charge of the Station's research unit investigating the biology and control of diseases of conifer forests, headquartered in Berkeley, Calif. He earned a bachelor of science degree (1953) and a doctorate (1957) in plant pathology at the University of California, Berkeley. He joined the Forest Service and the Station's staff in 1955.

Cover: Portion of plot 1 photographed at various intervals after the outbreak of Elytroderma disease *(upper left)* at Lake Tahoe Basin, California. *Upper right*: May 23, 1972—a year after the outbreak; *lower left*: June 15, 1973—both trees in the foreground now dead; *lower right*: June 24, 1976—nearly all Jeffrey pines now dead and removed, and only a few white firs, in center, remain alive.

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

April 1981

Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.) in northern California is often infected with the fungus *Elytroderma deformans* (Wier) Darker that causes a needle and twig disease of pines. Forest managers are concerned with growth loss and mortality that result from this disease and how to control it.

Little is known about the effects of Elytroderma disease on Jeffrey pines, but scientists have observed and studied the disease on ponderosa pine (*P. ponderosa* Dougl. ex Laws.) (Childs 1968; Childs and others 1971; Lightle 1954; Roth 1959; Waters 1957, 1962). Wier (1916) discovered this disease on ponderosa pine in the West, and since then several severe outbreaks have occurred and timber losses estimated to be enormous. Wagener and others (1949), and Childs (1968) reported that in Oregon and Washington, salvage cuttings of ponderosa pine were necessary to utilize millions of board feet of dead and dying timber. In addition, volume was lost in trees reduced in growth rate and in dead trees inaccessible to salvage.

Certain aspects of the biology and spread of the disease are known. Elytroderma disease is prevalent in the Western United States and Canada but only appears in epidemic outbreaks occasionally. After an outbreak, the disease persists in infected trees resulting in damage for many years. The disease often occurs repeatedly on the same sites. Ponderosa pine is the tree most commonly attacked, but Jeffrey pine and other pine species are also infected (Bynum and Miller 1964). Both growth loss and mortality result in infected trees. The extent to which Elytroderma disease spreads, builds up, and damages Jeffrey pines is not well understood.

Although widespread in California, Elytroderma disease is common on Jeffrey pines only in localized areas within the State. Lassen National Park and the Lake Tahoe Basin, for example, have a history of Elytroderma disease on Jeffrey pines (Lightle 1955, Wagener and others 1949). In the Lake Tahoe Basin, endemic levels of the disease have been observed for 40 years or more. Reports suggest that at least one outbreak took place in 1949-1950.[1] Since that time, no other outbreak of the disease has been reported in the Basin except for the one discussed in this paper.

The present outbreak of Elytroderma disease in the South Lake Tahoe area was first reported in 1969.[2] In the Eldorado National Forest, pines were heavily infected with Elytroderma disease from Tallac Village to Emerald Bay, north along the west shore of Lake Tahoe and in the vicinity of the present area of study. By June 1970, the disease was causing considerable discoloration of pines in many areas—particularly in the valley bottom but it was estimated that little, if any, tree mortality would occur unless heavy infection continued in succeeding years.[3]

By spring 1971, more and more Jeffrey pines on the Eldorado National Forest were dying, causing widespread concern among visitors to the Lake Tahoe Basin.[4] Consequently, the Pacific Southwest Forest and Range Experiment Station was asked by the California Region, Forest Service, U.S. Department of Agriculture, to investigate. The study was started in June, a progress report issued in November 1972,[5] and a further report issued in 1974.[6]

This paper reports on the incidence, rate of spread, and buildup of Elytroderma disease in Jeffrey pine stands after the epidemic outbreak of 1971, and discusses the effects of the disease on vigor, growth, and mortality of Jeffrey pines in the study area. The report illustrates how a single outbreak of Elytroderma disease can damage and kill Jeffrey pines over a period of years in certain conifer stands in the Lake Tahoe Basin, California.

METHODS

After completing a field survey with National Forest personnel, we selected plots on the basis of degree of infection, as judged by the severity of current foliage symptoms in the stand. Selection was not random, and was to include as much variation as possible among plots in levels of infection. Six plots containing about 100 Jeffrey pines each were chosen in areas judged light or heavy in disease intensity.

---

[1]Personal communication from Willis W. Wagener, California Forest and Range Experiment Station, to J. M. Miller, Bureau of Entomology and Plant Quarantine, Berkeley, Calif., May 7, 1951.

[2]Personal communication from Douglas R. Miller, California Region, Forest Service, U.S. Department of Agriculture, to Forest Supervisor, Eldorado National Forest, August 4, 1969.

[3]Personal communication from Douglas R. Miller to Forest Supervisor, Eldorado National Forest, July 6, 1970.

[4]Personal communication from James M. Olson, District Ranger, Lake Valley Ranger District, to Forest Supervisor, Eldorado National Forest, May 20, 1971.

[5]Scharpf, R. F., and R. V. Bega. One-year progress report on the impact of Elytroderma disease on Jeffrey and ponderosa pines at South Lake Tahoe, November 13, 1972. (Unpublished report on file, Pacific Southwest Forest and Range Experiment Station, Berkeley, Calif.)

[6]Scharpf, R. F., and R. V. Bega. Third year progress report on the impact of Elytroderma disease on Jeffrey and ponderosa pines at Lake Tahoe, June 24, 1974. (Unpublished report on file at Pacific Southwest Forest and Range Experiment Station, Berkeley, Calif.)

Plots were irregular in shape and ranged in size from about 0.2 acre to slightly more than 1 acre. The plots consisted mostly of Jeffrey pines but a few trees of other species, such as white fir, *Abies concolor* (Gord & Glend. Lindl. ex Hildbr.) and Sierra lodgepole pine (*P. contorta* ssp. *murrayana* [Balf.] Critchfield) were also present. Per acre basal areas of both host and nonhost trees were measured on all plots. All plots were within a few hundred yards of one another so that differences in topography, stand composition, and microclimatic conditions were kept to a minimum.

Only Jeffrey pines 0.5 inch or larger at 4.5 feet above the ground (d.b.h.) were included in the study. Test trees were measured for: d.b.h. to the nearest 0.1 inch; tree height to the nearest foot; crown class: (1) dominant, (2) codominant-intermediate, (3) suppressed; tree vigor: (1) good—trees with full crowns and normal needle complement (live crown ratios of 70 percent or more; 3 or more years of needle retention), (2) average—trees with somewhat less than full crowns, or less than normal needle complement, or both, (3) poor—trees with poor live crown ratios, or with sparse foliage, or both.

In addition to tree measurements, data on distribution and intensity of Elytroderma disease were recorded for test trees. Disease distribution was assessed by visually dividing the living crown into four parts (lower, lower-mid, upper-mid, and upper crown) and determining presence or absence of the disease in each portion. Proportion of the crown infected was used as a measure of disease distribution within the tree. Disease intensity was estimated on the percentage of foliage showing disease symptoms: (0) no infection; (1) light—from 1 to 10 percent of the foliage showing symptoms; (2) moderate—from 11 to 50 percent of the foliage showing symptoms; and (3) heavy—51 percent or more of the foliage showing symptoms.

Permanent photo points were set up on several plots to record visual changes in tree condition, disease distribution, and disease intensity. Trees were photographed in color at least once, sometimes twice each year, from June 1971 to October 1977. Mortality usually was recorded twice a year, once in late spring and again in early fall from 1971 through summer 1978.

At 2- and 6-year intervals after the start of the study, tree vigor, disease distribution, and disease intensity were again recorded.

RESULTS

Host and Disease–1971

At the beginning of disease outbreak, d.b.h. of the test trees ranged from about 1 to 40 inches. Mean d.b.h. was 8.9 inches with a standard deviation of 4.9. Most trees were in the pole size class but some saplings and sawtimber sizes were present, also. Basal areas ranged from about 53 to 225 square feet per acre among the plots. More than 95 percent of the basal area on all plots was in Jeffrey pines.

The various crown and vigor classes were fairly well represented in the study:

Crown class			Vigor class		
Dominant	Codominant-intermediate	Suppressed	Good	Average	Poor
	Percent			*Percent*	
43	37	20	29	40	31

Distribution and intensity of the disease, as recorded at the beginning of the study, were:

Disease distribution (proportion of crown affected)					Disease intensity			
None	¼	½	¾	All	None	Light	Moderate	Heavy
		Percent				*Percent*		
0	1	1	22	76	0	28	25	47

None of the Jeffrey pines on any of the plots was free from Elytroderma infection. In addition, the disease most often occurred throughout the crown of the trees, even when the infection was rated light. This pattern strongly suggests a windborne mechanism of spore dispersal resulting in a more or less random pattern of infection in trees. Also, the apparent random distribution of infection in trees of all sizes studied indicated that specific microclimatic conditions or unusual weather in the area did not limit the disease to any portion of the live crown or to trees of any particular size class. More than 80 percent of all trees had some infection within 6 feet of their tops.

Disease intensity varied among test trees. About one-half (47 percent) were heavily infected, one-fourth (25 percent) moderately infected, and about one-fourth (28 percent) lightly infected. Tree size (d.b.h.) had no noticeable effect on disease intensity in that the percentage of the trees at each rated level of infection was about the same for trees of different size class (*table 1*). Similarly, disease intensity did not appear to be related to tree crown class. The proportions of trees at each rated level of infection was nearly the same for trees of different crown classes, but intensity of infection differed among trees of the three vigor classes (*table 1*).

In general, trees of good vigor were lightly to moderately infected, whereas trees of poor vigor were heavily infected. According to Lightle (1954), Elytroderma disease causes de-

Table 1—*Infection ratings of Jeffrey pines, by sizes, crown, and vigor class, Lake Tahoe Basin, California, 1971*

Class	Infection rating: Light	Moderate	Heavy
Size (d.b.h.) (inches)		*Percent*	
0.5 to 6.0	27	26	47
6.1 to 12.0	27	27	46
> 12.0	34	24	42
Crown			
Dominant	29	25	46
Codominant-intermediate	31	27	42
Suppressed	19	29	52
Vigor			
Good	61	28	11
Average	23	34	43
Poor	5	13	82

Table 2—*Disease intensity of Jeffrey pines, by plot and total basal area, Lake Tahoe Basin, California, 1971*

Plot	Total basal area[1]	Disease intensity		
		Light	Moderate	Heavy
	sq. ft.		*Percent*	
1	99	16	15	69
2	112	9	24	67
3	207	29	31	40
4	196	9	20	71
5	53	59	31	10
6	224	50	33	17

[1]A X^2 value of 2.50 and significance probability > 0.25 demonstrated independence of disease intensity and basal area where basal area was classified as either low or high.

foliation and a marked reduction in the length of infected needles of ponderosa pines. It is not surprising, therefore, that with the rating system we used for vigor in this study, Jeffrey pines with thin crowns and short needles were lower in vigor than trees with a normal foliage complement.

Taken on a plot basis, disease intensity varied considerably but was not related to stand basal area. Plots 1, 2, and 4 contained a higher proportion of trees in the heavily infected class than did plots 3, 5, and 6 (*table 2*).

In summary, infection was fairly well distributed throughout the crowns of test trees of all sizes and live crown ratio classes in 1971. Similarly, levels of infestation were fairly proportional among trees of different size classes and live crown ratio classes with about one-half of the trees showing heavy infection, one-fourth showing light infection, and one-fourth showing moderate infection. Heavily infected trees rated lower in vigor than did light and moderately infected trees.

Disease Changes–1971 to 1977

1973

Trees were examined in June 1973 to assess changes in disease intensity, disease distribution, and tree vigor for a 2-year period. Of the 553 living trees, 62 percent had the same intensity rating in 1973 as in 1971; 30 percent rated one class higher (light to moderate or moderate to heavy infection) and 8 percent rated one class lower (heavy to moderate or moderate to light). No trees rated more than one class higher or lower than they did in 1971. About two-thirds of the trees, therefore, did not change in infection rating during the 2-year period. Of the remaining one-third, most increased in infection rating and a few decreased.

Of the trees living in 1973, 56 percent were heavily infected, 25 percent moderately infected, and 19 percent lightly infected. The disease ratings for all trees surviving in 1973, therefore, were similar to those made at the beginning of the outbreak in 1971. What apparently occurred during the 2-year period was that some heavily infected trees died and the infection ratings in the remaining trees increased slightly to keep the proportion of trees in each rating class similar to that observed 2 years previously.

Analysis of disease distribution in the crowns of test trees suggested that the fungus was somewhat more widely distributed through the crowns in 1973 than in 1971. Of the 553 trees examined in 1973, 22 percent showed an increase in disease distribution, 2 percent showed a decrease, and 75 percent showed no change. The disease had increased in distribution but not necessarily in intensity in some trees for the 2-year period.

Tree vigor changed noticeably from 1971 to 1973. Forty percent of the trees decreased in vigor, and only 5 percent increased in vigor. Vigor remained unchanged in about one-half (55 percent) of the trees. Of the 553 trees living in 1973, 55 percent were of poor vigor, 26 percent of average vigor, and 19 percent of good vigor. The overall vigor of the plot trees, therefore, had diminished substantially in 2 years.

1977

Changes in disease intensity, disease distribution, tree vigor, and tree growth were investigated in test trees in 1977, 6 years after initiation of the study. Of the 440 trees that were alive in 1977, about one-half (55 percent) showed no change, 38 percent increased, and 7 percent decreased in disease intensity rating. These results are similar to those obtained in 1973 and indicate that no dramatic change in disease intensity occurred in the test trees since 1971. The proportion of trees with different ratings of infection intensity was nearly the same in 1977 as it was in 1971 and 1973. In 1977, 55 percent of the surviving trees were heavily infected, 25 percent moderately infected, and 20 percent lightly infected or free from disease. A few trees, free from disease in 1977, had been rated lightly infected in 1971 and in 1973.

From 1971 to 1977, the proportion of living trees with light, moderate, or heavy levels of infection had remained fairly constant. Some increase in disease intensity had occurred in test trees over time, however, because of the 167 trees that died during the 6 years, about 90 percent were heavily infected. For intensity ratings to have remained constant over time, the disease must have intensified in a substantial proportion of the remaining trees.

In tree crowns in 1977, the disease was less widely distributed than it was in 1971. Of the 440 surviving trees in 1977, 12 percent showed an increase in disease distribution, 24 percent showed a decrease, and 64 percent showed no change. What appears to have happened in some trees is that the new shoot and top growth that developed since 1971 was free of disease, thereby reducing the proportion of the live crown affected by Elytroderma.

Host vigor continued to decline among the test trees. Vigor in 57 percent of the remaining trees declined at least one rating since 1971, in 4 percent increased, and in 39 percent remained unchanged. When one also considers that about three-fourths of the trees that died after 6 years were of poor vigor, it is easy to see that, overall, stand vigor declined dramatically. Of the remaining live trees, 54 percent were rated poor vigor, 34 percent moderate, and only 12 percent good. For the stands as a whole, therefore, not only had the level of stocking dropped noticeably after 6 years as a result of the Elytroderma outbreak,

Table 3—*Mean annual radial growth of Jeffrey pines 5 years before and 6 years after the outbreak of Elytroderma disease in 1971*

Disease rating	Trees	Before 1971	After 1971
		mm	
Light	76	1.2	1.1
Moderate	100	1.1	0.9
Heavy	196	1.0	0.7

but the average vigor of the surviving trees had also dropped markedly.

Radial growth rate of living trees was measured from increment cores taken at d.b.h. 6 years after the disease outbreak. Growth was measured for the 5 years before the outbreak and for 6 years afterwards (*table 3*). A two-way analysis of variance with a split plot on time indicated no interaction among variables. On the average, trees grew less per year after the outbreak than before ($F = 4.04; \propto 1$), and mean growth after infection showed a downward trend with an increase in disease intensity rating ($F = 5.01; \propto 5$). In general, most plot trees were growing slowly even before the disease outbreak, as indicated by an average radial growth rate of only about 1 mm per year. Elytroderma disease, therefore, reduced radial growth rate in trees already growing slowly. Reduction of radial growth in trees that died during the study was not determined.

Tree Mortality–1971 to 1978

Tree mortality was heavy during the 7-year study (*table 4*). Of the original 609 test trees, 192 died. Mortality, however, was not evenly divided among the plots. Plots 1 and 2 accounted for 118 of the dead trees; therefore, out of an initial 203 trees on plots 1 and 2, 58 percent died during the study. Only about 5 percent of the trees died on plots 5 and 6, however, and for all plots combined, about 32 percent of the trees died.

Of the trees that died, 169 (88 percent) were heavily infected with Elytroderma disease at the start of the study. Plots with the greatest numbers of heavily infected trees had the greatest mortality. In addition, heaviest mortality (67 percent) occurred among trees of poor vigor, and 32 percent occurred among trees of moderate vigor. Only 1 percent mortality occurred among trees with good vigor at the beginning of the study.

In general, mortality was fairly evenly divided among trees of different crown class. Of the dead trees recorded, 36 percent were dominant, 36 percent codominant or intermediate, and 28 percent suppressed. Mortality was not limited to any d.b.h. class, but was well distributed among trees of all diameters. Mean d.b.h. of the dead trees was 8.9 inches, exactly the same as the mean d.b.h. of all test trees.

Mortality of Jeffrey pines in the study area was not caused entirely by Elytroderma disease. In a biological evaluation in 1973 of about 800 acres in the general area of disease infestation, pest control specialists of the Forest Service, U.S. Department of Agriculture, reported several variables involved in tree mortality.[7] Probable cause of death of trees surveyed and sampled at random in the evaluation was recorded as: Elytroderma disease alone—11 percent; Elytroderma disease and Jeffrey pine beetle—44 percent; Jeffrey pine beetle alone—11 percent; other pests and unknown—34 percent.

In our study, we attributed nearly all of the mortality in Jeffrey pine to Elytroderma disease or to Elytroderma disease and Jeffrey pine beetle. As our data show, a large proportion of the trees that died were heavily infected with Elytroderma and were of poor vigor. Many of these trees were also invaded by Jeffrey pine beetle. Although a random sample was not taken on all plots, the 8 trees that died on plots 1 and 2 between 1972 and 1978 that were not heavily infected by the disease and were of good to average vigor were also heavily attacked by Jeffrey pine beetle. We concluded that these less severely diseased trees in the outbreak area were probably killed by high populations of bark beetles that were attracted to or had built up in the severely diseased stands. We saw little evidence that other diseases or insects were responsible for the tree mortality we recorded, although *Fomes annosus* was observed in the general area of Elytroderma outbreak.[2] Our observations as well as observations by local forest managers indicated that, outside the general area of disease outbreak, Jeffrey pines in the Tahoe Basin were not experiencing above-normal levels of bark beetle attack and mortality during the study.

We had expected that the severe drought of 1976-1978 would further weaken the trees and result in increased levels of mortality, particularly among the remaining trees of poor vigor and heavy infection. Results of the study showed this not to be true. The heaviest mortality recorded occurred between June 1974 and June 1976. We believe that this mortality was caused by continued stress from Elytroderma disease and associated bark beetle activity. Mortality during the prolonged drought in California, summer 1976 to summer 1978, was actually less than that recorded during the pre-drought years.

Although 7 years have passed since the outbreak of the Elytroderma disease at Lake Tahoe Basin, a substantial portion of the remaining trees continue to die on some of the study plots.

Table 4—*Tree mortality at intervals after the outbreak of Elytroderma disease in 1971*

Month and year	Living trees	Dead trees	
June 1971	607	—	—
June 1972	581	26	[1]4.3
June 1973	553	28	4.8
June 1974	522	29	5.2
June 1976	447	[2]74	14.2
June 1977	439	10	2.2
June 1978	433	6	1.4
Sept. 1978	414	19	4.4
		Total	Pct.
		192	[3]31.6

[1]Percentage of living trees.
[2]Mortality during a 2-year period. No data recorded in 1975.
[3]On the basis of 607 trees at the beginning of study.

[7]Pierce, John R., and Michael D. Srago. Biological evaluation—pest conditions in the Taylor Creek drainage between Fallen Leaf Lake and Lake Tahoe. March 5, 1974. (Unpublished report on file, Pacific Southwest Region, Forest Service, U.S. Department of Agriculture, San Francisco, Calif.)

Table 5—*Plot size, live trees, and change in per acre basal area for Jeffrey pines on the study plots in 1971 and 1978*

Plot	Plot size	1971 Live trees	1971 Per acre basal area	1978 Live trees	1978 Per acre basal area	Change in basal area, 1971-1978
	acre		*sq. ft.*		*sq. ft.*	*sq. ft.*
1	0.87	101	96	52	70	−26
2	.60	102	112	35	34	−78
3	.22	98	201	77	174	−27
4	.26	107	194	62	126	−68
5	1.07	99	53	95	52	− 1
6	.21	100	218	94	222	+ 4

This cumulative mortality has resulted in heavy reduction in levels of stocking and basal area on some plots (*table 5, cover*).

No relationship was found between the original level of stocking or basal area of Jeffrey pines and the severity of mortality on the plots during the study. Tree mortality resulted in an appreciable reduction of basal area on plot 2 and substantial reductions on plots 1, 3, and 4. On these plots, increased basal area from 7 years of growth in residual pines did not compensate for the high loss in basal area from tree mortality. On plot 5, basal area lost from mortality was almost equal to basal area gained through growth in plot trees. Only plot 6 showed an increase in basal area. On this plot, the increase in basal area from growth was just slightly greater than that lost through mortality after 7 years. On both plots 5 and 6, mortality occurred entirely among trees less than 6 inches d.b.h. As was reported earlier, growth rates of almost all plot trees were poor.

DISCUSSION

Mortality and growth reduction of Jeffrey pine continued during a 6-year period after an epidemic outbreak of Elytroderma disease in 1971 at South Lake Tahoe, California. Results of the study indicate that no additional outbreaks of the disease occurred from 1971 through 1977. Why, then, did the effects of an epidemic outbreak that occurred in only 1 year, persist for several years?

It is known from past research that *Elytroderma deformans* initially infects needles of pines, but over time, the fungus grows into twigs and branches. Once the fungus reaches the branch tissues, it grows systemically within the phloem region of the branch and persists for years, often invading the growing tip or buds of the branches (Childs 1968). Each succeeding year, therefore, newly produced needles are infected by the fungus living within the growing tips of the infected branches.

The proportion of the needle infections that become systemic branch infections is not well known. Our observation and photographs of some trees for several years suggest that many of the initial infections on needles result in systemic infections. Systemic infection also explains the fairly constant levels of the disease in stands for several years after an epidemic outbreak, even though climate and other variables do not favor new needle infection. Childs (1968) pointed out for ponderosa pine, and we found it true for Jeffrey pines, that epidemic outbreaks need not occur frequently for tree damage and mortality to result.

Some variables involved in mortality in this study were similar to those found by Childs (1968) in the Pacific Northwest:

- Mortality occurred among trees of all size classes.
- Mortality was highest in trees of poor vigor and with heaviest infection.
- Mortality was the result of not only Elytroderma disease but was associated with bark beetle attack.

Childs (1968) considered certain root disease fungi to be the agents which, when associated with Elytroderma, resulted in tree death. Childs and others (1971) reported that severely infected ponderosa pines are seldom attacked by bark beetles. Instead, they are more likely to die as a direct result of Elytroderma disease. Pines killed by bark beetles, according to them, are more likely to be the ones with about one-fourth to three-fourths of the needles on twigs infected. We observed, and Pierce and Srago[7] recorded, Jeffrey pine beetle as a principal agent in association with Elytroderma disease and tree death.

We noticed, as did Childs and others (1971) and Hunt and Childs (1957)[8] that local outbreaks of Elytroderma disease are generally restricted to certain areas. These areas are often sheltered situations such as bottoms of draws, meadows, forests along lake shores, and forested slopes subject to heavy dew or condensation from persistent fogs. Undoubtedly, epidemic outbreaks of the disease require certain weather conditions and, likely, specific climatic variables for heavy infection to occur. Unfortunately, we do not yet know precisely what variable(s) are involved in these infrequent but periodic outbreaks. Further study is needed to better understand the climate or other variables involved in the epidemiology of Elytroderma disease.

Knowledge about the occurrence of past outbreaks and surveys of present outbreaks allow the forest manager to better delineate sites on which outbreaks are apt to occur again. In the management of these high-risk sites it is necessary for the manager to realize that susceptible species will periodically suffer heavy mortality and growth loss from Elytroderma disease. In such areas, management may call for retaining or regenerating tree species not susceptible to the disease.

One observation we made during the study was that Sierra lodgepole pine throughout the area was almost uninfected by Elytroderma disease, even though the Rocky Mountain-intermountain race, *P. contorta* ssp. *latifolia* (Engelm.) Critchfield is reported to be a principal host of the disease in British Columbia, Canada. In a strip survey through a stand of mixed lodgepole and Jeffrey pines, we found only 5 lightly infected lodgepole pines out of 71 trees examined even though

[8]Hunt, John H., and T. W. Childs. 1957. Ponderosa pine needle blight in eastern Oregon during 1955 and 1956. (Unpublished report on file at Pacific Northwest Forest and Range Experiment Station, Corvallis, Oreg.)

40 Jeffrey pines examined in the survey were moderately to heavily infected. For reasons not determined in the study, lodgepole pines intermixed with Jeffrey pines in severely infected stands were nearly free from disease. It appears from our general observations throughout the area and from this strip survey that lodgepole pine, along with other resistant trees, can be considered as an alternative species for planting, management, or both, on high-risk sites.

Air pollution (smog) has been reported to be causing damage to trees in the Lake Tahoe Basin.[4] We saw no evidence of this on trees in the Elytroderma disease areas we examined. In fact, from 1971 to 1977, both concentrations and duration of ozone levels were considered below those required to cause visual symptoms of smog injury to pines in the Lake Tahoe Basin.[9]

The findings of our study that we consider most valuable for aiding forest managers in reducing Elytroderma disease are:

- Elytroderma disease occurs in epidemic proportions infrequently but periodically in certain stands of Jeffrey pine in the Lake Tahoe Basin. Mortality and growth losses during and for years after epidemics can be severe, particularly among heavily infected trees.
- High-risk areas should be defined by surveys shortly after disease outbreaks. Managers should biologically evaluate the possibility that heavy mortality and growth losses will disrupt current management plans or prevent reaching management goals.
- Level of stocking seems to have no influence on the incidence and severity of disease, but overstocked stands often contain many trees of poor vigor. Thinning or other means to increase stand vigor before an outbreak will probably not prevent other outbreaks from occurring but may help to reduce tree mortality resulting from the disease. Trees of all size and age classes appear equally susceptible to infection and damage from the disease; therefore, planting or favoring existing nonsusceptible tree species is the best way to control the disease in high-risk areas.
- Weakening of trees by the disease also predisposes the stand to attack by bark beetles, which further increases mortality and damage.

[9]Personal communication from Paul R. Miller, Pacific Southwest Forest and Range Experiment Station, Riverside, Calif., 1978.

LITERATURE CITED

Bynum, H. H., and Douglas R. Miller.
1964. ***Elytroderma deformans*** **found on knobcone pine in California.** Plant Dis. Rep. 48(10):828.

Childs, T. W.
1968. **Elytroderma disease of ponderosa pine in the Pacific Northwest.** USDA Forest Serv. Res. Paper PNW-69, 45 p. Pacific Northwest Forest and Range Exp. Stn., Portland, Oreg.

Childs, T. W., Keith R. Shea, and James L. Stewart.
1971. **Elytroderma disease of ponderosa pine.** USDA Forest Serv. Pest Leafl. 42, 6 p., illus.

Lightle, Paul C.
1954. **The pathology of *Elytroderma deformans* on ponderosa pine.** Phytopathology 44:557-569, illus.

Lightle, Paul C.
1955. **Experiments on control of Elytroderma needle blight of pines by sprays.** USDA Forest Serv., California Forest and Range Exp. Stn., Forest Res. Note 92, 6 p.

Roth, Lewis F.
1959. **Perennial infection of ponderosa pine by *Elytroderma deformans*.** Forest Sci. 5:182-191, illus.

Wagener, Willis W., T. W. Childs, and J. W. Kimmey.
1949. **Notes on some foliage diseases of forest trees on the Pacific slope.** Plant Dis. Rep. 33(4):195-197.

Waters, Charles W.
1957. **Some studies on *Elytroderma deformans* on ponderosa pine.** Montana Acad. Sci. Proc. 17:43-46.

Waters, Charles W.
1962. **Significance of life history studies of *Elytroderma deformans*.** Forest Sci. 8:250-254, illus.

Weir, James R.
1916. ***Hypoderma deformans*, an undescribed needle fungus of western yellow pine.** J. Agric. Res. 6:277-288.

Scharpf, Robert F., and Robert V. Bega.

1981. **Elytroderma disease reduces growth and vigor, increases mortality of Jeffrey pines at Lake Tahoe Basin, California.** Res. Paper PSW-155, 6 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

A disease of Jeffrey pines (*Pinus jeffreyi* Grev. and Balf.) at Lake Tahoe Basin, California, caused by Elytroderma disease (*Elytroderma deformans*) was studied for 7 years after a severe outbreak of the fungus in 1971. Among 607 Jeffrey pines on six plots, about one-half were heavily infected and about one-half were moderately or lightly infected in 1971. No uninfected trees were observed. During the 7-year study, about one-half of the trees remained unchanged in vigor, disease intensity, or both, and about one-half decreased in vigor, became more heavily infected, or both. Of the original 607 trees studied, nearly one-third died before 1978. Average radial growth of surviving trees was less per year after the outbreak than before, and heavily infected trees were growing more slowly than lightly infected trees. Intensity of the disease, however, was not related to stand basal area.

Retrieval Terms: Pinus jeffreyi, Pinus ponderosa, Pinus contorta, parasitic fungi, *Elytroderma deformans*, Lake Tahoe Basin, forest protection, mortality rate.

United States Department of Agriculture

Forest Service

Pacific Southwest Forest and Range Experiment Station

Research Paper PSW- 156

West Coast Tree Improvement Programs: a break-even, cost-benefit analysis

F. Thomas Ledig Richard L. Porterfield

The Authors:

F. THOMAS LEDIG is in charge of the Station's forest genetics research, with headquarters in Berkeley, California, and field facilities at the Institute of Forest Genetics, Placerville, California. He was formerly professor of forest genetics, Yale University, New Haven, Connecticut. He earned a forestry degree at Rutgers University (1962) and master's (1965) and doctoral (1967) degrees in genetics at North Carolina State University. **RICHARD L. PORTERFIELD** is director, Raw Materials Supply, Timberlands Division, Champion International Corporation, Stamford, Connecticut. He earned a bachelor's degree in forestry and business administration (1968) at Ohio State University, a master's degree (1970) in forestry and economics at North Carolina State University, and a doctorate in forestry and economics (1973) at Yale University.

Acknowledgments:

We thank the following persons for their contributions to this study: *Roy R. Silen*, Pacific Northwest Forest and Range Experiment Station, Corvallis, Oregon, for cost figures on the progressive tree improvement program; *Jay H. Kitzmiller*, Pacific Southwest Region, Forest Service, San Francisco, California, for cost data on the Pacific Southwest tree improvement program; and *Jack Wanek*, St. Paul Seed Orchard, Salem, Oregon, and *Virgil Allen*, Dennie Ahl Seed Orchard, Shelton, Washington, for information on seed yields and on the costs of establishing and maintaining Douglas-fir seed orchards.

Cover: Pines at the Institute of Forest Genetics, Pacific Southwest Forest and Range Experiment Station, Placerville, California (photo by Dennis Galloway).

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

August 1981

West Coast Tree Improvement Programs: a break-even, cost-benefit analysis

F. Thomas Ledig Richard L. Porterfield

CONTENTS

IN BRIEF...

Ledig, F. Thomas, and Richard L. Porterfield.
1981. **West Coast tree improvement programs: a break-even, cost-benefit analysis.** Res. Paper PSW-156, 8 p. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Retrieval Terms: tree improvement, economic analysis, *Pinus ponderosa, Pseudotsuga menziesii,* sensitivity analysis, minimum genetic gain

Most previous economic analyses have focused on improvement programs for short rotation southern pines or for spruce in the Northeast and Canada. It may be more difficult to justify tree improvement for western conifers, not only because rotations are longer, but because local adaptation to a complex topography may prevent improved trees from being used over as wide an area as in eastern North America. The smaller the breeding zone, the greater the cost per acre planted.

We used a break-even, cost-benefit analysis to explore profitability for three representative programs: the Pacific Southwest's program for ponderosa pine in the Sierra Nevada and both a first-stage and a second-stage of the Pacific Northwest's progressive tree improvement program for Douglas-fir. The analysis used the best cost data available to determine the minimum volume improvement required to earn a fixed rate of return, 8 percent in our calculations. Sensitivity analysis, allowing assumptions to vary one at a time or in sets, was used to judge the risks associated with uncertain estimates.

The ponderosa pine program is in the traditional mode of southern pine improvement. Moderately rigorous selection is practiced in natural stands, and selected trees are grafted into seed orchards. Progeny tests provide information on which trees are, in fact, inferior, and these are removed from the orchard. Only a 6.3 percent volume improvement from the genetic approach will bring an 8 percent return on the investment, and based on experience in other species, 6.3 percent seems easily attainable.

Progressive tree improvement programs in the Pacific Northwest differ from the traditional approach. Selection is frequently weak, and seed for planting is collected from the selected trees where they stand, so that progeny have only one selected parent. Many selections are made and breeding zones are narrow. Progeny test information is used to determine which of the original selections should be eliminated. Although anticipated improvement is small, costs are low, so that only 1.8 percent volume improvement would return 8 percent on investment.

Progressive programs can enter a second, high-intensity stage at any time. Seedling seed orchards are established by thinning progeny test plantations to the best individuals in the best families. For a second-stage program for Douglas-fir, only an additional 1.0 percent improvement will pay for the investment, and this seems highly likely.

Sensitivity analysis of the underlying assumptions indicate that economic factors and silvicultural decisions affect profitability more than program design. The choice of interest rate and length of rotation are particularly crucial. With long rotations (120 years for ponderosa pine and 80 years for Douglas-fir) tree improvement will only be profitable if returns are possible from intermediate thinnings. Otherwise, rotations should be shortened to 50 years. Less improvement is necessary to justify expenditures on land of high site index than on sites of low productivity. The primary attributes over which the breeder has control are the number of selections, the size of the breeding zones, and the type of orchard. Small breeding zones, such as those in the progressive tree improvement scheme, reduce profitability. On the other hand, large zones such as those in the Pacific Southwest's program entail greater biological risks of planting nonadapted trees. The differences in establishment costs for grafted compared to seedling seed orchards seems less important. We conclude that with reasonable rates of interest, a realistic price increase for timber value, and good silviculture, both programs will be quite profitable.

Tree improvement can be a highly profitable investment (Porterfield and others 1975, Carlisle and Teich 1978, Davis 1967). In general, only small levels of improvement are needed to justify expenditures (Perry and Wang 1958). However, most previous analyses have dealt with southern pines that are grown on short rotations, and none have dealt with western conifers grown on long rotations.

Programs for the improvement of Pacific Coast conifers, such as Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) and ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.), have unique features not common to programs for eastern species. Western forests are characterized by long rotations and complex topography that may result in local adaptation, thereby narrowing breeding zones—the operating unit for which improved trees are bred.

Our objective was to explore the economic justification of representative tree improvement programs for western conifers. Two contrasting programs were chosen as illustrations. The National Forest System's regional tree improvement program for the Pacific Southwest is in the traditional mode and depends on early establishment of seed orchards. Long rotations distinguish it from programs managed by industrial cooperatives, such as those in the Southeast and Pacific Northwest. The Pacific Northwest's progressive tree improvement program is characterized by small breeding zones, large numbers of selections, and seed collection from selected trees *in situ* rather than establishment of seed orchards. Major reliance is placed on progeny tests—tests of a parent's breeding value or its ability to produce superior progeny—rather than intensive selection in the forest (Silen and Wheat 1979, Silen 1966). The cost and benefit structure may be considerably altered in a progressive tree improvement program compared with the traditional approach.

Previously, we applied benefit-cost analysis to tree improvement programs in the Northeastern United States and Canada (Porterfield and Ledig 1977), and compared two proposals for improvement of black spruce (*Picea mariana* [Mill.] B.S.P.). Seedling seed orchards—orchards established with seedling progeny of wind-pollinated selections rogued to leave the best trees by using family test information—proved superior to a traditional grafted seed orchard program. However, sensitivity analysis revealed that initial estimates of seed yield and length of harvest rotation accounted for most of the difference between programs.

PROCEDURES

The programs analyzed are actual, on-going programs: the Pacific Southwest's program for conifers in the Sierra Nevada (Kitzmiller 1976), and the Pacific Northwest's program for Douglas-fir (Silen and Wheat 1979). In the initial analysis, we tried to adhere closely to the published descriptions of these programs. Later, we suggested the effects to be achieved by various changes.

The benefit-cost ratio is the present value of benefits divided by the present value of costs. A ratio of 1.0 or greater indicates a rate of return on investment equal to or greater than the interest rate used in the analysis. Because definitive information on economic benefits usually is not available in the early stages of tree improvement, program justification is difficult. We used a simple, break-even analysis that required a minimum of proven data. Essentially, we determined the minimum volume improvement required to earn the fixed rate of return used in the investment calculation. Such an analysis allows comparison of programs and enables an objective choice between competing proposals. Also, it permitted us to vary factors one at a time or jointly, to measure sensitivity of required volume gains to modifications in the program, or to judge the risks associated with uncertainty in market values.

We used an interest rate of 8 percent for our base rate, but examined the effect of different rates with sensitivity analysis. Higher or lower rates might apply, depending on the situation, but 8 percent seems a realistic compromise. Interest rates include a fraction due to inflation and a remainder that is a true interest component. Over the long term appropriate to investments in forestry, inflation has run about 5 percent. A rule of thumb is that the real rate is about one-half the nominal. For public investments a return of 5 to 6 percent is commonly used (6.2 percent was the rate for the Forest and Rangeland Renewable Resources Planning Act, but a case has been made for a rate of 4 percent). For National Forest programs, a 5- to

6-percent rate may be appropriate. For industrial members of tree improvement cooperatives a higher rate might be desirable, say 11 percent, reflecting present interest rates.

PONDEROSA PINE PROGRAM

The Pacific Southwest Region's tree improvement program for the National Forests includes several species and breeding zones of California conifers (Kitzmiller 1976), but our analysis was restricted to one species, ponderosa pine, and one breeding zone. Within a breeding zone, 200 selections are made. Wind-pollinated seed is collected to establish progeny tests early in the program. Simultaneously, cuttings are collected to establish a grafted seed orchard at 15 by 15 feet. With progeny test results as a guide, the orchard will be rogued to the best 50 selections by age 15.

Characteristics and economic base for the ponderosa pine tree improvement program are:

Characteristics

Number of trees selected	200 trees
Number of acres of orchard	14 acres
Commercial seed production of orchard begins	14 years
Orchard phased out	44 years
Rotation age	120 years
Operating area	336,000 acres
Annual planting	2,800 acres

Economic Assumptions

Interest rate	8 percent
Current stumpage price	$110 per Mbf
Normal yield of unimproved forest (site III)	
at 120 years	100 Mbf
at 60 years	35 Mbf

Present value of costs per acre of orchard is $32,646 (*table 1*) and each acre is expected to produce sufficient seed to regenerate 200 acres of plantation each year of its commercial life. Although the tree improvement plan calls for establishing a grafted clone archive to facilitate crosses among the selections, and a program of matings, we ignored those costs. They are aspects of a second generation improvement program, produce no benefits for the first generation, and should not be charged to the first generation.

The ponderosa pine program assumes a 120-year rotation, but improved yields will be harvested in intermediate thinnings at 40, 50, 60, 70, 80, 90, 100, and 110 years. Final harvested volume at 120 years will be the same for improved stands as for unimproved stands. The assumption is not unreasonable, implying that biomass per acre is limited but the rate at which the limit is reached can be improved. We distributed 20 percent of the total genetic gain in volume for the rotation to the thinning at age 40, 40 percent to age 50, and 6.5 percent to thinnings in each of the next six decades. The benefits occur at the harvest age plus 14 years (the time between the start of the program and establishment of the first commercial plantations) for each seed crop over the commercial life of the orchard.

To evaluate the program, present values of tree improvement costs per acre planted were equated to the present value of incremental benefits. In general form:

$$\$163.23 = B \times \frac{I}{C},$$

in which:

B = a discounting factor giving the present value of receiving one dollar each year for the 30-year production life of the orchard (age 14 to 44),

I = the value increase per acre of plantation (volume gain × value per unit) as the result of genetic improvement, necessary to return 8 percent on the investment,

C = a discounting factor required to bring benefits back in time (the years before commercial seed collection plus the years until the first improved plantations are thinned).

Because thinning takes place in several cycles, I/C is a weighted sum under the present assumptions:

$$\$163.23 = [(1.08^{30} - 1)/(0.08)(1.08^{30})] \times [0.2I/1.08^{54} + 0.4I/1.08^{64} + 0.065I/1.08^{74} + 0.065I/1.08^{84} + 0.065I/1.08^{94} + 0.065I/1.08^{104} + 0.065I/1.08^{114} + 0.065I/1.08^{124}].$$

The break-even value for I is $2,250.75; in words, each acre of improved plantation must be worth $2,250.75 more than unimproved plantation for the benefit-cost

Table 1—*Present value of costs per acre of seed orchard in the ponderosa pine tree improvement program, Pacific Southwest Region, Forest Service, U.S. Department of Agriculture*

Activity	Present value per acre orchard (@ 8 percent)	Year cost incurred
Selection and cone collection	$1,971	1
	1,825	2
Orchard establishment	4,942	3
	4,576	4
	4,237	5
Orchard maintenance (annual)	4,260	4 to 44
Progeny test establishment	5,007	3
	4,636	4
Progeny test maintenance	92	4
	171	5
	158	6
	73	7
Progeny test maintenance (annual)	217	8 to 20
Progeny test evaluation	68	5 to 8
	413	9 to 20
Total present value per acre orchard	$32,646	
Total present value per acre plantation	$163.23[1]	

[1]Obtained by dividing cost per acre of seed orchard by 200 acres plantation per acre seed orchard.

ratio to be 1.0 and the return on the tree improvement investment to be just 8 percent. To translate this into volume improvement we assume a current value of $110 per Mbf, which is the California Board of Equalization's projected timber value harvest schedule for the Central Sierra projected for the first half of 1980. The California Board of Equalization collects data and publishes commodity prices. However, our best estimate is that timber value will continue to follow the historic trend of 1.5 percent per year real price increase (USDA Forest Service 1974). Allowing for a 1.5 percent price increase, we solve for the required volume improvement. Required gain in value to return 8 percent on investment is:

$$\$2{,}250.75 = \sum_{i=1}^{8} V_i \times W_i \times T,$$

in which:

V_i = value per Mbf at time of the i^{th} thinning
W_i = proportion of the total increase in cut removed at the i^{th} thinning
T = total increase in volume cut during rotation.

Therefore:

$$\$2{,}250.75 = [(\$245.79)(0.2) + (\$285.25)(0.4) + (\$331.04)(0.065) + (\$384.18)(0.065) + (\$445.86)(0.065) + (\$517.44)(0.065) + (\$600.51)(0.065) + (\$696.92)(0.065)] \times T$$

Solving, T = 6.3 Mbf required gain in volume per acre over normal unimproved plantation to return 8 percent on the investment. Kitzmiller (1976) uses 16,100 cf as unimproved yields, and it is implicit in his other assumptions that this is equivalent to 80.5 Mbf. But, unimproved yields of 80.5 Mbf per acre seem unreasonably small. Given a 120-year rotation, we anticipate more than 100 Mbf on a medium site at final harvest alone. Therefore, the required improvement to return the investment of 8 percent interest is probably close to 6.3 percent. Thinning is likely to salvage timber that would otherwise be lost so total yield for the entire rotation would exceed 100 Mbf per acre. The effect of a higher estimate for unimproved yields would be to reduce the percentage improvement necessary to attain the break-even point. Nevertheless, a gain of 6.3 percent in volume from tree improvement seems easily attainable. In southern pine improvement programs, 15-percent gain is expected in the first generation. A 15-percent gain in the ponderosa pine program would pay a high internal rate of return on investment.

We examined the effects of modifications to the ponderosa pine program by varying the assumptions and recalculating the improvement necessary to break even (*table 2*). An interest rate of 5 percent reduces required improvement to such ridiculously low levels that an economic return seems certain. However, a rate of 11 percent requires an improvement of 35.4 percent over normal unimproved yields, and it is doubtful that such a substantial increase could be achieved by one generation of selection with the selection intensity currently used.

Table 2—*Sensitivity analysis for the ponderosa pine tree improvement program, Pacific Southwest Region, Forest Service, U.S. Department of Agriculture*

Assumptions	Required volume improvement	
	Mbf per acre	Percent
Base case	6.3	6.3
Changes		
Interest rate is 5 percent	0.9	0.9
Interest rate is 11 percent	35.4	35.4
No real price increase	20.5	20.5
No thinnings	539.9	539.9
No thinnings, rotation is 60 years	13.0	37.1
No thinnings, rotation is 60 years interest rate is 11 percent	116.4	332.6
Site index increased, normal unimproved yields 150 Mbf per acre	6.3	4.2
Breeding zone halved	9.1	9.1
Seed yield doubled	4.6	4.6
Seed yield doubled, planting program doubled	3.2	3.2

Real price changes also have a major effect on prospective returns. In the unlikely event that real price did not increase for the next 120 years, required volume improvement would be 20.5 percent, a marginal possibility.

The success of tree improvement programs in western conifers depends on the application of intensive silviculture, including intermediate cuts or thinning. If no thinnings were made so that all improvement was realized at rotation age 120 years, an improvement program could not possibly pay for itself. Even if the rotation were reduced to 60 years, the required improvement in volume would be 30 percent.

Site index also affects profitability in inverse fashion. If site productivity is doubled, the improvement necessary to attain the break-even point is halved. The lesson is that tree improvement should be practiced on the most productive sites first.

In common with most improvement programs, the ponderosa pine program runs a biological risk of losing locally adapted populations. It uses a high selection intensity with the assumption that widely adapted parents can be found in adequate numbers to maintain a broad genetic base. The larger the scale (that is, the higher the selection intensity and the broader the breeding zone in which the selected parents will be used), the greater the economic returns, but the greater the biological risk. Would the ponderosa pine program be profitable if breeding zones were reduced in size so that they supported a planting program of only 1400 acres as against 2800 acres? A breeding zone supporting a planting program of 1400 acres is suggested because it is comparable in size to those in the Pacific Northwest's progressive tree improvement program. Because of lower seed requirements, the orchard is cut to 7 acres, a size that increases the present value of costs to $47,276 per acre of orchard or $236.38

per acre of plantation. Costs per acre are increased even though establishment and maintenance costs are reduced because selection and progeny test costs remain the same and there are fewer acres over which to spread these costs. In this situation the required improvement is 9.1 Mbf per acre, or 9.1 percent (*table 2*) compared with only 6.3 percent for the larger original program, despite higher total costs for the latter. The difference could be one of profitability or nonprofitability, and emphasizes the economic desirability of large breeding zones. However, smaller breeding zones involve less biological risk and a 9.1-percent gain to return 8 percent on the investment is not unattainable through the genetic approach. Therefore, smaller breeding zones may be justifiable, depending on goals and investment policy.

Doubling seed yield is more problematic. Most analyses have indicated that the profitability of improvement programs strongly depends on seed yields (Danbury 1971, Marquis 1973). But this conclusion is reached by assuming that higher seed yields can be used to expand the planting program. If doubling seed yield merely results in halving the size of the seed orchard and its associated costs, then the required increase in volume in improved plantations is 4.6 percent, only 1.7 percentage points lower than the base case. This results because the cost reduction for orchard establishment and maintenance is a relatively small amount compared with costs of selection and progeny evaluation. The only way to substantially reduce costs is by reducing the genetic base, a highly undesirable approach. In addition, small orchards present a problem in pollen management.

If doubling seed yields in the ponderosa pine program means doubling the planted acreage, then even without a reduction in orchard costs it would only be necessary for improved plantations to yield 3.2 Mbf per acre more at maturity than unimproved plantations to break even as against the 6.3 Mbf required with lower seed yields. Note that doubling the planting program means doubling the size of the breeding zone, and with the same number of selections is equivalent to a reduction in the genetic base per unit operating area. Increasing the scope of the planting program (or, what is the same thing, the size of the breeding unit) offers potential for improving profitability, but entails a biological risk.

In summary, economic factors such as interest rate and real price changes are the major determinants of profitability in a long-rotation, western conifer. The silvicultural system in which tree improvement is applied is also important. Length of rotation and utilization of thinnings have more effect on profitability than program design. However, program design and operation are under control of the breeder, whereas interest rate and price changes are not. Reducing the size of the breeding zone will increase costs per acre of improved plantation and increase the amount of improvement required to earn the desired return on investment. Increasing seed yields in the seed orchard will have a limited effect on profitability unless the increased yields can be used to increase the size of the planting program, which is equivalent to increasing the size of the breeding zone. The exception would be efforts to improve seed yields at early orchard ages, either by attempting to reach commercial production prior to age 14 and/or increasing early yields. We were forced to assume a uniform level of seed production in the analysis, whereas actual production is low in the beginning and increases throughout the early years of the orchard.

FIRST-STAGE PROGRESSIVE PROGRAM FOR DOUGLAS-FIR

In a progressive tree improvement program, better-than-average trees are selected along roadsides by subjectively grading them against some perceived standard for the breeding zone. Accessibility and evidence of cone production are the major criteria because the selected trees must provide seed for planting without further multiplication in seed orchards. A large number of trees are selected, perhaps 300 for each 100,000-acre operating unit, to ensure a broad genetic base. Because of the emphasis on accessibility and cone production and the desire to maintain the genetic base, selection intensity in many cooperatives is low for growth rate and form.

Characteristics and economic base for the progressive tree improvement program for Douglas-fir are:

Characteristics	
Commercial seed production of selected trees	1 to 18 years
Rotation age	80 years
Operating area	100,000 acres
Annual planting	1,250 acres
Seedlings planted per acre	500 seedlings
Economic assumptions	
Interest rate	8 percent
Stumpage (second growth)	$275 per Mbf
Normal yield of unimproved forest at 80 years, site III land, site index of 130 (McArdle and others 1961)	66.8 Mbf

The initial seed collections are used for progeny testing. When progeny tests reveal differences among parents, seed collection from the poorer parent trees is discontinued. Eventually, seed collection is concentrated on the 75 trees that produce the best progeny. At this point, several options are available for moving into a second-stage program; for example, either collecting the superior parents into a clonal seed orchard or initiating another generation by selecting among the best of the progeny. Because it is likely that a second-stage program will follow, we assumed for purposes of calculation that seed collection from the selected trees will continue only from year 1 to year 18. Costs for this initial program include only selection and progeny testing (*table 3*). Costs of seed collection are not included because these would be at least as high if there was no improvement program. Similarly, we ignore costs

Table 3 — *Incremental costs per acre of improved plantation for a first-stage, progressive tree improvement program for Douglas-fir*[1]

Activity	Cost per acre planted (1979 dollars)	Year cost incurred
Tree selection and release	$ 10.93	1
Progeny testing	189.32	1 to 16
Total present value of cost @ 8 percent	$166.48	

[1]Data in 1974 dollars supplied by Roy R. Silen, Pacific Northwest Forest and Range Experiment Station, Corvallis, Oregon. Costs brought to 1979 at 8 percent, a rate approximating the 1974-1979 change in the producer price index for all commodities.

of plantation establishment and culture, which would be the same with or without tree improvement.

Although Silen and Wheat (1979) assume an 80-year rotation without thinning, it seems likely that thinning will become more common in the Pacific Northwest. For land with a site index of 170 on the Siskiyou National Forest in Oregon, a volume of 63.9 Mbf per acre is expected without thinning on a rotation of 85 years. If the same stands are thinned at 10-year intervals beginning at age 25, then the accumulated cut from thinnings and harvest at 85 years would be 105.3 Mbf per acre. Therefore, for our analysis we assumed thinnings at 40, 50, 60, and 70 years. For arguments similar to those used for the ponderosa pine program, we distributed most benefits to the earliest thinnings, 30 percent of the total genetic gain in volume for the rotation to the thinning at 40 years, 40 percent at 50 years, and 10 percent to thinnings at 60 and 70 years and to the harvest at 80 years.

To evaluate the program, we set the present marginal value of costs per acre planted, $166.48 (*table 3*) equal to the present value of benefits:

$$\$166.48 = B \times \frac{1}{C}$$

$$= [(1.08^{18} - 1)/(0.08)(1.08)^{18}] \times [0.31/1.08^{41} + 0.41/1.08^{51} + 0.11/1.08^{61} + 0.11/1.08^{71} + 0.11/1.08^{81}],$$

in which factors are as in the analysis of the ponderosa pine program. The break-even value for I is $799.56 over returns from normal unimproved plantations.

A conservative value for second-growth Douglas-fir stumpage in the Pacific Northwest is currently $275 per Mbf. We assume a real price increase of 1.5 percent per year and solve for T, the volume improvement equivalent to the break-even value of $799.56:

$$\$799.56 = [(\$506.34)(0.3) + (\$587.63)(0.4) + (\$681.96)(0.1) + (\$791.45)(0.1) + (\$918.51)(0.1)] \times T$$

Solving, T = 1.2 Mbf per acre increase over the base of 66.8 Mbf per acre of normal unimproved plantation, a 1.8 percent improvement. However, 66.8 Mbf per acre is volume at final harvest. Accumulated thinnings would bring production to more than 100 Mbf per acre, so the required improvement in volume to reach the break-even point would be less than 1.2 percent.

A sensitivity analysis (*table 4*) was used to explore several factors and how they affected the profitability of the progressive program. As for the ponderosa pine program, site quality and changes related to appreciation of timber values and utilization of smaller logs have a major effect on profitability. Failure to realize any real annual price increase will more than double the amount of improvement necessary to break even at 8 percent. Length of rotation also has a major effect. Most industrial landowners in the Pacific Northwest currently think in terms of short rotations. For a rotation of 50 years the required volume increase to break even on the investment in tree improvement even without thinnings is only 1.5 Mbf per acre or 4.9 percent more than the yield of normal unimproved stands (31.4 Mbf per acre at 50 years with a site index of 130; McArdle and others 1961). But a reduction in rotation age from 80 to 50 years is equivalent to increasing the size of the planting program to 2000 acres per year and can be accomplished only if the selected trees produce adequate seed to serve the additional planting requirement. Short rotations will substantially reduce the improvement required to break even on an 8-percent-interest rate. If tree improvement efforts are restricted to sites of higher quality, the required improvement is even more easily attainable. With a site index of 170, only a 1.2-percent improvement in yield will pay for a tree improvement program.

We assume that program costs can be reduced only by reducing the scope of the program. If half as many

Table 4 — *Sensitivity analysis for a first-stage, progressive tree improvement program for Douglas-fir*

Assumptions	Required volume improvement	
	Mbf per acre	Percent
Base case	1.2	1.8
Changes		
Interest rate is 5 percent	0.3	0.4
Interest rate is 11 percent	4.8	7.3
No real price increase	2.9	4.4
No thinnings	9.9	14.8
No thinnings, rotation is reduced to 50 years	1.5	4.9
No thinnings, rotation is reduced to 50 years, no real price increase	3.3	10.4
No thinnings, rotation is reduced to 50 years, interest rate is 11 percent	7.1	22.6
Number of selections is halved to 150	0.6	0.9
Number of selections is halved, no thinnings	4.9	7.4
Selected trees are used for seed production twice as long (that is, 36 years)	1.0	1.4
Site index is 170	1.2	1.2
Site index is 170, no thinnings	9.9	9.6

selections will suffice at the risk of narrowing the genetic base, the required volume increase for improved plantations drops from 1.8 percent to only 0.9 percent. Assuming a longer period of seed production for the selected trees has less effect, doubling their productive life drops the required improvement only 0.4 percentage points to 1.4 percent, so there is little economic advantage in delaying the start of a second-stage program.

In summary, because of the low cost of the progressive program only small improvements are necessary to return the investment. This is well, because initial gains are not expected to be large either. As was the situation for the ponderosa pine program, interest rate, real price changes, length of rotation, and thinning have major effects on profitability. Program changes such as reducing the number of selections or increasing the size of the breeding zone will increase profitability but will also increase the biological risk.

SECOND-STAGE PROGRESSIVE PROGRAM FOR DOUGLAS-FIR

At some point, the present progressive tree improvement cooperatives must decide whether to enter the second stage; that is, to establish seed orchards. A likely second-stage scenario for Douglas-fir is to establish seed orchards with seedling progeny of selected parents. Seedling seed orchards avoid incompatibility, a common problem in grafted Douglas-fir seed orchards. The seedling orchard is established by pairing the 300 selected parents in any desired combination and crossing them to produce full-sib seedling progeny; that is, progeny with both parents known. The full-sib families are planted in a standard design to maximize separation between replicates of the same family, and when progeny test results are available, the poorer families and the poorer individuals in superior families are removed, leaving the best individuals in the best families. At the earliest, the orchard can be established 3 years after inception of the second stage program and commercial seed production will begin 15 years later. Usable life of the orchard is 18 years, or until the 36th year of the program, at which time another orchard should be in production if the program progresses to a third stage.

To make the scope of the program comparable to that of the first stage we assumed that an orchard of 1 acre could supply an annual planting program of 1250 acres. The assumption is predicated on the basis that 1 acre of orchard is sufficient to supply between 982,000 to 1,767,000 seed[1] (Silen 1978, Owston and Stein 1974). Therefore, with a 50-percent nursery cull and a planting density of 500 seedlings per acre, 1 acre of properly sited orchard should be capable of supplying an annual planting of 1000 to 1800 acres. The estimate is lower than that of some orchards. In the St. Paul Seed Orchard in Salem, Oregon, 1 acre of orchard, with one good seed year in every three, can supply sufficient seed to plant 6000 acres, but a safety factor of two is allowed.[2] Within reasonable limits, seed yields per acre will be independent of orchard density, although yields per tree decline with increasing density. Our assumption that an acre is sufficient to plant 1250 acres per year is likely conservative. However, we realize that such a small orchard would present management problems and be an inefficient operation.

We assumed that a first-stage progressive program was already underway so costs of selection and progeny testing were not included in the second-stage analysis.

Program characteristics and economic base for a second-stage, progressive tree improvement program are:

Characteristics

Number of trees selected	300 trees
Number of single pair matings	150 crosses
Commercial seed production of orchard begins	18 years
Orchard phased out	36 years
Production per acre of orchard per year	625,000 seedlings
Rotation age	80 years
Operating area	100,000 acres
Annual planting	1,250 acres
Seedlings planted per acre	500 seedlings
Seed yield per acre of orchard	1,250,000 seed
Nursery cull	50 percent

Economic Assumptions

Interest rate	8 percent
Stumpage (second growth)	$275 per Mbf
Normal yield of unimproved forest at 80 years, site III land, site index of 130 (McArdle and others 1961)	66.8 Mbf

[1] Personal correspondence from Virgil Allen, Dennie Ahl Seed Orchard, Shelton, Washington, May 31, 1979.

[2] Personal correspondence from Jack Wanek, St. Paul Seed Orchard, Salem, Oregon, June 1, 1979

Table 5 *Costs per acre of seedling seed orchard in a second-stage, progressive tree improvement program for Douglas-fir*[1]

Activity	Cost per acre orchard (1979 dollars)	Year cost incurred
Single pair crossing	$37,500	2
Seedling production	80	3
Orchard establishment	1,000	5
Orchard maintenance[2]	100 yr	6 to 36
Total present value per acre orchard	$36,360	
Total present value per acre plantation	$29.09[3]	

[1] Based on personal correspondence with Roy R. Silen, Pacific Northwest Forest and Range Experiment Station, Corvallis, Oregon, and Jack Wanek, St. Paul Seed Orchard, Salem, Oregon.

[2] Maintained as progeny test from years 6 through 18.

[3] Obtained by dividing cost per acre of seed orchard by 1250 acres plantation per acre seed orchard.

Table 6—*Sensitivity analysis for a second-stage, progressive tree improvement program for Douglas-fir*

Assumptions	Required volume improvement	
	Mbf per acre	Percent
Base case	0.6	1.0
Changes		
Interest rate is 5 percent	0.1	0.1
Interest rate is 11 percent	4.2	6.3
No real price increase	1.9	2.8
No thinnings	4.9	7.4
No thinnings, rotation is reduced to 50 years	0.8	2.5
No thinnings, no real price increase, rotation is reduced to 50 years	2.1	6.7
No thinnings, rotation is reduced to 50 years, interest rate is 11 percent	5.8	18.5
Selection and progeny testing charged to second stage	4.3	6.5
Selection and progeny testing charged to second stage but size of breeding zone increased tenfold	0.5	0.7

Using these data and *table 5*, we set costs per acre of plantation equal to benefits as before:

$$\$29.09 = [(1.08^{18} - 1)/(0.08)(1.08^{18})] \times [0.31/1.08^{58} + 0.41/1.08^{68} + 0.11/1.08^{78} + 0.11/1.08^{88} + 0.11/1.08^{98}],$$

where factors are as in previous equations. Solving, the break-even point, I, is a present-valued return of $516.98. Allowing for a 1.5-percent real price increase in stumpage, this translates to 0.6 Mbf per acre increase over normal, unimproved plantation yields or only 1.0 percent of 66.8 Mbf per acre. Differences of this degree are not detectable in most field tests and seem easily attainable by tree improvement.

A sensitivity analysis was run to test the effect of several factors on profitability (*table 6*). What happens when selection and progeny testing are charged to the second stage of the progressive program? This is equivalent to the situation in which an incipient progressive program enters a seed orchard phase from the beginning without relying on selections for *in situ* seed collection. The progressive program then converges in approach with the Pacific Southwest program. In that situation, the required volume improvement to pay an 8-percent return on investment is 6.5 percent, an expectation well within reasonable limits of the genetic approach. However, if we speculatively increase the scope of the program (continuing to charge selection and progeny testing to the second stage) to serve 1,000,000 acres rather than 100,000, the required improvement is reduced nearly tenfold, to 0.5 Mbf per acre or 0.7 percent of unimproved yields. The difference between 6.5 percent and 0.7 percent improvement illustrates the influence of scale on profitability, but increase in scale increases the risk of losing locally adapted populations.

CONCLUSIONS

Economic assumptions and silvicultural decisions have more effect on the profitability of the three tree improvement programs analyzed than do program design or costs. Tree improvement combined with intensive silviculture and better utilization of smaller materials in thinnings results in a highly profitable picture. Tree improvement is only one component of intensive forest management practices to improve forest production. If returns from tree improvement are realized early in the rotation through commercial thinnings, only small improvements in growing stock can amply repay the investments in a breeding program. In fact, under reasonable expectations internal rates of return should be substantially higher than 8 percent. However, without intermediate cutting, realistic rates of interest cannot be carried over long rotations of 80 to 120 years without substantial benefits that seem beyond the possibilities of the genetic approach. With shorter rotations of 50 years, investment in tree improvement can be easily justified.

Benefits from improvement in stem and crown form were not considered in our analysis, but such gains are anticipated and would improve the financial outlook. Almost all tree improvement programs select for stem and crown form. Straighter stems and smaller branches reduce handling costs and improve grade recovery and merchantable yields.

In time the Pacific Southwest and the progressive programs will converge in practice, particularly as better information develops on the genetic resource. The second stage progressive program with costs of selection included differs from the Pacific Southwest program in the emphasis placed on selection of trees on the basis of their appearance, in the size of the breeding zone, and in slightly lower costs of establishment for seedling rather than clonal orchards. Genetic improvement is almost certain to be greater in the Pacific Southwest program where select trees interbreed in seed orchards than in the first stage progressive program. Although the required improvement to return the investment is small for a first stage progressive program, neither are large gains anticipated. Improvement is directly proportional to selection intensity, and in the first-stage progressive program, selection intensity is low. Furthermore, select-trees are wind-pollinated *in situ*, so that the pollen parents represent unselected trees, presumably the population average. Crossing of select parent trees back to the population should result in only half the improvement attainable by intercrossing of selected parents in seed orchards. Conversely, the larger breeding zone and higher selection intensity of the Pacific Southwest program constitute a biological risk that cannot be evaluated without detailed information on seed source and progeny variation. Nor is it conclusively demonstrated that selection in natural stands is effective for western conifers. In the second-stage progressive program, progeny from seed orchards are likely to equal or exceed the gains achieved in first generation orchards made up of selections from natural stands, as used in more traditional programs.

Direct economic comparison of the programs for the two species is not possible because of differences in biological assumptions. For example, seed production of Douglas-fir and ponderosa pine differ, so the ratio of seed orchard to planting acreage differs greatly. In addition, costs, although current, are not the same for the two analyses. Orchard maintenance for ponderosa pine in the Pacific Southwest is manyfold greater than similar figures we obtained for Douglas-fir in the Pacific Northwest. Despite their differences both approaches appear to be quite profitable given the available information.

LITERATURE CITED

Carlisle, A., and A. H. Teich.
1978. **Analysing benefits and costs of tree-breeding programmes.** Unasylva 30(119-120):34-37.

Danbury, D. J.
1971. **Seed production costs for radiata pine seed orchards.** Aust. For. 35:143-151.

Davis, L. S.
1967. **Investment in loblolly pine clonal seed orchards.** J. For. 65:882-887.

Kitzmiller, J. H
1976. **Tree improvement master plan for the California Region.** Region 5, Forest Serv., U.S. Dep. Agric., San Francisco, Calif., 123 p.

McArdle, R. E., W. H. Meyer, and D. Bruce.
1961. **The yield of Douglas-fir in the Pacific Northwest.** U.S. Dep. Agric. Tech. Bull. 201, 74 p. U.S. Gov. Print. Off., Washington, D.C.

Marquis, D. A.
1973. **Factors affecting financial returns from hardwood tree improvement.** J. For. 71:79-83.

Owston, P. W., and W. I. Stein.
1974. ***Pseudotsuga* Carr. Douglas-fir.** *In* Seeds of woody plants in the United States. C. S. Schopmeyer (tech. coord.), U.S. Dep. Agric., Agric. Handb. 450, Washington, D.C., p. 674-683.

Perry, T. O., and C. W. Wang.
1958. **The value of genetically superior seed.** J. For. 56:843-845.

Porterfield, R. L., and F. T. Ledig.
1977. **The economics of tree improvement programs in the Northeast.** *In* Proc. Twenty-fifth Northeast. Forest Tree Improv. Conf. [July 27-29, 1977], Orono, Maine, p. 35-47.

Porterfield, R. L., B. J. Zobel, and F. T. Ledig.
1975. **Evaluating the efficiency of tree improvement programs.** Silvae Genetica 24:33-44

Silen, R. R.
1966. **A simple, progressive tree improvement program for Douglas-fir.** U.S. Forest Serv. Res. Note PNW-45, 13 p. Pacific Northwest Forest and Range Exp. Stn., Portland, Oreg.

Silen, R. R.
1978. **Genetics of Douglas-fir.** USDA Forest Serv. Res. Paper WO-35, 34 p. Forest Serv., U.S. Dep. Agric., Washington, D.C.

Silen, R. R., and J. G. Wheat.
1979. **Progressive tree improvement program in coastal Douglas-fir.** J. For. 77:78-83.

USDA Forest Service.
1974. **The outlook for timber in the United States.** U.S. Dep. Agric. Forest Serv., Forest Resour. Rep. 20, Washington, D.C., 374 p.

The Forest Service of the U.S. Department of Agriculture

...Conducts forest and range research at more than 75 locations from Puerto Rico to Alaska and Hawaii.

...Participates with all State forestry agencies in cooperative programs to protect and improve the Nation's 395 million acres of State, local, and private forest lands.

...Manages and protects the 187-million-acre National Forest System for sustained yield of its many products and services.

The Pacific Southwest Forest and Range Experiment Station

...Represents the research branch of the Forest Service in California, Hawaii, and the western Pacific.

Ledig, F. Thomas, and Richard L. Porterfield.
1981. **West Coast tree improvement programs: a break-even, cost-benefit analysis.** Res. Paper PSW-156, 8 p. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Three tree improvement programs were analyzed by break-even, cost-benefit technique: one for ponderosa pine in the Pacific Northwest, and two for Douglas-fir in the Pacific Northwest—one of low intensity and the other of high intensity. A return of 8 percent on investment appears feasible by using short rotations or by accompanying tree improvement with thinning. Interest rates, length of rotation, the inclusion of thinnings, and site index had greater effects on profitability than program design. Large breeding zones improved profitability, although they incur the biological risks of nonadaptation to local conditions and loss of local genetic resources. Increasing orchard seed yield affected the results only slightly unless the planting program could be expanded, which is equivalent to increasing the size of the breeding zone. If the increase in seed yield merely reduced the required acreage of seed orchard and associated costs, the financial results improved only slightly.

Retrieval Terms: tree improvement, economic analysis, *Pinus ponderosa, Pseudotsuga menziesii,* sensitivity analysis, minimum genetic gain

United States
Department of
Agriculture

Forest Service

**Pacific Southwest
Forest and Range
Experiment Station**

Research Paper
PSW-157

Economic Efficiency of Fire Management Programs at Six National Forests

Dennis L. Schweitzer Ernest V. Andersen Thomas J. Mills

The Authors:

At the time of this study, **DENNIS L. SCHWEITZER** was a forest economist in the Policy Analysis Staff, Forest Service, U.S. Department of Agriculture, Washington, D.C. He is now assigned to the Forest Service's Land Management Planning Staff, Washington, D.C., and stationed at Fort Collins, Colo. **ERNEST V. ANDERSEN,** a staff specialist in the Forest Service's Aviation and Fire Management Staff at the time of the study, is now leader, Law Enforcement Group, Fiscal and Accounting Management Staff, Washington, D.C. **THOMAS J. MILLS** is a forest economist with the Pacific Southwest Forest and Range Experiment Station, stationed at Riverside, Calif.

Foreword:

This paper reports on the first national scope economic analysis of the fire management program on National Forests. Subsequent national scope study has been completed which includes some of the conceptual advances proposed here. This paper documents an important step in the evolution of more complete economic evaluation capability for fire management programs.

Acknowledgments:

Several people in the Forest Service, U.S. Department of Agriculture, contributed to the successful completion of this study. Everett L. Towle and Lawrence A. Amicarella were the study leaders. Assistance in overall study design and interpretations was provided by Charles Harden, Robert W. Mutch, C. Bentley Lyon, Gregory R. Super, and Gary E. Cargill. The following persons were primarily responsible for the National Forest case study analyses: Tonto, Joseph J. Wagenfehr and David F. Aldrich; San Bernardino, Robert L. Solari; Deschutes and Willamette, Frank E. Lehto; Francis Marion, Wayne E. Ruziska; and Huron-Manistee, David R. Seaberg, Jr.

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

January 1982

Economic Efficiency of Fire Management Programs at Six National Forests

Dennis L. Schweitzer Ernest V. Andersen Thomas J. Mills

CONTENTS

IN BRIEF...

Schweitzer, Dennis L.; Andersen, Ernest V.; Mills, Thomas J. **Economic efficiency of fire management programs at six National Forests.** Res. Paper PSW-157. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 29 p.

Retrieval Terms: fire economics, initial attack, aviation operations, fire suppression, marginal analysis, economic efficiency, risk

The economic efficiency of the initial attack and aviation component of the fire management program on six widely placed National Forests was evaluated using a marginal analysis format. The cost of an increment to the initial attack and aviation program was compared to the resulting change in the fire suppression costs and the net value of resource output and structures. Minimization of the program cost plus the net change in the value of resource outputs and structures (C + NVC) was the economic efficiency criterion used to implement this marginal analysis.

Four program or budget levels (PL_1 through PL_4) were evaluated. The program levels varied from 20 percent below the fiscal year 1979 funding level to 40 percent above the 1979 funding level at approximately 20 percent increments. Each program level was evaluated for 3 years of varying fire year severity from relatively low (Year A) through relatively high (Year C) on each Forest, with the exception of 2 years on one Forest where data were limited.

Each of the six Forests is a unique combination of fuels, fire severity, access, resource characteristics, and many other factors which influence fire program efficiency. In spite of this diversity, there are some common results among the case studies. This commonality is an argument for the possibility that the results may apply to areas beyond these six Forests.

There were four categories of results from this study. First, the lowest program level tested (PL_1) was the most efficient in the majority of the simulated fire years, 12 out of 17 years. PL_1 was the most efficient initial attack and aviation program level tested in all years simulated on three of the six Forests: the Francis Marion (in South Carolina), the Huron-Manistee (in Michigan), and the Deschutes (in eastern Oregon). PL_1 was the most efficient on the San Bernardino (in southern California) except in the most severe fire year (Year C). In the future, if Year C occurs less frequently than 2 years in 3, PL_1 will also be the most efficient long-term program level.

The highest program level (PL_4) will be the most efficient program on the Willamette (in western Oregon) if Year C occurs as frequently as 1 year in 5. If the severe Year C occurs less frequently than every 5 years, the lowest program level tested (PL_1) will be the most efficient long-run program on the Willamette too. PL_3 was the most efficient program on the Tonto (in Arizona) in all 3 fire years, due largely to the reductions in suppression costs which result from the increase in initial attack and aviation program input.

Second, the most efficient initial attack and aviation program level was not affected by the severity of the fire year in four of the six Forests: The Francis Marion, the Huron-Manistee, the Deschutes, and the Tonto. The fire year severity had a marginal effect on the most efficient program level on the San Bernardino. Only on the Willamette did the severity of the fire year have a major influence on which program level was the most efficient.

One implication of this result is that economically justifiable requests for supplemental appropriations for the presuppression program in severe fire years may be small. Increased fire year severity may not mean a higher program level is more efficient. Conversely, presuppression budget savings may be small in years of low fire severity even if it were possible to predict severity far enough in advance to make substantial changes in presuppression expenditures.

Third, the simulated fire suppression cost dropped in response to increases in the initial attack and aviation program level in all case studies. The amount of the decline varies from very little on the Francis Marion to a substantial decline on the Tonto. This result is in strong contrast to the historical rise in suppression costs that occurred at the same time that presuppression budgets were increasing.

Fourth, the net value change of resource outputs and structures caused by the fires was a very small percentage of the total C + NVC in 13 of the 17 years studied. The net value change was a moderate percentage of the total on the Deschutes (Year C) and the Tonto (Year A). They were a substantial percentage on the Willamette (Year C) and the San Bernardino (Year C). Even in these 4 years when the net value change was a noticeable percentage of the total, the net value change usually did not drop enough in response to increases in the initial attack and aviation program to cover the cost of the program increment.

The most efficient initial attack and aviation program level was insensitive to reasonable changes in either per unit resource values or fire effect estimates. This indicates that the impact of potential errors in these two model components is not as great as it was previously thought to be. The vast majority of the net value change was the loss of commercial timber and structures. This general result was also found in a recent efficiency analysis of the fire management program on 41 separate National Forests (U.S. Dep. Agric., Forest Serv. 1980b), but in that study beneficial effects on wildlife outputs were also relatively large. While there has been considerable discussion about the value of many wildland resource outputs, the per unit value of commercial timber and structures seldom has been at the center of the debate.

The cost of the fire management organization in the Forest Service, U.S. Department of Agriculture, has increased substantially in recent years. This increase, and continuing concern about the efficiency of all government programs, has led to questions about the economic efficiency of the fire program.

Forest Service fire management obligations for presuppression activities rose from $44 million (1972 constant dollars) in 1969 to $110 million in 1977. Obligations for fire suppression fluctuated from year to year, largely in response to variations in fire year severity, but they also show an upward trend, reaching $105 million in 1977. Total acres burned fluctuated from year to year, but showed no notable decline in response to the increases in obligations (*fig. 1*) (U.S. Dep. Agric., Forest Serv. 1973, 1978a, 1979a, 1980a).

In 1975, the Office of Management and Budget requested the Forest Service to identify the fire management practices which are best as shown by an evaluation of appropriate costs and results. The real program cost trends were documented but the "best" practices could not be identified, largely because no adequate analysis procedure existed (U.S. Dep. Agric., Forest Serv. 1977).

In 1978, the Forest Service revised its fire protection policy. The revised policy requires that the fire management program be cost-effective and compatible with land management objectives (U.S. Dep. Agric., Forest Serv. 1978b). Rapid implementation of the revised policy was difficult, however, again largely because there were no adequate analytical tools capable of evaluating the efficiency of alternative fire management programs.

During the review of the Forest Service's fiscal year 1979 fire management budget request, questions about the fire program efficiency arose again. The United States Senate Appropriations Committee said "presuppression costs have risen dramatically in recent years, but the Committee is unable to discern any marked benefits stemming from these expenditures" (U.S. Senate 1978).

The fiscal year 1979 fire management appropriation was $24 million less than the budget request. Line item appropriations were prepared for five separate components of the fire program which before this time were combined in a single line item. This greater budget detail reduced flexibility in program execution. The *appendix* provides examples of items included in each line item. The United States Congress also directed the Forest Service to conduct "an analysis of the benefits of both fire presuppression and suppression activities and consider such in developing future budget requests" (U.S. Congress 1978). This analysis was initiated as a preliminary response to that request.

The objective of this study was to estimate the economic efficiency of two fire program components—attack force and aviation operations—at several alternative program levels on six diverse National Forests. Other program components must be considered in the final determination of program composition, and even

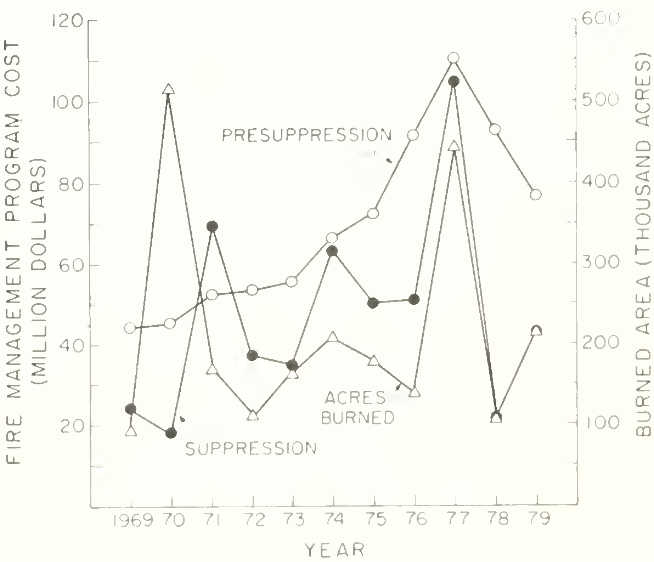


Figure 1—Fire management obligations for fire protection (presuppression) and fighting forest fires (suppression) for the Forest Service are compared with acres burned inside the Forest Service protection area, 1969-1979

six widely diverse Forests cannot provide analyses extensive enough to direct program decisions on a national scope. These case study results do, however, provide illustrations which should help guide deliberations on the fire program size and structure.

An important constraint of this analysis was the need to complete it in 2 to 4 months. This constraint dictated the use of available data and analytical tools. Because analysis models for the initial attack and aviation operation components were available, the efficiency analysis was restricted to those program components.

This was the first economic efficiency analysis of fire management programs which responded to the concerns expressed by the U.S. Congress and the Office of Management and Budget. Building on the experience gained, a follow-up study of 41 National Forests was made the next year (U.S. Dep. Agric., Forest Serv. 1980b). A handbook procedure for analyzing fire management programs, which incorporates many points from both of those analyses, is now available (U.S. Dep. Agric., Forest Serv. 1980c).

COMPONENTS OF A FIRE MANAGEMENT ANALYSIS

Before considering the study methods and results of this analysis, we need to examine the basic concepts applicable to economic analyses of fire management programs. It is particularly important to identify the types of information which should be provided. As a minimum, three categories of information should be developed for each fire management alternative evaluated: a measure of economic efficiency, a display of the risk associated with each program selection, and a display of the impacts of fires upon resource outputs. Additional information such as secondary impacts on employment and income, impacts on income distribution, and energy costs would also be useful.

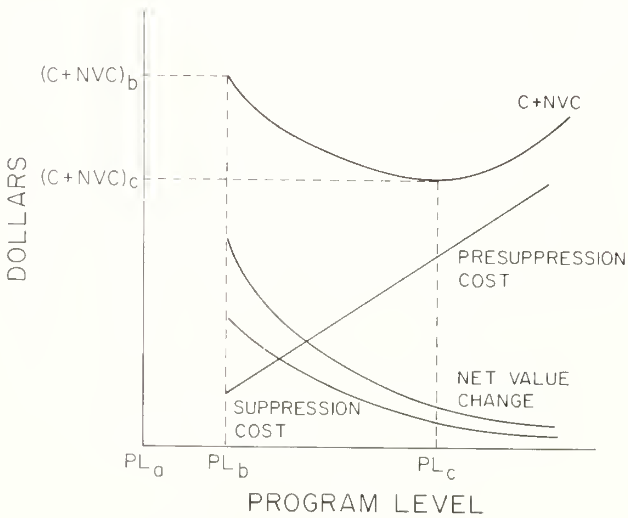


Figure 2—The model for cost plus net value change by fire management program level shows that the most efficient program level for the situation shown is PL_c.

Although the attributes described in this section should be considered in any fire economic analysis, all studies do not successfully include them, and this study does not either. They do, however, provide the context for evaluation of this study's results.

Economic Efficiency

The most efficient fire management program level is the one where the sum of the program costs (both presuppression and suppression costs) and the net value change of resource outputs is minimized, PL_c in *figure 2*. Gorte and Gorte (1979) describe the evolution of the cost plus net value change (C + NVC) criterion from its first application to fire programs in 1925. This criterion is well suited to fire program evaluation because of the way net value change is derived. The other more common financial return measures, such as benefit/cost and present net worth, can be derived from the components of the C + NVC calculation (Mills 1979).

Net value change is defined as:

$$\sum_{i=1}^{n} (VQ_{Ai} - VQ_{Pi})$$

where

i = resource category
VQ_A = value of resource outputs in the absence of fire
VQ_P = value of resource outputs in the presence of fire

The net value change can therefore be either positive, for detrimental fires that reduce resource outputs, or negative, for beneficial fires that increase outputs above the "no fire" level. A negative sign for an output gain may seem the reverse of conventional practice, but it permits the addition of net value change directly to cost.

The definition of net value change using a "no fire" benchmark is somewhat different from the typical program evaluation structure which compares the output "with" the fire management program to the output "without" the program. The "no fire" benchmark addresses the difficulty of estimating how large fires would actually become if no fire management organization existed, PL_a in *figure 2*. The implication of this net value change definition is that fire programs can only be evaluated through a marginal analysis format, by which the efficiency of one program level is compared to that of another. No efficiency conclusions can be reached from the evaluation of a single program level alone, for example PL_b.

The suppression cost and net value change are calculated only for the area burned by the fire plus the direct offsite effects of that burned area. The C + NVC calculation for each program level does not include an estimate of the net value changes or suppression costs that would have occurred if any fires had grown larger. Fires are often suppressed while burning in low value areas so they will not spread into high value resources.

The marginal analysis implications of the C + NVC criterion covers this consideration, however. No conclusion can be drawn from the results of a single program level simulation. Efficiency conclusions can only be drawn from a comparison of programs. If, at a lower program level, the fires can still be suppressed before they reach the high value resources, the lower program level is more efficient. If, at the lower program level, the fires spread into the higher value resource, the net value change and C + NVC for that program level will be higher. The impact of the potential spread of fires into high value resource areas is thus included in the analysis through an incremental evaluation of several different fire management program levels.

At the minimum point on the C + NVC curve, the change in present net worth of the fire program between two PL's is equal to the difference in the C + NVC's, for example, $(C + NVC)_c - (C + NVC)_b$. This is still an incremental or marginal estimate of program efficiency; an estimate of the return to the total program would be derived from $(C + NVC)_c - (C + NVC)_a$ (Mills 1980).

The minimization of C + NVC is a valid economic efficiency criterion for marginal analysis but that is all it is. One reason why the economic analysis of fire programs has evolved slowly is that a model capable of yielding the relationships in *figure 2* has not been available.

Such a model should include the several components or modules shown in *figure 3*. A description of the resource, topography, and fuel characteristics of the planning area are model inputs. The fire occurrence and weather characteristics, preferably in the form of probability distributions, are also model inputs. The model must contain a fire behavior processor or module to transform the weather, terrain, and fuel loading input into fire behavior characteristics such as fireline intensity and forward rate of spread. The fire behavior module, in combination with the module which estimates the effectiveness of the fire management program inputs, must yield a description of the fires at the point of containment. The fire behavior output and model input on resource character are together the input to the fire effects module. The fire effects output is a description of the fire impact on resource output levels through time. The per unit resource values are assigned in the resource value module which yields the net value change estimate. This estimate, in combination with the estimate of fire management program cost, provides the C + NVC estimate for a single program configuration applied to a planning area.

When used for the evaluation of program alternatives, this model must be operated over the total number of fire ignitions occurring throughout the season in the area served by the inputs of the fire management program. One simulation through the model for a given fire management program and a season's fires produces one point on the C + NVC curve. Each of the fire management inputs available is then increased or decreased by a given increment, and another simulation of fire program efficiency and C + NVC is made. This produces a second point on the C + NVC curve. The simulations must then be repeated until the minimum C + NVC is located.

Risk

The total number of fire ignitions varies from season to season as does the dispersion of the fire ignitions among the fuel, terrain, and resource classes within an area. Fire-related weather conditions also vary, particularly windspeed and fuel moisture. Although all of these parameters can be important determinants of the most efficient fire management program, they cannot be satisfactorily predicted. To be useful in decisions about the size and composition of the overall fire management program, therefore, they should ideally be included stochastically as entire probability distributions rather than as single point estimates. They should be incorporated throughout the model in such a way that the probability distribution of C + NVC can be derived. The expected value C + NVC can then be estimated by weighting each possible C + NVC by its respective probability of occurrence. The fire program level and composition which has the minimum expected value C + NVC is the most economically efficient in the long run, although it may lead to a less than optimum program level for a single year.

The distribution of C + NVC provides important information about the risk associated with each program decision. How that risk is assessed depends on the decisionmaker's view of risk-taking. A decisionmaker who is risk-adverse may select the fire program which produces an expected value C + NVC within 10 percent of the minimum C + NVC and which also has the lowest probability of a C + NVC twice as large as the minimum. Even if he works on the basis of expected value, a decisionmaker needs estimates of the probability that fire suppression costs and fire effects will be substantially above or below the expected value estimate.

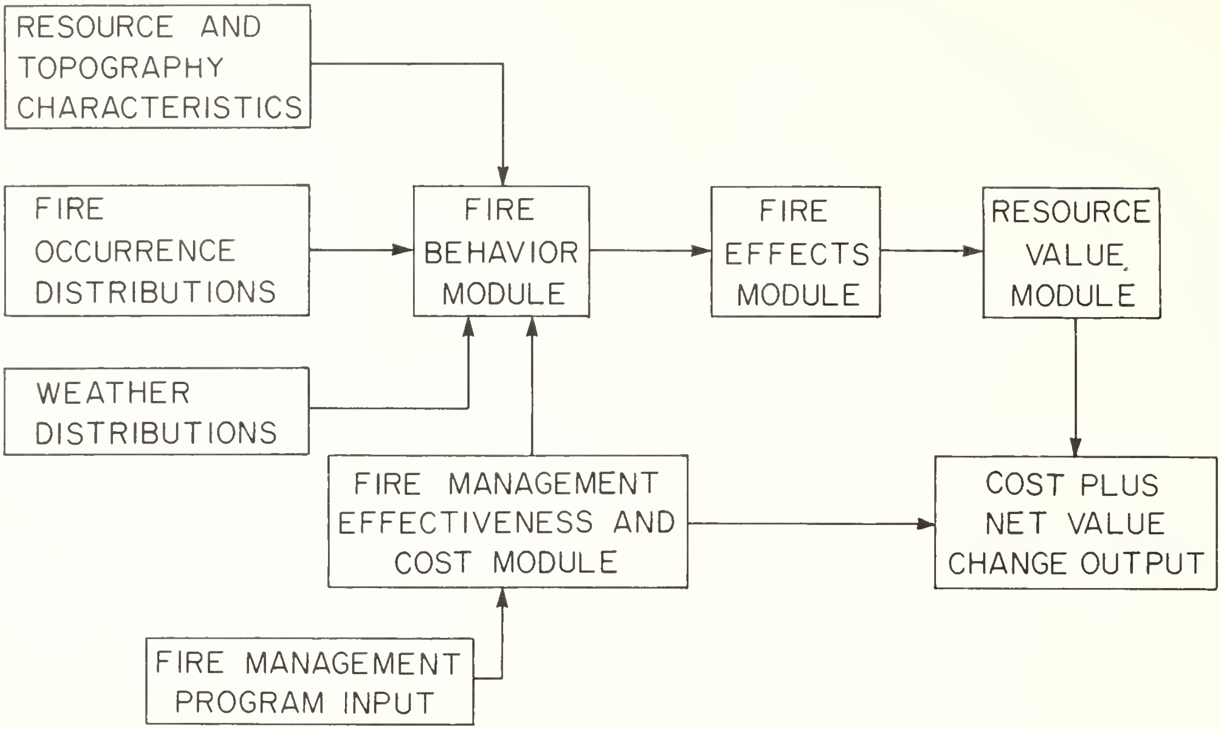


Figure 3—A complete fire economic evaluation model includes these basic components.

The probabilistic aspect of fire management programs may be addressed through complete joint probability functions or simply by evaluating several conditions of varying fire severity. The important point, however, is that the variability of program efficiency resulting from this underlying variation in fire weather and fire occurrence must be explicitly evaluated. Selecting and evaluating only an "average" year or an "average worst" year is inadequate.

Resource Impacts

The net change in resource outputs caused by fire, and the value of that resource output change is included in the net value change component of the C + NVC calculation. The resource output impacts are often important decision parameters themselves, however, so they should be reported separately. Land management objectives are often expressed directly in terms of resource output targets. The fire program impact on those outputs must be estimated to permit a full integration of the fire program within the whole of integrated land management (Nelson 1979). Ideally, the estimates of resource output impacts should be displayed as impacts across time for several resource categories such as commercial timber, recreation, and usable water.

The resource output estimates also provide information on the incidence of the fire program impacts on potential user groups. The relative impacts on the timber industry, recreationists, and the agricultural sector which is dependent upon irrigation water, for example, can be inferred from the resource impact estimates in combination with income and employment multipliers.

Even though economic efficiency, risk, and resource impact information produced through fire program economic analysis would be very valuable in making fire management program decisions, that is only part of the information needed to make fire program decisions. Additional factors such as social and environmental impacts should also be assessed before the fire management program decision is made. An economic model yielding efficiency, risk, and resource impact estimates would therefore only yield a partial analysis, but then that's all any analytical process can provide.

STUDY METHOD AND SCOPE

Alternative program levels for the initial attack force and aviation operation portions of the Forest Service presuppression appropriations were evaluated in this study. These are budget line items 113 and 114 (*app.*). The other presuppression program components, fire prevention (item 111), fire detection (item 112), and fuel reduction (item 115), were assumed constant in this

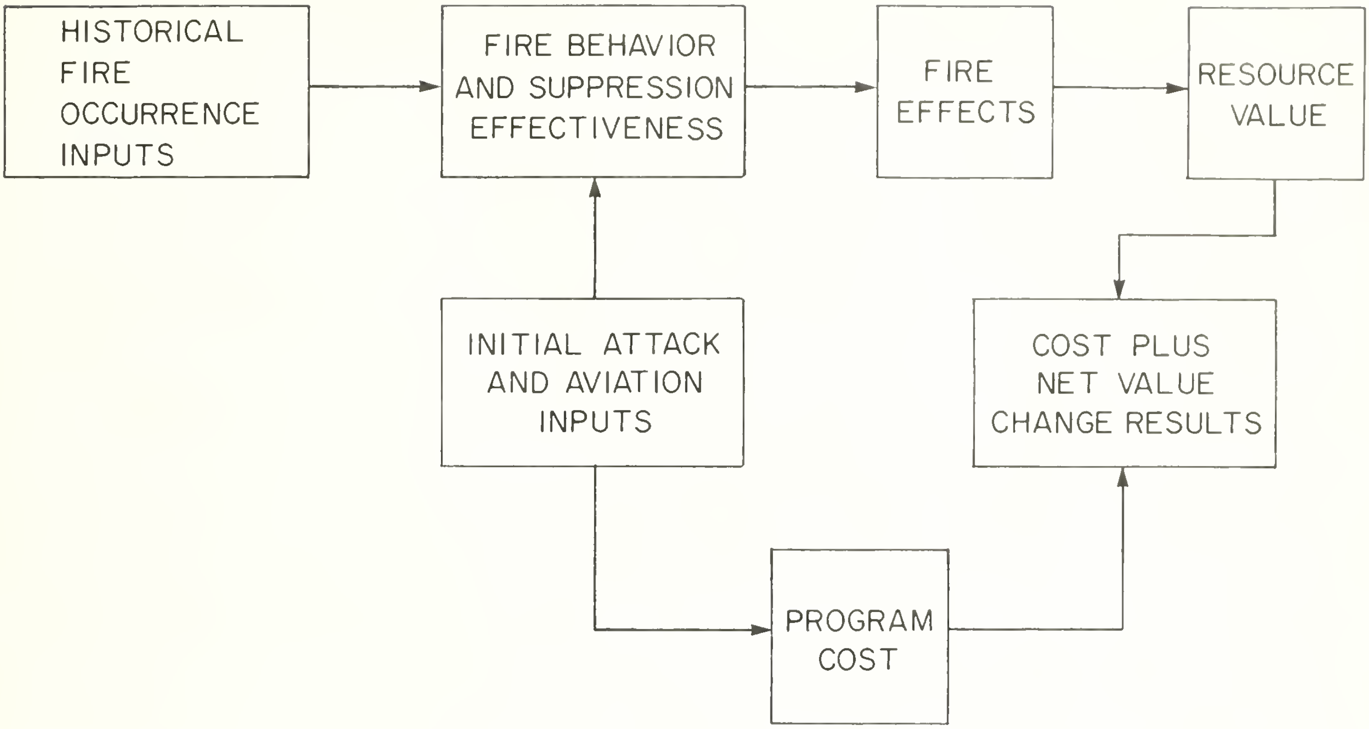


Figure 4—The model used in this six-Forest study includes these analysis components.

study. In 1979, the initial attack and aviation components accounted for $95.4 million or almost three-fourths of the National Forest System fire management presuppression budget.

Case Study Forests

This study includes separate analysis of six National Forests: the Francis Marion on the coastal plain of South Carolina, the Huron-Manistee in the lower peninsula of Michigan, the Willamette on the western side of the Cascade Mountains in Oregon, the Deschutes on the eastern side of the Cascades in Oregon, the San Bernardino in southern California, and the Tonto in central Arizona. These Forests were selected because they could provide fire occurrence and road network information prepared in a manner compatible with the only reasonable fire management effectiveness model we could use. Coincidentally, they represent a broad range of fuels, topography, resources, and fire occurrence levels. Together, the six Forests accounted for about 12 percent of the Forest Service's initial attack and aviation appropriations in fiscal year 1979.

The analysis on each Forest progressed through six steps:

1. Determine the alternative initial attack and aviation program levels.
2. Compile the fire occurrence data for selected historical years.
3. Evaluate the effectiveness of the initial attack and aviation inputs.
4. Translate the estimates of numbers of fires by size and fire intensity into estimates of the effects upon resource outputs.
5. Calculate the value of those changes in resource output.
6. Compute the C + NVC (*fig. 4*).

Initial Attack and Aviation Program Levels

The four budget or program levels (PL) for the initial attack forces evaluated were

PL_1 20 percent below the actual fiscal year 1979 appropriation

PL_2 Fiscal year 1979 appropriation

PL_3 20 percent above the fiscal year 1979 appropriation. This approximated the fiscal year 1978 program level on average across the Forest Service.

PL_4 40 percent above the fiscal year 1979 appropriation

The general intent was to vary the budget for the aviation component of the fire management program by the same proportions. This constant proportional adjustment was not made in all Forests, however, as noted in the separate discussions. Therefore, the resulting initial attack and aviation program levels are not always different by 20 percent increments.

The program levels studied were limited to this −20 percent to +40 percent range because of difficulties that would have been encountered in expert opinion gaming of large fire suppression effectiveness under more widely varying programs. The program level restriction was also based upon an initial hypothesis that the most efficient program lay within this broad budget range. One consequence of this program level restriction is that the program level which leads to the overall minimum C + NVC may not fall within the range tested.

Fire Severity Levels

Each of the initial attack and aviation programs was evaluated against the fires which occurred throughout an entire fire season. The random nature of fire occurrence and fire weather was recognized in the study by evaluating 3 separate historical years for each Forest—years which varied in their "fire year severity." The fire starts in each of these years were identified by location on the Forest. The fire intensity and rate of spread were developed for each historical fire by a variety of methods using weather, fuel, and fire location records. Fire year severity was determined separately by each Forest but was generally based on the number of fire starts and the severity of the fire weather. The 3 fire years selected for analysis were given a relative rating of A, low; B, moderate; and C, high.

The objective of covering a full range of fire year severities was not fully met for several reasons. First, the case study Forests had a limited number of years of fire occurrence data stored in the format required for this analysis. The historical fire records which were available in the desired form were often for years of above average severity, at least when acres burned were used as an index of severity. Therefore, the 3 fire years chosen may not be assessed accurately with respect to all possible fire years. They are probably biased toward the high severity years.

Second, burning conditions vary within a year as well as between years. A year of average overall severity may contain a brief period of numerous fire starts and adverse fire weather which gives rise to large fires and very adverse fire effects. Judging severity by an entire year is therefore imprecise. Third, the potential fire effects are as much a function of the location of the fire as they are of the weather. Fire effects in a low severity year may therefore be more extensive when the fires occur near structures or in commercial timber than in a high severity year when the fires occur in light brush or grass.

It is essential to note that each of the 3 fire years is a unique historical array of fire locations, fire causes, and burning conditions. They are not, as in some studies, the same set of fires simulated under varying burning conditions. The years chosen are not the same years for all six Forests.

Although the fire locations, fire numbers, and weather conditions were those peculiar to the actual year, the fuel and resource characteristics were not. For each Forest, the fuel loadings in place at the time of this study were used in the fire behavior module for all 3 fire severity years. Also, the interdisciplinary team which assessed fire effects assumed that the current resource conditions existed in all the simulated fire years.

The selection of varying fire year severities recognizes that the efficiency of a fire management program should not be evaluated against just one point on the distribution of fire year severities. By selecting several years, we are able to display some information on the range of possible consequences even though we did not analyze the full probability distribution of possible events. The number of acres burned on each Forest from 1958 to 1977 is shown in *table 1*.

Evaluating Fire Program Effectiveness

The FOCUS computer model was used to estimate the eventual size of each fire and to estimate the cost of the fire suppression activity (Bratten and others 1980). The fire start locations and the elapsed time between ignition and detection were determined from the historical records, and the location of the initial attack and aviation forces was set in each Forest. The initial attack and aviation forces were allocated to each fire based upon predetermined dispatching rules and model-calculated arrival times of different attack forces to the specific fire location. The productivity of the dispatched forces, expressed as the rate of fireline construction per hour, was then compared with the rate of fire perimeter growth to determine if the fire could be contained.

If this computer simulation showed that the fire burned to 100 acres or for more than 12 hours and was still not contained, the fire was identified as "escaped" and the computerized simulation of initial attack and aviation effectiveness was stopped. Beyond 100 acres or 12 hours, the fire behavior model assumptions about homogeneity in fuels, weather, and terrain are violated so much that the computerized modeling cannot be continued.

FOCUS model output for each escaped fire included the location, the character of the fire, and the amount of fireline built at the time of escape. With this information and the list of available initial attack and aviation inputs, fire specialists versed in the latest fire behavior technology studied each fire, defined the best suppression strategy, and then estimated the size the fire would reach when extinguished.

The fire suppression strategy used in the expert opinion gaming of large fires was consistent with the actual sup-

Table 1—*Acreages burned in fires recorded on National Forests studied, 1958-1977*[1]

Year	Huron-Manistee	Willamette	Deschutes	Tonto	San Bernardino
1977	535	48	2,810	687	1,332
1976	1,678	280	4	24,053	1,889
1975	466	53	96	17,996	6,943
1974	446	155(B)	50	4,143(B)	14,937
1973	24	241	16	1,379	7,078(B)
1972	657	487	4	239(A)	2,860(A)
1971	168	430	21	707	52
1970	317	131(A)	59(A)	16,127(C)	64,320(C)
1969	93	126	450	12,352	1,529
1968	829(B)[2]	49	1,823	5,167	7,991
1967	98(A)	12,815(C)	2,061(B)	1,722	259
1966	301(C)	338	16	23,808	2,476
1965	150	176	65	1,169	778
1964	269	9	93	7,387	16,237
1963	199	14	5	559	273
1962	152	142	155	464	1,710
1961	557	55	1,079(C)	3,563	1,036
1960	155	134	675	499	5,451
1959	16	181	14,301	30,838	18,733
1958	171	1,186	36	1,599	1,922

[1]Data for Francis Marion National Forest are not shown here because such data were not available separately from other National Forests in South Carolina. On the Francis Marion, 1970 was chosen as Year B and 1968 was Year C.

[2]The letters in parentheses are the fire years simulated in this year.

pression strategy used in 1979 on those Forests. The revision of the fire management policy on National Forest lands occurred in 1978, but was not fully implemented in 1979.

The suppression cost for fires which were contained before reaching escape size or escape time was calculated internal to the FOCUS model from prespecified equipment and manpower costs. The suppression cost for escaped fires was calculated by hand using the same per unit costs.

The suppression costs were reported separately for three categories of inputs:

1. Forest Service primary inputs—firefighting program inputs generally financed from fire management presuppression appropriations.

2. Forest Service secondary inputs—the salary and equipment costs of Forest Service inputs, generally financed through nonfire program appropriations, which are temporarily diverted to fire suppression activities, such as timber stand improvement crews and road building equipment.

3. Cooperator inputs—the salary and equipment costs of other Federal, State, and private contractors who provide fire suppression inputs upon request.

The direct cost of using Forest Service suppression inputs which are shared between several forests, and the cost of cooperator inputs, was charged to the case study Forests as suppression costs.

Secondary Forest Service inputs were assumed to be available when needed, but their response time was greater than for primary inputs. Cooperator inputs were assumed to be available at all program levels, but fewer were available during high fire severity years when demands for them would be greater elsewhere.

A secondary cost incurred when secondary Forest Service inputs are utilized, but not registered in this study, is the disruption of the activities to which crews and equipment are normally assigned, such as timber sale administration and road maintenance. While these inputs are assigned to fire suppression activities, their costs are paid by supplemental appropriations through the fighting forest fire (FFF) account, however, rather than from the budget for their originally assigned activities. Therefore, no budget reduction for the nonfire activities results from using secondary forces.

Fire Effects

Interdisciplinary teams of resource experts on each Forest estimated the fire effects upon resource outputs. Maps of the fires, estimates of fire size and intensity, historical records of fire damages, and local knowledge of the Forest were the information available to the teams.

The interdisciplinary team estimated the fire effects for each fire greater than 100 acres. For fires 10 to 100 acres in size, effects were estimated using 10 sample fires from that size class, well distributed throughout the fire year. Results from the sample were then expanded to the entire set of fires in the size class as follows:

$$\left(\begin{array}{c}\text{Total value of fire}\\ \text{effects for}\\ \text{10- to 100-acre fires}\end{array}\right) = \left(\begin{array}{c}\text{Value of fire effects}\\ \text{on the sample fires}\end{array}\right) \times \left(\begin{array}{c}\dfrac{\text{Total acres burned in 10- to 100-acre fires}}{\text{Acres burned in sample fires}}\end{array}\right)$$

If less than 10 fires occurred in the 10- to 100-acre size class, effects were estimated for all of them.

The fire effects for 0- to 9-acre fires were estimated using an assumption that the per acre value of effects was the same as the average per acre effect for 10- to 100-acre fires by:

$$\left(\begin{array}{c}\text{Total value of fire}\\ \text{effects for}\\ \text{0- to 9-acre fires}\end{array}\right) = \left(\begin{array}{c}\text{Per acre value of}\\ \text{fire effects for}\\ \text{10- to 100-acre fires}\end{array}\right) \times \left(\begin{array}{c}\text{Total acres burned}\\ \text{in 0- to 9-acre fires}\end{array}\right)$$

This may overestimate the detrimental effects of the 0- to 9-acre fires. Smaller fires are often less intense than larger fires and some detrimental effects, such as soil erosion, are positively correlated with fire size.

Fire effects were estimated for each of the resource categories shown in *table 2*. Only the net resource change for each category was recorded and valued. For example, the net effect on commercial timber output is the present value of the timber that would have been harvested in the absence of the fire minus the value of the burned timber salvaged. Potential second rotation timber harvests beyond the immediate postfire salvage harvest were not included in the net value calculations. This may have led to a larger-than-actual net detrimental change in the timber resource category.

The net fire effects could be either positive or negative. Much of the rangeland grazing, wildlife effects, and effect on usable water quantity, for example, were negative; yields were greater with the fire than without it. Effects on water storage capacity, on the other hand, were positive; the capacity was less with the fire than without it. Similarly, fire effects were only recorded if there was an actual change in resource outputs. Tree mortality in a wilderness area was not registered as a commercial timber effect, for example, because it would not have been harvested even if it had not burned. The tree mortality may have led to a change in recreation usage, however, which would have been included as a recreation effect. Again, negative numbers imply beneficial effects and positive numbers imply detrimental effects.

Direct offsite fire effects, such as downstream flooding and siltation, were included in the total effects estimate along with the direct fire-site effects. The only exception to this offsite rule was in the San Bernardino Forest, where effects were measured off the fire site but not beyond the Forest boundary. Effects on resource outputs which extend into the future were also included. The present net worth of the future harvest of seedling and sapling and of poletimber stands was included for example rather than their current market value.

It was assumed that the effects upon commercial forage, water use, fish habitat, wildlife habitat, and recreation would occur for a period of up to 7 years. For discounting purposes, a simplifying assumption was made that those 7 years of effects all occurred during year 3. The simple sum of 7 years' effects was therefore multiplied by the per unit resource values and discounted 3 years to the present. Annual estimates of water volume loss due to the siltation of water storage facilities were derived for 25 years. A 10 percent discount rate was used.

Three fire effects were estimated by the interdisciplinary team but not valued in dollar terms. The first was effects upon unique resources such as historical and cultural sites, unique ecosystems, and endangered and threatened flora and fauna. The second was an estimate of the number of days that fires would cause air quality to fall below accepted standards. The third was the number of days when fires would cause water quality to deteriorate below accepted standards.

The only major direct fire effect excluded was the long-term effect on soil productivity sometimes caused by fire. No secondary impacts on the wages and employment in affected local economies was included.

Table 2—*Resource categories for which net fire effects were estimated and subsequently valued*

Resource category	Unit of measure
Commercial timber	
Sawtimber, hardwoods	Thousand board feet
Sawtimber, softwoods	
Poletimber stands	Acres
Seedling and sapling stands	
Commercial range	Animal unit months
Usable water	Acre-ft
Water storage capacity	Acre-ft
Fish habitat	
Warm water fish	User days
Cold water fish	
Anadromous fish	
Wildlife habitat	
Big game animals	User days
Other game animals	
Nonconsumptive uses	
Recreation	
Developed	User days
Dispersed	
Wilderness	
Structures	
Federal management	Number of units
Federal administrative	
Privately owned	
Miscellaneous	

It would have been desirable to have more comprehensive empirical data on which to base the fire effects estimates rather than to depend so greatly on the expert opinion of the interdisciplinary team. However, because the same team estimated the fire effects for each year and each program level on a given Forest, fire effects biases or errors most likely cancel out in a marginal analysis study like this one. In a marginal analysis, the incremental change in the fire effects between program levels, rather than the total fire effects, is the important quantity.

Resource Values

The fire effects upon resource outputs were valued using average regional per unit values. The values were marginal willingness-to-pay estimates, which include some consumer surplus as well as the revenue captured in a market transaction. The use of willingness-to-pay values permits uniform application of the same valuation concept across all resource categories. These values were preliminary estimates developed for the evaluation of alternative Forest Service programs defined in accordance with the Forest and Rangeland Renewable Resources Planning Act (*table 3*) (U.S. Dep. Agric., Forest Serv. 1978c). This provided consistency in the values used in the evaluation of all Forest Service programs and among resource categories. Fire effects upon structures were valued on the basis of their replacement cost.

Application of regional value averages to the respective case study Forests and the difficulty in deriving values for the nonmarket commodities like recreation and wildlife led to less precise resource value estimates than initially desired. Especially when the difficulties of resource valuation were combined with those related to deriving fire effects from expert opinion, questions arose about the quality of the net value change estimate. The real question, however, is whether more accurate data in this phase of the analysis would affect the conclusions of the study. Some fairly simple sensitivity analysis for each Forest shed light on this.

All of the *table 3* values are current dollar values per unit of output with the exception of the commercial timber values for immature poletimber and seedling and sapling stands. The loss incurred from burning an immature timber stand is the value of the foregone harvest volume that the stand would have generated. This was calculated by compounding all future harvests to the end of the rotation. The immature timber values in *table 3* are the future values per acre at the time of harvest. Those future values were then discounted back to a stand age of zero. A more accurate calculation of foregone value per acre burned is the future net value at time of final harvest discounted back to the current stand age. The calculation we used underestimates the timber value loss from immature stands in this study but subsequent sensitivity analysis demonstrates that the error has no effect on the conclusions reached.

The poletimber stand regimes assume one commercial thinning and a final harvest. The seedling and sapling stands assume two potential commercial thinnings, because they are younger when burned, and a final

Table 3—*Average dollar values per unit of resource output affected by fire for the National Forests studied*

Resource Category	Output unit	Tonto	San Bernardino	Deschutes	Willamette	Francis Marion	Huron-Manistee
		Dollars/unit					
Commercial timber							
Mature, hardwood	MBF	0.00	0.00	0.00	0.00	34.00	44.00
Mature, softwood	MBF	84.00	131.00	166.00	166.00	107.00	37.00
Pole stands	Acres[1]	1,083.00	6,202.00	6,555.00	8,316.00	7,303.00	742.00
Seedlings-saplings	Acres[1]	8,040.00	70,367.00	24,964.00	19,522.00	54,218.00	1,362.00
Commercial range	AUM	3.90	3.30	3.00	3.00	2.45	3.35
Water use	Acre-ft	0.50	2.60	1.50	1.50	1.50	1.00
Water storage	Acre-ft	0.50	2.60	1.50	1.50	1.50	1.00
Fish habitat							
Warm water	User days	4.25	4.25	4.25	4.25	4.25	4.25
Cold water	User days	6.25	6.25	6.25	6.25	6.25	6.25
Anadromous	User days	—	19.50	19.50	19.50	—	19.50
Wildlife habitat							
Big game	User days	10.50	10.50	10.50	10.50	10.50	10.50
Other game	User days	8.00	8.00	8.00	8.00	8.00	8.00
Recreation resources							
Nonconsumptive	User days	7.25	7.25	7.25	7.25	7.25	7.25
Developed	User days	3.00	3.00	3.00	3.00	3.00	3.00
Dispersed	User days	3.00	5.50	3.00	3.00	5.50	5.50
Wilderness	User days	8.00	10.00	10.00	10.00	15.00	14.00

[1]Per acre net future value at time of final harvest.

harvest. The compounded value of that first commercial thinning is the reason for the larger seedling and sapling net future value at maturity than for the poletimber stands.

The results for each Forest are presented separately. Information is provided on the initial attack and aviation program levels tested, the C + NVC results, suppression costs, and net value change in resource outputs and structures. The case studies should be read in the order they are presented since complexities of analysis are discussed as they are encountered.

FRANCIS MARION NATIONAL FOREST

The Francis Marion National Forest, located in South Carolina, is typical of the coastal plain forests of the Southwest. The area is well drained by numerous, slow-moving streams. Southern pines are the predominant woody vegetation, but hardwoods dominate in areas where fire or some other ecosystem modifier, such as timber harvesting, has not retarded the progression toward climax vegetation.

The Francis Marion is the smallest Forest in the study, covering 249,000 acres (U.S. Dep. Agric., Forest Serv. 1979a). Although ownership within the Forest boundary is mixed, 60 percent of the acreage is National Forest ownership. On average, 40,000 acres are burned by prescription each year to meet various resource management and hazard reduction objectives.

The fire season generally extends from April to late October. In most years, relatively short periods of severe burning conditions in the spring and late fall are separated by moist midsummer conditions.

Fire Years

Only 2 fire years were simulated in this case study Forest. Of the 6 years of fire occurrence data stored in a FOCUS-compatible form, 5 years were essentially the same. One of these five was designated Year B (relatively moderate), and the sixth was designated Year C, relatively high. (See *tables 1* and *4*, for a comparison of fire years among the Forests.) There was a total of 87 fires in Year B and 133 fires in Year C. There were 0.35 fires per thousand acres of Forest acreage in Year B and 0.53 fires per thousand acres in Year C.

Program Levels Tested

The initial attack program levels tested ranged from \$46,000 at PL_1 to \$80,000 at PL_4 (*table 5*). No aviation program was included in the Francis Marion fire management program. The initial attack cost at the PL_2 level was \$0.23 per acre within the Forest boundary (*table 6*). Recall that the program level is only part of the presuppression budget for the Forest. The fuel treatment, fire prevention, and detection program components are not included.

Economic Efficiency Results

The initial attack program level with the lowest C + NVC in Year B was PL_1. PL_1 was therefore the most economically efficient program, based upon the inputs evaluated in this study and the value of resource outputs included in this study (*table 5*). Since PL_1 was the smallest program tested, the overall minimum C + NVC could occur at a program level below PL_1. The \$10,000 difference in C + NVC between PL_2 and PL_1 is the estimated increase in the present net worth for each year that the initial attack program is reduced from PL_2 to PL_1.

The major determinant of the Year B minimum C + NVC was the change in the initial attack program input level itself. The net value change was small relative to the total C + NVC, and it changed very little from one program level to the next. The suppression cost was a larger percentage of the total C + NVC than the net

Table 4—*The number of fire starts by fire year and by National Forest*

National Forest	Number of fires			Fire starts per thousand acres[1]		
	Year A	Year B	Year C	Year A	Year B	Year C
Francis Marion	—	87	133	—	0.35	0.53
Huron-Manistee	47	116	146	0.051	0.13	0.16
Deschutes	403	238	340	0.25	0.15	0.21
Willamette	363	237	432	0.22	0.14	0.26
San Bernardino	377	364	499	0.60	0.58	0.79
Tonto	251	278	262	0.09	0.10	0.09

[1]The acreage includes all National Forest land within the respective Forest boundary.

Table 5—*Economic efficiency of fire management program levels as measured by cost plus net value change (C + NVC), Francis Marion National Forest*

Fire severity year and initial attack program level	Components of C + NVC			Total C + NVC	Quality standards violations		Simulated area burned
	Initial attack forces budget[1]	Suppression cost	Net value change in resources[2]		Air	Water	
	Thousand dollars				*Days*		*Acres*
B:							
PL_1	46	13	1	[4]58	44	0	920
PL_2	57	11	[3]	68	44	0	898
PL_3	68	10	[3]	78	44	0	812
PL_4	80	8	[3]	88	44	0	648
C:							
PL_1	46	37	3	[4]80	50	0	2,344
PL_2	57	29	2	84	18	0	1,978
PL_3	68	27	-2	93	18	0	1,920
PL_4	80	25	-2	103	18	0	1,761

[1]No aviation operation was included in the program for this Forest.

[2]Net value change is negative for net beneficial fires (resource outputs greater "with" the fires than "without"), and positive for net detrimental fires. There were no effects on unique resources at any level for any year tested.

[3]Less than $0.5 thousand.

[4]Program level with lowest C + NVC; therefore most economically efficient of those tested for that severity year.

Table 6—*Cost of fire management program components studied, in fire year B, at program level 2, by National Forest*

National Forest	Initial attack and aviation	Suppression
	Dollars per acre[1]	*Dollars per acre burned*
Francis Marion	0.23	12
Huron-Manistee	0.15	19
Deschutes	0.66	3651
Willamette	0.64	2043
San Bernardino	11.77	99
Tonto	0.51	166

[1]The acreage includes only National Forest land within the respective Forest boundary.

value change, but it too changed little by program level. These patterns are quite clear in the C + NVC bar graphs in *figure 5*. In a marginal analysis, the most efficient program level, and therefore the location of the minimum C + NVC point, is controlled by what changes from one PL to the next and not the absolute magnitude of the components at any one program level. Even a large contributor to the total C + NVC does not affect the location of the C + NVC minimum if it is relatively constant across program levels.

The most efficient program in the more severe Year C was also PL_1, the lowest program level tested. A smaller present net worth increase was achieved in moving from PL_2 down to PL_1 in the relatively high severity year (C) ($4000) than in the moderate year (B). The increase in fire year severity still did not lead to an increase in the size of the most efficient program, however. This was true in spite of the estimate that almost two and a half times as many acres burned in Year C (2344 acres) at PL_1 than in Year B at the same program level (920 acres).

Again, the relevant question is not just how many acres burn but how much fires affect the value of resource outputs, and whether that change in the value of resource outputs resulting from fire can be affected by the size of the initial attack program. In the Francis Marion case study, the fires caused very little net value change and even that small amount was not affected by program size above PL_2 in either year tested.

Suppression Costs

The Francis Marion suppression costs in Year B were a relatively small percent of the total C + NVC, 23 percent at PL_1. The suppression cost per acre burned was also relatively low, $12/acre. This was the lowest suppression cost per acre burned of any of the Forests studied when Year B and PL_2 is used as the point for comparison.

Suppression costs per acre burned are not an index of economic efficiency. Low costs per acre burned are not inherently more efficient than high costs. Lower costs may simply result from larger fires. The suppression costs per acre burned do provide a rough indication, however, of the relative suppression program intensity between Forests.

One reason that suppression costs were low on the Francis Marion was that the fuel loadings were relatively

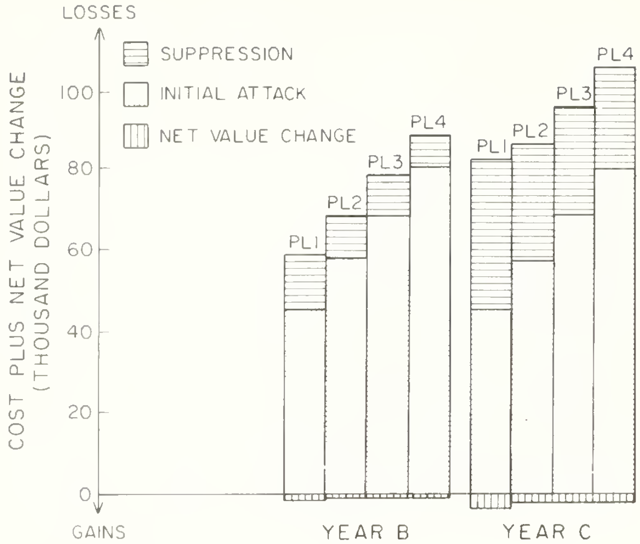


Figure 5—Determinants of minimum cost plus net value change are evident in the chart for the Francis Marion National Forest. (The program for this Forest did not include aviation.)

low as a result of their 30-year history of prescribed fire. The current prescribed burning program on the Forest costs $100,000 annually, which is twice the cost of the initial attack program. Prescribed fire has been used primarily as a silvicultural tool for timber production and to enhance other resources such as wildlife habitat, but a side benefit is an easier fire suppression job. In addition to the prescribed fire history, the gentle terrain and easy access to most points on the Forest contributed to low suppression costs.

On the premise that at least one well-trained fire specialist be available on the Forest during the fire season, the initial attack budget at PL_1 ($46,000) cannot be reduced indefinitely. The minimum may be as small as one-half a year's salary for the fire specialists plus transportation and equipment, however, if secondary forces are available for suppression actions. It is noteworthy, though, that secondary forces were not needed on the Francis Marion in the simulated fire years.

Resource Value Change

A striking feature of the net value change estimates in both simulated years was that, on net, all of them were beneficial changes. The fires resulted in more resource output than would have occurred in the absence of fire.

The net value changes at PL_2 were as follows:

Resource category:	*Year B*	*Year C*
Usable water	$ 43	$ 166
Wildlife habitat	408	1,867
Total	$451	$2,033

These are among the same resource outputs that are enhanced by the prescribed burning program.

The fires had no impact upon unique resources and did not lead to any violations of water quality standards. There were 44 days of air quality standards violated in Year B, but the number of days did not change at different program levels. In Year C, 50 days of air quality standards were violated at PL_1. This dropped to 18 days at levels PL_2 to PL_4.

If we assume that the air quality violation was the only impact excluded from the economic efficiency calculations, we can calculate the minimum opportunity cost for a day's violation in Year C. The change between PL_1 and PL_2 was $4000 in C + NVC and 32 days of violation. Therefore, if it is worth at least $125 ($4000/32 days) to prevent a day of air quality standard violation, PL_2 was the most efficient program level in Year C.

These estimates from the 2 years studied on the Francis Marion do not imply that detrimental fires never occur. For example, fires sometimes kill the seedlings in the pine plantations that were established for timber production. Particularly adverse fire weather, fuel, terrain, and fire ignition conditions on the Francis Marion certainly would lead to detrimental changes in resource outputs. The simulation of 220 fires in this study did not result in any detrimental fires, however.

Another striking feature of the Francis Marion net value change estimates is that they are a very small percent of the total C + NVC, reaching a maximum of 4 percent in Year C at PL_1. This minor contribution to C + NVC and the minor changes in net value change between program levels indicates that the fire effects and the per unit resource values used would have to be in substantial error before the location of the most efficient program level would change.

HURON-MANISTEE NATIONAL FOREST

This Forest of 923,000 acres is located in the northern half of the lower peninsula of Michigan. Hardwoods are the predominant vegetation but intermixed conifer stands of mostly jack pine and red pine are common. The topography is gentle, varying from flat to rolling hills as a result of the past glaciation. The land is well drained and contains numerous inland lakes. The lakes support a large native fish population and some of the rivers contain anadromous fish from Lake Michigan.

A significant portion of the Forest is composed of reforested farmland abandoned in the early 1900's. As a result, small communities are common within and adjacent to the Forest. Only 45 percent of the acreage within the Forest boundary is National Forest ownership, a smaller percentage than for any of the six Forests.

Table 7—*Economic efficiency of fire management program levels as measured by cost plus net value change (C + NVC), Huron-Manistee National Forest*

Fire severity year and initial attack program level	Components of C + NVC: Initial attack forces budget[1]	Components of C + NVC: Suppression cost	Components of C + NVC: Net value change in resources[2]	Total C + NVC	Quality standards violations: Air	Quality standards violations: Water	Simulated area burned
	Thousand dollars				*Days*		*Acres*
A:							
PL_1	110	5	1	[4]114	0	0	323
PL_2	138	6	-1	143	0	0	307
PL_3	166	6	-1	171	0	0	307
PL_4	193	6	-1	198	0	0	292
B:							
PL_1	110	18	-10	[4]118	0	0	1,030
PL_2	138	17	-6	149	0	0	890
PL_3	166	17	-5	178	0	0	839
PL_4	193	18	-2	209	0	0	792
C:							
PL_1	110	19	9	[4]138	0	0	1,646
PL_2	138	19	6	163	0	0	1,292
PL_3	166	18	6	190	0	0	1,246
PL_4	193	16	7	216	0	0	1,236

[1]No aviation operation was included in the program for this Forest.

[2]Net value change is negative for net beneficial fires (resource outputs greater "with" the fires than "without"), and positive for net detrimental fires. There were no effects on unique resources at any level for any year tested.

[3]Less than $0.5 thousand.

[4]Program level with lowest C + NVC; therefore most economically efficient of those tested for that severity year.

The fire season normally extends from mid-April to mid-August with an additional period in the month of October. Summer weather is often damp and moderately humid, but selected years may include drought periods in the spring, summer, and fall, leading to higher fire severity.

Fire Years

Year B had 116 fires, a fire density of 0.13 fires per thousand acres of Forest ownership. This is similar to the fire density for Year B on the Willamette, Deschutes, and Tonto National Forests.

Program Levels Tested

The initial attack program levels tested on the Huron-Manistee varied from $110,000 at PL_1 to $193,000 at PL_4 (*table 7*). As on the Francis Marion, there was no aviation component in the fire management program on the Huron-Manistee. The initial attack cost at PL_2 was $0.15 per acre, the lowest of the six Forests.

Economic Efficiency Results

The most economically efficient program level on the Huron-Manistee in Year B was PL_1, just as it was on the Francis Marion. The increase in program present net worth achieved by the reduction from PL_2 to PL_1 in Year B was $31,000. PL_1 was also the most efficient program of those tested in Year A and Year C.

The major determinant of the most efficient program was the change in the initial attack program level (*fig. 6*). The net value change and suppression costs were again a small percentage of the total C + NVC, and they changed very little in response to initial attack program level changes.

Suppression Costs

The suppression cost in Year B at PL_2 was $17,000 for the year. This was 11 percent of the total C + NVC. Suppression costs were fairly constant from one program level to the next, showing no significant decline as the initial attack program size was increased.

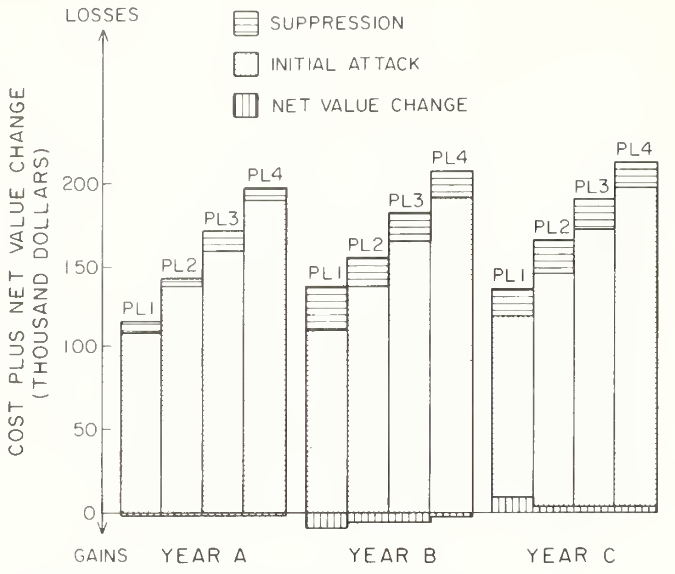


Figure 6—Determinants of minimum cost plus net value change are evident in the chart for the Huron-Manistee National Forest. (The program for this Forest did not include aviation.)

Table 8—*Net value change on the Huron-Manistee National Forest by fire year, resource category, and program level (PL_1 lowest)*

Fire year and resource category	Net change[1]			
	PL_1	PL_2	PL_3	PL_4
	Thousand dollars			
A:				
Commercial timber	3	3	3	3
Wildlife habitat	-4	-4	-4	-3
Total	-1	-1	-1	0
B:				
Commercial timber	3	5	5	4
Wildlife habitat	-13	-11	-11	-6
Total	-10	-6	-6	-2
C:				
Commercial timber	6	3	2	2
Wildlife habitat	[2]	[2]	[2]	[2]
Recreation	1	[2]	[2]	[2]
Structures	5	4	4	4
Total	9	7	6	7

[1]Columns may not add due to rounding.
[2]Less than $0.5 thousand.

Almost all of the fires were less than 100 acres in size. In Year C, 3 fires out of 146 exceeded 100 acres at PL_1. This was the greatest number to exceed 100 acres in any year or program level of those simulated on the Huron-Manistee. The number of fires in the 10- to 100-acre size class was also almost constant from one program level to the next. This fire size distribution and its consistency from one program level to another helps explain why suppression costs were relatively low and constant.

The per acre suppression costs on the Huron-Manistee were relatively low, $19 per acre, lower than any other of the case Forests except the Francis Marion. Because the Huron-Manistee has a relatively low biomass productivity, fuels have accumulated slowly since the land was removed from agricultural use. The gentle topography and ready access, and assistance by Forest visitors in the rapid detection and suppression of fires, helped to keep suppression costs low as did the generally low fuel loadings.

All fires were suppressed by primary Forest Service fire management personnel supported by the initial attack budget. The low initial attack budget on the Huron-Manistee led to 20 "no dispatch" fires in Year C at PL_1 and 9 "no dispatch" fires in Year C at higher program levels. A "no dispatch" fire is identified in FOCUS model output when all initial attack forces which are identified as available for fire suppression have already been dispatched to an existing fire. The fire then spreads naturally until attack forces are free. Because of the small initial attack program level, if a large number of fires started near the numerous private structures interspersed throughout the Forest, substantial damage could occur. This did not happen in the simulated years. Some structural losses occurred in Year C, but the losses were lower than they might be.

Resource Value Change

The net change in the value of resource outputs was a very small percentage of the total C + NVC, reaching a maximum of 9 percent in Year B at PL_1. Like those on the Francis Marion, the fires tested on the Huron-Manistee in Year A and Year B in net were beneficial. The increased value of wildlife output which resulted from the fires outweighed the detrimental impact upon commercial timber output *(table 8)*.

The net value change in Year C was detrimental. Wildlife habitat benefits resulting from the Year C fires were small. Detrimental effects were estimated in commercial timber, recreation, and in the loss of structures. This predominance of commercial timber and structural losses relative to the other resource categories was repeated throughout many of the other case study Forests.

All of the fires over 100 acres were started when debris-burning fires escaped due to strong winds. All of these occurred during wet periods in the fall of the year. No net value changes were recorded, either positive or negative, for those fires. No air or water quality standards were violated as a result of the fires, and no unique resources were affected.

Questions about the accuracy of the fire effects and regional average resource value data arose here too. For example, the Resources Planning Act average regional values for commercial timber used in this study are over three times as high as the actual average stumpage price of timber sold on the Huron-Manistee in fiscal year 1978. Just as in the Francis Marion case, however, the relevant question is whether the data errors change the results. Given the relatively small contribution of net value changes to the total C + NVC, and its relative constancy from one program level to the next, the reduction of the estimated commercial timber stumpage prices by two-thirds would not change the minimum C + NVC location, nor would reasonable changes in the other resource effects or values do so.

Selection of Fire Year for Simulation

The historical fire years were selected on the basis of their relative severity. Since many factors influence the actual burned area, the simulated acres burned may not coincide exactly with the actual burned area (*table 1*). Equally important, the selected years are simply three points on the full distribution of potential fire year severity. Years more severe than Year C and less severe than Year A have occurred in the past and may occur in the future.

The Mack Lake fire in 1980 on the Huron-Manistee burned 24,790 acres and several structures. This fire points up the hazard of using too few points on the probability distribution of fire year severity or of failing to remember that Year C is not the most severe year possible. In the relatively infrequent years when fire severity is very high, the almost continuous poletimber stands of jack and red pine can, and have, led to large, detrimental fires. Although it is very difficult to determine the probability of occurrence of those infrequent severe events, their possibility should not be ignored.

Table 9—*Economic efficiency of fire management program levels as measured by cost plus net value change (C + NVC), Deschutes National Forest*

Fire severity year and initial attack program level	Components of C + NVC			Total C + NVC	Quality standards violations		Simulated area burned
	Initial attack forces budget[1]	Suppression cost	Net value change in resources[2]		Air	Water	
	Thousand dollars				*Days*		*Acres*
A:							
PL_1	533	460	60	[4]1,348	0	0	282
PL_2	688	421	46	1,517	0	0	249
PL_3	899	187	41	1,489	0	0	234
PL_4	1,181	191	37	1,763	0	0	226
B:							
PL_1	532	303	65	[4]1,196	0	0	129
PL_2	688	303	41	1,394	0	0	83
PL_3	899	132	33	1,426	0	0	65
PL_4	1,181	104	28	1,667	0	0	57
C:							
PL_1	532	743	323	[4]1,894	5	0	964
PL_2	688	730	267	2,047	5	0	901
PL_3	899	400	265	1,926	5	0	864
PL_4	1,181	440	277	2,252	5	0	865

[1]No aviation operation was included in the program for this Forest.

[2]Net value change is negative for net beneficial fires (resource outputs greater "with" the fires than "without"), and positive for net detrimental fires. There were no effects on unique resources at any level for any year tested.

[3]Less than $0.5 thousand.

[4]Program level with lowest C + NVC; therefore most economically efficient of those tested for that severity year.

DESCHUTES NATIONAL FOREST

The Deschutes is located on the eastern slope of the Cascade Mountains in central Oregon. The topography is generally mountainous and the wide range of elevations on the Forest results in ecosystems which range from semiarid high desert to alpine forest. Ponderosa pine is the major commercial tree species throughout the Forest. Resident and anadromous fish are found on the Forest, and big game hunting is a major activity.

The Forest covers 1,603,000 acres. In sharp contrast to the two eastern Forests, most of the acreage within the Deschutes boundary (87 percent) is National Forest land. There are a few small towns on the edge of the Forest. The fire season usually extends from May through November. Unlike the relatively wet summers in the two eastern Forests, the summers here are usually quite dry and dry thunderstorms are common.

The number of fire starts in Year B was 238. The fire start density on National Forest land in Year B was 0.15 fires per thousand acres.

Program Levels Tested

The initial attack and aviation program level tested varied from $828,000 to $1,535,000 (*table 9*). The initial attack and aviation cost was $0.66 per acre at PL_2, considerably higher than the $0.23 for the Francis Marion and $0.15 for the Huron-Manistee.

One result of the separate line item appropriations for initial attack and aviation operations in the 1979 budget was that the fiscal year 1979 initial attack and aviation program balance was not efficient. At PL_2, the program was too heavily weighted toward aviation. Therefore, instead of varying initial attack alone by ±20 percent increments in the simulation, the entire initial attack and aviation program level was changed by approximately ±20 percent increments. The aviation program was reduced in PL_1. It was held at about the same level in PL_3 and PL_4 as it was in PL_2. The initial attack component was increased greatly in PL_3 and PL_4 to bring it into a more efficient balance with aviation inputs.

The imbalance toward aviation was retained in the PL_2 starting point, however, since it was dictated by the 1979 budget. The impact of this imbalance can be seen in the suppression cost estimates which were heavily influenced by the extensive use of high cost aircraft on initial attack.

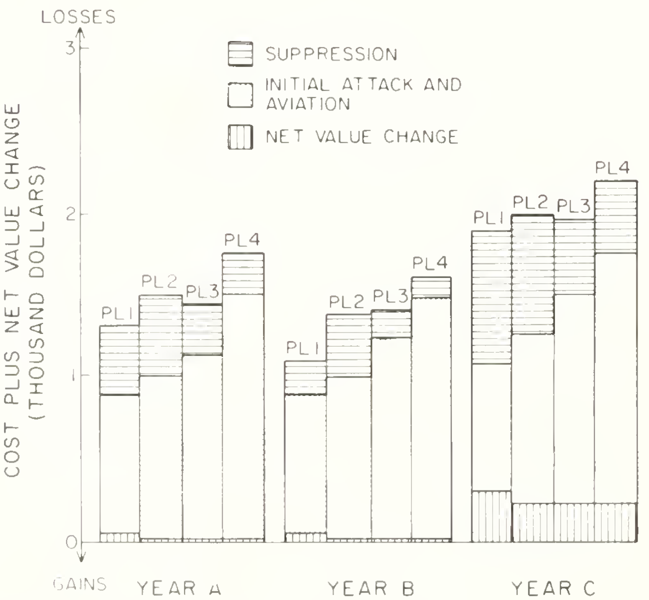


Figure 7—Determinants of minimum cost plus net value change are evident in the chart for the Deschutes National Forest.

Economic Efficiency Results

The program level with the least C + NVC in Year B in the Deschutes case study was PL_1 just as it was in the Francis Marion and the Huron-Manistee (*fig. 7*). The majority of the C + NVC was again composed of the initial attack and aviation program input with a smaller portion of suppression costs and a very small portion of net value change in resource outputs and structures. The most efficient program level in Years A and C was also PL_1. The severity of the fire year again influenced the suppression and net value change but not by enough to change the most efficient program level.

In contrast to the trend shown for the two Forests discussed earlier, there was no smooth C + NVC transition from PL_4 to PL_1. The C + NVC of PL_3 is less than that for PL_2 in Year A and Year C, and the two C + NVC's are very close in Year B. The initial attack and aviation imbalance and its impact upon suppression costs caused this. The relative overabundance of aviation inputs in PL_1 and PL_2 led to a higher use of relatively expensive aircraft simply because they were available. A more appropriate initial attack and aviation program mix would reduce the PL_1 and PL_2 suppression costs below those simulated here and probably also reduce the total C + NVC in turn.

This change in the initial attack and aviation program composition across the four program levels tested, and the impact it had on C + NVC, points out that a family of C + NVC curves actually exists, one for each program composition or mix (Mills 1980). The discontinuity of the C + NVC results on the Deschutes illustrates the hazard of trying to find the minimum C + NVC by changing program mixes and program levels simultaneously. A more certain way to locate the overall

C + NVC minimum is to trace the entire family of C + NVC curves by holding the program mixes constant one at a time while a range of program levels is evaluated. The program mix should then be changed and the program levels incremented again. The overall frontier of C + NVC minimum points can then be derived from the family of C + NVC curves and the overall minimum can be located on that frontier.

Suppression Costs

The cost of suppression in Year B at PL_2 was $303,000, 22 percent of the C + NVC. The PL_1 and PL_2 suppression costs were similar in all 3 simulated years and the same was true of the PL_3 and PL_4 suppression costs (*fig. 7*), again because of the program imbalance.

Very few fires reached a size greater than 100 acres—one in Year A and one in Year C. The greatest number exceeding even 10 acres was five in Year C at PL_1. This small size distribution, in combination with the terrain and access characteristics which required use of aircraft for rapid initial attack, led to an average suppression cost in Year B at PL_2 of $3651 per acre burned. The corresponding cost in Year A was $1691 per acre, and Year C was $810 per acre. This suppression cost per acre burned was roughly 10 times as large as the cost in the two eastern Forests.

It is again important to note that suppression costs per acre burned are not a reliable measure of economic efficiency. The C + NVC minimization is the proper indicator for that. The per acre suppression costs and the relation between suppression costs and net value changes do provide some hints, however, about whether alternative fire suppression strategies should be investigated. In Year B at PL_2, for example, the $3651 per acre suppression cost occurred coincidentally with a net value change of $494 per acre burned. It *cannot* be concluded from this that suppression is too aggressive. The acres burned and net value change could increase substantially under a less aggressive, and perhaps less costly, suppression strategy. The ratio of suppression to net value change does indicate, however, that alternative suppression strategies should be evaluated.

The bulk of the suppression cost on the Deschutes was primary Forest Service fire inputs in Year A and Year B. In Year C, a heavier portion came from secondary inputs. Cooperator inputs were small in all fire years. The suppression costs at PL_2 by year are as follows:

	Year A	*Year B*	*Year C*
Source:		*Thousand dollars*	
Primary Forest Service	$368	$261	$406
Secondary Forest Service	50	40	321
Cooperator	3	2	3
Total	$421	$303	$730

Resource Value Change

The net value changes in Years A and B were a small percentage of the total C + NVC. The highest in Year B was 5 percent when the net value change reached $65,000 at PL_1. The net value change estimated in Year C was quite a bit higher, reaching $323,000 at PL_1. This was 17 percent of the total C + NVC. Year C on the Deschutes was the first time in the three case studies described so far where the net value change exceeded 5 percent of the total C + NVC.

Almost all of the net value change on the Deschutes was damage to commercial timber (*table 10*). The $166 per thousand board feet timber value used in this study was 40 percent lower than the fiscal year 1978 stumpage price received on the Deschutes, so the net value changes were underestimated. An increase in the stumpage price would lead to a proportional net value change increase. Because the net value change is relatively constant here across program levels, however, the increase would not affect the selection of the most efficient program level.

No fire-related water quality standard violations were reported on the Deschutes, and no unique resources were affected. Air quality standards were violated in Year C (5 days), but the number of days affected was not sensitive to the level of initial attack and aviation program.

Table 10—*Net value change on the Deschutes National Forest by fire year, resource category, and program level (PL_1 lowest)*

Fire year and resource category	Net change[1]			
	PL_1	PL_2	PL_3	PL_4
	Thousand dollars			
A:				
Commercial timber	60	46	41	37
Commercial forage	[2]	[2]	[2]	[2]
Water use	1	1	[2]	[2]
Water storage	[2]	[2]	[2]	[2]
Structures	1	1	—	—
Total	60	46	41	37
B:				
Commercial timber	65	41	33	28
Commercial forage	[2]	—	—	—
Water use	[2]	[2]	[2]	[2]
Total	65	41	33	28
C:				
Commercial timber	323	264	262	275
Water use	[2]	[2]	[2]	[2]
Water storage	[2]	[2]	[2]	[2]
Wildlife habitat	[2]	1	1	1
Recreation	2	2	2	2
Structures	2	2	2	1
Total	323	267	265	277

[1] Columns may not add due to rounding.
[2] Less than $0.5 thousand.

WILLAMETTE NATIONAL FOREST

The Willamette is on the western slope of the Cascade Mountains in the Douglas-fir region of Oregon. Although the Willamette is adjacent to the Deschutes National Forest, the higher rainfall on the western slope has led to more productive timber stands, particularly at lower elevations. The timber species include old-growth Douglas-fir and other commercially valuable softwoods. Slopes are steep and well drained. Most of the streams contain spawning and rearing areas for salmon, steelhead, and other sea-run trout.

Because of the highly productive ecosystem and the relatively slow rate of decay, fuel volumes are very high. Fog and summer rain moderate burning conditions in most years, but during dry years, the heavy fuel loadings and steep terrain create a difficult fire control situation. Fire damage during these dry years is often high because of the commercial timber losses. Fire is used as a management tool to reduce fuel loadings following timber harvest.

This Forest covers 1,675,000 acres, almost the same amount as the Deschutes, and 93 percent of the land within the Forest boundary is National Forest land.

Year B had 237 fires, a fire density of 0.14 fires per thousand acres, almost identical to the number on the Huron-Manistee and the Deschutes.

Program Levels Tested

The initial attack and aviation program levels tested varied from $931,000 at PL_1 to $1,492,000 at PL_4. The initial attack and aviation program at PL_2 cost $0.64 per acre, almost identical to the Deschutes and higher than the two eastern Forests.

Because of an imbalance between initial attack and aviation in PL_2, the total PL_1 level was not 20 percent below PL_2. The initial attack program was reduced 20 percent but the aviation component was only reduced 4 percent, so the total was only 13 percent lower. The PL_3 and PL_4 levels were approximately 20 and 40 percent above PL_2. The PL_2 program was 58 percent initial attack and 42 percent aviation. This was slightly heavier toward the aviation component than on the Deschutes where aviation was 35 percent of the initial attack and aviation program at PL_2. The aviation program was a heavier component of the initial attack and aviation program on these two Pacific Northwest Forests than on any of the other four case study Forests.

Economic Efficiency Results

The most efficient program level in Year B was PL_1, the lowest program level tested (*table 11*). Reduction in suppression cost and net value changes as initial attack

Table 11—*Economic efficiency of fire management program levels as measured by cost plus net value change (C + NVC), Willamette National Forest*

Fire severity year and initial attack program level	Components of C + NVC: Initial attack forces budget[1]	Components of C + NVC: Suppression cost	Components of C + NVC: Net value change in resources[2]	Total C + NVC	Quality standards violations: Air	Quality standards violations: Water	Simulated area burned
	Thousand dollars				*Days*		*Acres*
A:							
PL_1	493	800	300	[4]2,031	0	0	268
PL_2	618	779	295	2,146	0	0	263
PL_3	769	582	252	2,117	0	0	225
PL_4	948	584	237	2,313	0	0	187
B:							
PL_1	493	562	158	[4]1,651	0	0	266
PL_2	618	529	154	1,755	0	0	259
PL_3	769	406	88	1,777	0	0	188
PL_4	948	311	74	1,877	0	0	140
C:							
PL_1	493	4,468	3,503	8,902	37	50	3,312
PL_2	618	4,142	3,385	8,599	37	50	3,133
PL_3	769	3,737	3,217	8,237	37	50	2,954
PL_4	948	2,568	1,981	[4]6,041	32	20	1,730

[1]No aviation operation was included in the program for this Forest.

[2]Net value change is negative for net beneficial fires (resource outputs greater "with" the fires than "without"), and positive for net detrimental fires. There were no effects on unique resources at any level for any year tested.

[3]Less than $0.5 thousand.

[4]Program level with lowest C + NVC; therefore most economically efficient of those tested for that severity year.

and aviation program levels increased was not enough to offset the increased initial attack and aviation program input cost..The total C + NVC in PL_1 of Year B was 56 percent initial attack and aviation input costs, 34 percent suppression costs, and 10 percent net value changes (*fig. 8*). This was a relatively lower percentage contribution of initial attack and aviation and a higher contribution of suppression costs than in the three Forests previously discussed.

PL_1 was also the most efficient program level in Year A, although there was little difference between the C + NVC of PL_1, PL_2, and PL_3. The initial attack and aviation contribution was an even smaller percentage of the total in Year A than in Year B, because both the suppression costs and the net value change contributions were greater. This relation existed because the years tested are actual historical years, each containing unique fire start locations. The delineation of actual fire year severity contains many factors of varying weight. These factors were only approximated here.

In Year C, PL_4 was the most efficient program level. This is the first Forest of the four so far described where some program level other than PL_1 was most economically efficient. It is also the first where the most efficient initial attack and aviation program level was influenced by the severity of the fire year. The C + NVC was lower in Year C at PL_4 because both the suppression cost and net value change were much reduced, either one being more than sufficient to offset the $209,000 increase in initial attack and aviation program cost between PL_3 and PL_4.

A major cause of these results was the impact that initial attack and aviation increments had on the number of acres burned, especially in fires over 100 acres. The number of acres burned at PL_1, PL_2, and PL_3 was 2206

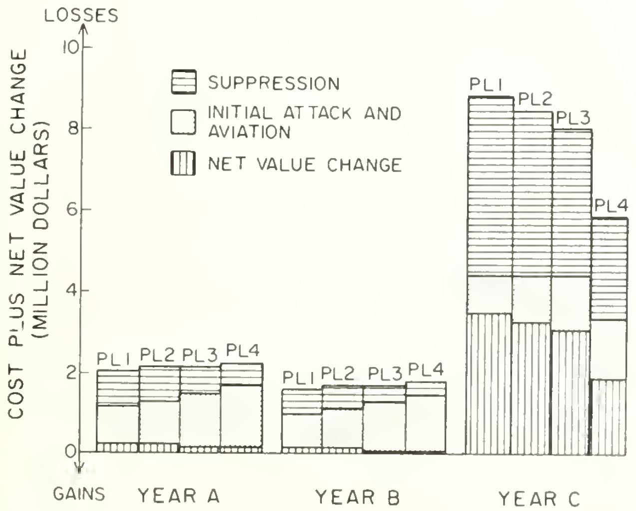


Figure 8—Determinants of minimum cost plus net value change are evident in the chart for the Willamette National Forest.

acres. From PL_3 to PL_4, the burned area dropped from 2206 to 1006 acres.

It is not possible to determine in advance when a severe fire year will occur, at least not far enough to permit substantial change in the initial attack and aviation program. In Forests such as the Willamette, where fire season severity influences the most economically efficient program level, the single most efficient level for the long run must be determined by weighting C + NVC results in each of various years by the probability that the year will occur in the future.

The expected value C + NVC of any given program level across time is derived by

$$C + NVC_{Exp} = (C + NVC_A)(P_A) + (C + NVC_B)(P_B) + (C + NVC_C)(P_C)$$

where

$C + NVC_{Exp}$ = the expected value C + NVC at the given PL

$C + NVC_A$ = C + NVC for Year A at the given PL

P_A = probability of Year A occurring in the future

For example, the expected value C + NVC in thousand dollars for the PL_1 level assuming a 0.025 probability for Year C and assuming a probability for Years A and B of 0.4875, is

$$\$2020 = (2{,}036)(0.4875) + (1{,}651)(0.4875) + (8{,}902)(0.0250)$$

At these same assumed probabilities, the expected value C + NVC of PL_2, PL_3, and PL_4 is all higher than the C + NVC of PL_1 (*table 12*). Therefore, if the Year C probability is 0.025—or stated another way, if Year C occurs once every 40 years—it would be more efficient to sustain greater losses and higher suppression costs in that severe year than to provide greater initial attack and aviation inputs than were needed in the less severe years.

PL_1 is also the most efficient long-run program level if the more severe Year C occurs once every 20 or once every 15 years, representing probabilities of 0.0500 and 0.0667, respectively (*table 12*).

If Year C occurs once every 10 years or more frequently, then PL_4 is the most efficient long run program. The resource losses averted in the severe years would then be large enough to cover the added program cost in the intervening less severe years.

The impact of varying fire severity years upon the most efficient long-run fire management program in the Willamette highlights the importance of considering the stochastic element in fire management analyses. The stochastic nature of fire occurrences and fire weather

Table 12—*Expected value C + NVC for the Willamette National Forest case study under varying probabilities of the three fire years by program level*

Probability of occurrence			Expected value C + NVC			
Year A	Year B	Year C[1]	PL_1	PL_2	PL_3	PL_4
			Thousand dollars			
0.4875	0.4875	0.0250	[2]2020	2117	2104	2176
.4750	.4750	.0500	[2]2196	2283	2262	2275
.4667	.4667	.0667	[2]2314	2394	2367	2358
.4500	.4500	.1000	[2]2549	2615	2576	2473
.4000	.4000	.2000	3255	3280	3205	[2]2869

[1]Corresponding frequencies, reading down, are 1 in 40 years, 1 in 20, 1 in 15, 1 in 10, and 1 in 5.
[2]Minimum C + NVC program level.

Table 13—*Net value change on the Willamette National Forest by fire year, resource category, and program level (PL_1 lowest)*

Fire year and resource category	Net change[1]			
	PL_1	PL_2	PL_3	PL_4
	Thousand dollars			
A:				
Commercial timber	301	296	253	238
Recreation	-1	-1	-1	-1
Total	300	295	252	237
B:				
Commercial timber	159	155	89	74
Recreation	1	-1	1	[2]
Total	158	154	88	74
C:				
Commercial timber	3,287	3,175	3,005	1,976
Water storage	–[2]	–[2]	–[2]	–
Fish habitat	47	47	47	–
Wildlife habitat	120	113	111	35
Recreation	-41	-40	36	30
Structures	90	90	90	–
Total	3,503	3,385	3,217	1,981

[1]Columns may not add due to rounding.
[2]Less than $0.5 thousand.

must be captured in the data and the analysis model must be capable of displaying the consequences of this inherent variation.

Suppression Costs

The cost of fire suppression activities in Year B at PL_2 was $529,000 or $2043 per acre burned. This was almost identical to the per acre suppression cost for the Deschutes Forest.

The use of secondary Forest Service suppression forces was heavier for the Willamette than for the other five Forests. The suppression cost by source at PL_2 was as follows:

	Year A	*Year B*	*Year C*
	Thousand dollars		
Source:			
Primary Forest Service	$254	$176	$ 410
Secondary Forest Service	522	351	3,726
Cooperator	3	2	6
Total	$779	$529	$4,142

The secondary Forest Service source was greater in all 3 fire years and fully 90 percent of the total suppression cost in Year C. The forces funded under initial attack and aviation appropriations are generally used for initial attack and small fire suppression. Secondary forces are used when the fires escapes initial attack or when multiple fire starts deplete the initial attack and aviation capability. The heavier fuel loadings and occasional incidence of multiple fires are two of the causes for this heavy use of secondary source suppression forces on the Willamette.

The low cooperator cost reflects the role of the Forest Service as the supplier of fire program assistance to other agencies in severe fire years. This helps to explain the heavy aviation component in both the Willamette and Deschutes programs, which may create an imbalance for the Forest alone.

Resource Value Change

The net value change in resource outputs in Year A and Year B was a very small percentage of the total C + NVC. Essentially all of the net value change was a reduction in commercial timber outputs due to fire, just as it was for the Deschutes (*table 13*).

The year C net value change was a higher percentage of the total C + NVC than it was in Years A and B. It was also a higher percentage than that of any Forests previously discussed. The net value change in Year C ranged from a high of $3,503,000 at PL_1 to $1,981,000 at PL_4. The PL_4 net value change per acre burned was $1145.

The Willamette National Forest is very heavily forested, and there is substantial harvesting of high-value, old-growth timber. The greatest loss of merchantable timber due to fire, as estimated by the interdisciplinary team of resource experts, was 4500 board feet per acre, even though timber stand volumes 10 to 15 times as large are not uncommon. This suggests that the resource experts recognized the 80 to 95 percent salvage rate which has historically occurred after fire.

The regional average price for timber which was applied in the Willamette case was $166 per thousand board feet. The actual sale price for timber on the Willamette National Forest in fiscal year 1978 was 70 percent higher. This price underestimate, along with the conservative assumption that timber salvaged after a burn can command the same price as green timber, means that the net value change in this study was underestimated. This underestimate would not affect the selection of the most efficient program level in any one of the fire severity years.

The impact of this timber price change would influence the results of the expected value analysis, however. An increase in the net value change lowers the probability at which Year C must occur before PL_4 is the most efficient long-run program level. For example, if the per unit value of timber were doubled, the threshold probability for Year C would be less frequent than the 1 in 5 years derived from the values in *table 12*. Data errors do not always have a linear effect on study results, even in a marginal analysis.

Fish and wildlife habitat net value changes were not materially affected in Years A and B, but their effect was larger and detrimental in Year C. This in part reflects the sensitivity of some resource effects to the size and intensity of fires, both of which were greater in Year C.

Air and water quality standards were not violated in Years A and B. Fifty days of water quality standards were violated in Year C at PL_1, PL_2, and PL_3. Twenty days were violated at PL_4. Air quality standards were violated 37 days in Year C at PL_1 but declined only to 32 days at PL_4. No unique resources were affected.

SAN BERNARDINO NATIONAL FOREST

The San Bernardino National Forest covers 633,000 acres in southern California east of the Los Angeles basin. The Forest is bounded on the east by desert. It contains more interspersed ownership than the two case Forests in the Pacific Northwest; 78 percent of the land within the boundary is National Forest.

The principal vegetation is chaparral with smaller areas of hardwoods and conifers at higher elevations. A large number of recreationists visit the Forest because of its close promixity to the large southern California population centers and there are a relatively large number of primary and secondary homes on the interspersed privately-owned land. Watershed management is an important activity. The watershed objective is production of both domestic and irrigation water and the prevention of flood damage. The terrain is quite steep and access is moderate.

Fire Years

The number of fires in Year B was 364 and the fire density in Year B was 0.58 fires per thousand acres, higher by far than in any of the other Forests studied. The most severe fire weather occurs when dry, east, Santa Ana winds reduce fuel moisture and substantially increase the fire's rate of spread.

Program Levels Tested

The initial attack and aviation program on the San Bernardino varied from a low of $6,266,000 at PL_1 to $11,300,000 at PL_4, the largest program of any of the six Forests. This was an average initial attack and aviation cost at PL_2 of $11.77 per acre of National Forest land. This was considerably higher than on any of the other five Forests, where the initial attack and aviation cost ranged from $0.15 per acre on the Huron-Manistee to $0.66 per acre on the Deschutes. Ninety percent of the PL_1 and 81 percent of the PL_4 program was initial attack. The aviation component of the program was almost tripled between PL_2 and PL_3 while the initial attack component was only increased 4 percent. This, in part, represents an initial PL_2 imbalance of too few aviation inputs, just the opposite of the PL_2 imbalance on the Deschutes.

There is a great deal of cooperation among the several governmental fire control agencies in southern California. As much as possible, the availability of cooperator assistance was held constant as the Forest's initial attack and aviation level was changed to avoid the assumption

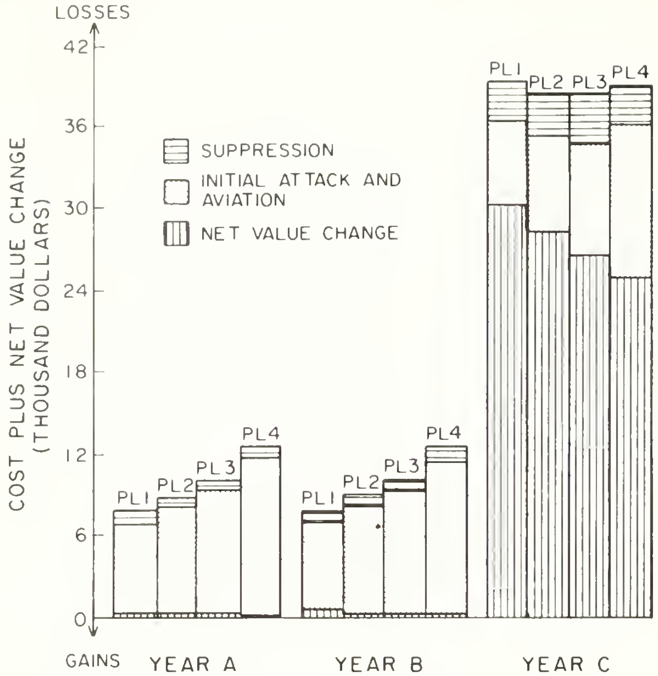


Figure 9—Determinants of minimum cost plus net value change are evident in the chart for the San Bernardino National Forest.

that the cooperators would fill in the slack created by a lower Forest program.

Economic Efficiency Results

The most economically efficient program in Year B was PL_1. Its C + NVC was $888,000 less than PL_2 (*table 14, fig. 9*). The total C + NVC at PL_1 in Year B was 77 percent initial attack and aviation cost, 15 percent suppression cost, and 8 percent net value change. Suppression cost and net value change declined as the initial attack and aviation program level increased but not by enough to overcome the increase in the cost of program input. PL_1 was also the most efficient program level in Year A and the C + NVC makeup was similar.

In Year C, PL_3 produced the lowest C + NVC. The suppression costs and net value change decline between PL_1 and PL_3 was greater than the increased cost of the initial attack and aviation program. The composition of the C + NVC was quite different in Year C than in Years A and B: 23 percent initial attack and aviation cost, 7 percent suppression cost, and 70 percent net value change at PL_3. Detrimental effects upon resource outputs were

Table 14—*Economic efficiency of fire management program levels as measured by cost plus net value change (C + NVC), San Bernardino National Forest*

Fire severity year and initial attack program level	Components of C + NVC: Initial attack forces budget[1]	Components of C + NVC: Suppression cost	Components of C + NVC: Net value change in resources[2]	Total C + NVC	Quality standards violations: Air	Quality standards violations: Water	Simulated area burned
	Thousand dollars				*Days*		*Acres*
A:							
PL_1	5,645	1,006	486	[4] 7,758	46	1,401	4,661
PL_2	6,895	940	430	8,818	41	1,269	3,702
PL_3	7,171	852	416	10,011	37	1,354	3,022
PL_4	9,122	777	226	12,303	37	1,501	2,414
B:							
PL_1	5,645	1,192	635	[4] 8,093	21	765	11,860
PL_2	6,895	1,081	452	8,981	21	730	10,963
PL_3	7,171	983	372	10,098	14	562	9,897
PL_4	9,122	907	287	12,494	13	562	9,192
C:							
PL_1	5,645	2,983	30,037	39,286	29	1,260	57,889
PL_2	6,895	2,749	28,461	38,658	23	1,434	54,323
PL_3	7,171	2,572	26,674	[4]37,989	23	1,697	51,485
PL_4	9,122	2,589	25,128	39,017	17	1,186	49,534

[1]No aviation operation was included in the program for this Forest.

[2]Net value change is negative for net beneficial fires (resource outputs greater "with" the fires than "without"), and positive for net detrimental fires. There were no effects on unique resources at any level for any year tested.

[3]Less than $0.5 thousand.

[4]Program level with lowest C + NVC; therefore most economically efficient of those tested for that severity year.

higher in total in Year C on the San Bernardino than on any other case study Forest. The C + NVC for PL_1 and PL_2 in Year C was very close to the PL_3 level, only 3 percent and 2 percent higher respectively. This is probably a finer distinction than can be made with the accuracy of this study. In Year C then, where efficiency was almost the same from PL_1 to PL_3, initial attack and aviation program increments were traded almost equally for reductions in net value changes, mostly structural damage in this case.

Since the most efficient program level was sensitive to the severity of the fire year in the San Bernardino, an expected value threshold calculation can be made much as it was for the Willamette Forest. The C + NVC in Year C dropped by $1,297,000 between PL_1 and PL_3, but it increased in Years A and B by $2,252,000 and $2,004,000, respectively. If we assume that the remaining probability is equally split between Years A and B, Year C must occur with a probability of 0.625 or greater before PL_3 gives the lowest expected value C + NVC. At lower probabilities of Year C, PL_1 is the more efficient program. From the historical record of acres burned on the San Bernardino, it appears that a year as severe as Year C is likely to occur far less often than the almost 2 out of 3 years required to make PL_3 the optimum level. As discussed above, these economic efficiency results must be weighted together with social and environmental inputs, which are not included in this study, before a program level decision can be reached.

Suppression Costs

The suppression costs for the San Bernardino Forest were a smaller percentage of the total C + NVC than for any other Forests studied except one. In Year B at PL_2, the suppression costs were $1,081,000 which was 12 percent of the total C + NVC. The average of $99 per acre burned was higher than on the two eastern Forests but far less than the per burned acre suppression cost in the two Pacific Northwest Forests.

Suppression costs decreased as the initial attack and aviation program was increased, but they did not drop by much. In Year B, for example, the suppression costs dropped from $1,192,000 to $907,000 or 24 percent between PL_1 and PL_4. In Year C, they only declined by 13 percent over the same program level range. In Year C, the suppression costs dropped by $394,000 in response to a $5,035,000 increase in initial attack and aviation budget.

This relatively stable suppression cost was paralleled by a similarly stable distribution of fires by fire size class. At PL_1, in Year B, 16 fires exceeded 10 acres and at PL_4, 14 fires exceeded 10 acres, a decline of only two fires and a corresponding drop in total acres burned of only 22 percent. In Year C, the number of fires over 10 acres at PL_1 was 28 and at PL_4 was 25, a decline of only three fires and a corresponding drop in total acres burned of only 14 percent. Burning conditions were so severe in Year C that even the substantial increases in initial attack and aviation program levels between PL_1 and PL_4 were only able to modify the acres burned by a small amount.

The majority of the suppression costs were primary Forest Service firefighting forces. The division by source at PL_2 was as follows:

Source:	*Year A*	*Year B*	*Year C*
	Thousand dollars		
Primary Forest Service	$617	$ 583	$1,865
Secondary Forest Service	166	445	807
Cooperator	157	53	77
Total	$940	$1,081	$2,749

Table 15 *Net value change on the San Bernardino National Forest by fire year, resource category, and program level (PL_1 lowest)*

Fire year and resource category	Net change[1]			
	PL_1	PL_2	PL_3	PL_4
	Thousand dollars			
A:				
Commercial timber	134	119	120	138
Commercial forage	1	-1	1	-1
Water use	8	6	-5	-3
Water storage	1	[2]	[2]	[2]
Fish habitat	5	5	5	4
Wildlife habitat	1	9	13	14
Recreation	3	2	2	2
Structures	353	320	308	100
Total	486	430	416	226
B:				
Commercial timber	264	127	96	50
Commercial forage	[2]	-[2]	[2]	[2]
Water use	18	16	15	13
Fish habitat	[2]	[2]	—	—
Wildlife habitat	74	66	59	53
Recreation	4	3	3	3
Structures	311	272	229	194
Total	635	452	372	287
C:				
Commercial timber	2,047	2,042	1,858	1,672
Commercial forage	4	-4	3	-3
Water use	74	68	64	60
Water storage	[2]	[2]	[2]	[2]
Fish habitat	459	457	457	457
Wildlife habitat	432	406	377	350
Recreation	20	19	18	17
Structures	27,157	25,609	24,031	22,695
Total	30,037	28,461	26,674	25,128

[1]Columns may not add due to rounding.
[2]Less than $0.5 thousand.

A smaller percentage of the suppression costs was borne by secondary Forest Service sources here than for the Willamette Forest, but they still made a major contribution. Cooperator inputs, which were minimal for the four Forests discussed so far, provided 17 percent of the Year A suppression costs but a small percentage of the Year C costs (3 percent), because in Year C they would be required elsewhere. This reflects the mutual assistance agreements common between fire agencies in California.

Resource Value Change

The net value change on the San Bernardino, 6 and 8 percent, in Years A and B at PL_1, was a small percentage of the total C + NVC. The per acre burned net value change at PL_1 was $104 and $54 for those years respectively. The total and per acre net value change declined as the program level increased.

The net value change in Year C was a much higher percentage (70 percent) of C + NVC at the most efficient program level (PL_3) than in Years A or B. The net value change per acre burned was also much higher, $519 per acre, than in Years A and B. Although this net value change was a higher percentage of the total C + NVC than in any other case study, it was a lower per acre loss than in Year C on the Willamette where high value timber was affected. The net value change per acre burned at the most efficient program level on the Willamette (PL_4) in Year C was $1145.

There was some loss of commercial timber on the San Bernardino in all 3 fire years (*table 15*). The timber impact was probably overestimated, however, since the fiscal year 1978 stumpage price on the Forest was only 30 percent as large as the $166 per thousand board feet regional average price used in this study. The change in the stumpage price data would moderately reduce the estimated net value change but it would not affect selection of the most efficient program level.

In Year B, there was a detrimental effect on wildlife and recreation output and a beneficial effect on forage output. These nontimber effects were greater in Year C but in total were much smaller than the commercial timber or structural effects.

The majority of the net value change in all years was structural loss. The Year C structural loss at PL_3 was $24,000,000, 90 percent of the net value change and 63 percent of the total C + NVC. On average, the net value change in the structural category, for both structures burned and those affected by increased waterflows after the fires, was distributed in the following manner:

Structural class	*Percentage of structural net value change*
1. Water-related structures, including "trash racks," designed to stop the downstream flow of large debris, and debris basins, designed to slow water velocity enough that silt and other fine debris can settle out.	45
2. Forest management structures, such as fences and cattle guards.	5
3. Public utilities, such as powerlines and telephone lines.	5
4. Privately owned structures on the Forest under special use permit, primarily second homes.	15
5. Second homes on private in-holdings within the Forest boundary.	15
6. Primary residences on private in-holdings within the Forest boundary.	15

All structures were valued at their replacement cost. That valuation approach which measured the actual benefits derived from the structures was beyond the scope of this study. No fire effects were estimated beyond the Forest boundary in the San Bernardino case. This leads to a net value change underestimate by an unknown amount. The San Bernardino study results must be used with caution unless the assumption is made that the off-Forest fire effects are the same at all four program levels.

The large impact on water-related structures and the detrimental impact on fish habitat is a result of the steep terrain and the highly erodible soils on the Forest. The increased waterflow following the fire's removal of vegetation also leads to stream siltation in excess of the water quality standards to a much greater extent on this Forest than in any other case study. In Year C at PL_3, for example, the 499 fires that burned 51,485 acres would result in an estimated 1697 days of water quality standard violation, partly because several streams were affected. Air quality standards were violated 23 days in the same year at the same program level. Adverse effects on unique resources were listed for archeological sites, one sensitive plant species, and a 200-year loss of habitat for the bald eagle, spotted owl, and rubber boa. Beneficial effects were listed for wildlife habitat diversity, two sensitive plant species, and burro forage.

The high total losses in Year C on the San Bernardino again highlight an important element in the evaluation of fire management program efficiency. The absolute magnitude of the fire loss is not relevant in determining the most efficient program level. What is relevant is how much of the losses can be averted under different program levels. The added cost of a program increment must be offset by equal or greater reductions in the combined suppression cost and fire losses. If they are not, the increment is not an efficient addition no matter how large the absolute loss is.

TONTO NATIONAL FOREST

The Tonto covers 2,875,000 acres in west-central Arizona adjacent to the Phoenix metropolitan area. Almost all of the land within the boundary, 97 percent, is National Forest ownership. The principal vegetation types are desert shrub at the lower elevations, conifer timber at the higher elevations, and chaparral and oak woodlands in the intervening elevations. The wide variation in elevation and associated rainfall within the Forest has resulted in many rare or unique plant and animal communities. Water production and water-oriented recreation are important outputs from the area.

Fire Years

The fire season is normally most severe during May and June. Burning conditions are normally moderated by heavy thunderstorm activity during July and August. There were 251 fires in Year A, 278 fires in Year B, and 262 fires in Year C. The average number of fires in Year B was 0.10 per thousand acres of Forest land, lower than any other Forests studied.

Program Levels Tested

The initial attack and aviation program levels analyzed here varied from \$1,175,000 at PL_1 to \$2,056,000 at PL_4. This was achieved by ±20 percent increments in both the initial attack and aviation components of the program. The average initial attack and aviation cost at PL_2 was \$0.51 per acre of Forest land. This was higher than for the two eastern Forests, about three-quarters as large as the Pacific Northwest Forests, and considerably lower than the \$11.77 per acre cost for the San Bernardino.

Economic Efficiency Results

PL_3 was the most economically efficient program level in Year B (*table 16*). PL_3 was also the most efficient in Years A and C, so again the fire season severity did not affect selection of the most efficient program level even though it did influence the total C + NVC.

The net value change contribution to C + NVC in Years B and C was very small, never reaching more than 4 percent. The suppression cost component was larger in Years B and C than on any other Forest studied, reaching 55 percent in Year B and 61 percent in Year C. The suppression cost declines much more in this case in response

Table 16—*Economic efficiency of fire management program levels as measured by cost plus net value change (C + NVC), Tonto National Forest*

Fire severity year and initial attack program level	Components of C + NVC			Total C + NVC	Quality standards violations		Simulated area burned
	Initial attack forces budget[1]	Suppression cost	Net value change in resources[2]		Air	Water	
	Thousand dollars				*Days*		*Acres*
A:							
PL_1	981	3,536	1,596	6,307	7	9	22,306
PL_2	1,226	1,463	1,229	4,160	7	0	6,114
PL_3	1,471	907	625	[4]3,295	2	0	1,519
PL_4	1,716	865	625	3,546	2	0	1,738
B:							
PL_1	981	5,705	185	7,065	22	19	39,204
PL_2	1,226	3,849	203	5,521	14	0	23,206
PL_3	1,471	2,188	6	[4]3,957	13	0	8,644
PL_4	1,716	2,039	2	4,097	21	0	7,658
C:							
PL_1	981	8,595	215	9,985	10	21	54,260
PL_2	1,226	4,357	52	5,878	10	0	27,869
PL_3	1,471	2,788	52	[4]4,603	9	0	13,838
PL_4	1,716	2,833	53	4,942	9	0	13,769

[1]No aviation operation was included in the program for this Forest.

[2]Net value change is negative for net beneficial fires (resource outputs greater "with" the fires than "without"), and positive for net detrimental fires. There were no effects on unique resources at any level for any year tested.

[3]Less than \$0.5 thousand.

[4]Program level with lowest C + NVC; therefore most economically efficient of those tested for that severity year.

to initial attack and aviation increments than in any other Forest studied. In these 2 years, the suppression cost changes are solely responsible for the location of the most efficient program level (*fig. 10*).

The fire start locations in Year A happen to be near structures, so in that year the net value change contributed as much as 30 percent of the total C + NVC. Remember that the 3 fire years simulated are separate historical years with unique fire start locations and fire weather conditions. In Year A, the program cost increase between PL_1 and PL_3 was less than the reduction in net value change. Suppression costs contributed a larger share of the C + NVC than the net value change at all program levels, however, and suppression costs declined even more than net value change with increase in the program level.

One question prompted by the comparison of suppression costs and net value changes in Years B and C is why so much was spent on fire suppression when the net value change was so small. Alternative program levels and strategies for suppression of escaped fires were not evaluated in this study, however, so there is no way of determining from these results alone whether the suppression cost was an efficient or inefficient expenditure. The ratio of suppression cost to net value change indicates, however, that alternative suppression strategies should be studied.

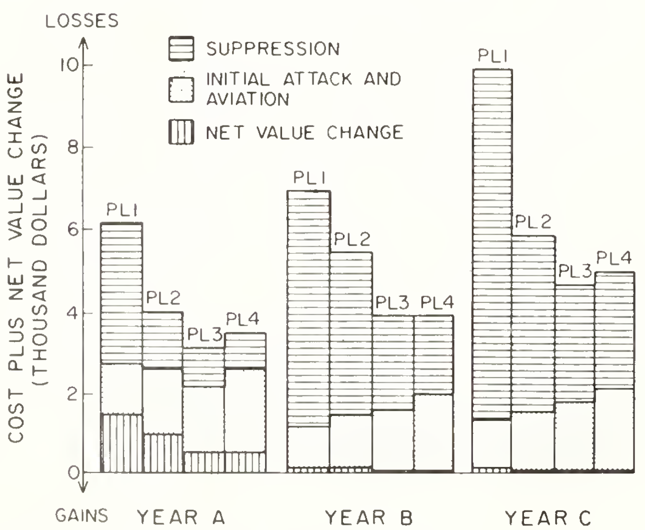


Figure 10—Determinants of minimum cost plus net value change are evident in the chart for the Tonto National Forest.

Suppression Costs

The PL_2 suppression cost on the Tonto in Year B was $166 per acre burned, higher than the San Bernardino but still far less than the $3655 on the Deschutes and $2043 on the Willamette.

The total suppression costs are high on the Tonto because lightning storms often produce multiple fire starts which, if left unattended in the "flashy" grass and brush fuels and steep terrain, spread to a large size quickly. Restricted access on much of the Forest has led to a program heavily weighted toward aircraft retardant drops and helicopter transport of fire crews. Aircraft costs accounted for about half of the total suppression cost, well above the national average.

The increased initial attack and aviation programs, coupled with aggressive fire suppression activities, led to a significant decline in simulated acres burned, in Year B, for example, from 39,204 acres at PL_1 to 7658 acres at PL_4. The average fire size declined over the same program range from 142 acres to 28 acres per fire. The simulated suppression strategy was effective at keeping fires smaller, but it was expensive relative to the amount that net value change declined.

The majority of the suppression cost was borne by primary Forest Service sources. Cooperator sources were a higher percentage of the total than for any other Forest, 19 percent in Year B at PL_2. The relative suppression costs by source at PL_2 were as follows:

	Year A	*Year B*	*Year C*
	Thousand dollars		
Source:			
Primary Forest Service	$ 948	$2,683	$2,943
Secondary Forest Service	113	433	494
Cooperator	402	733	920
Total	$1,463	$3,849	$4,357

Resource Value Change

The greatest net value change in Years A and B comes from structures, primarily fences, bridges, and other administrative structures (*table 17*). The wildlife habitat output, as measured in user days by recreationists for consumptive and nonconsumptive uses, is increased in Years B and C by fire. The recreation resource output is reduced, particularly in Year C. Recreational use is concentrated along the scarce water courses and the camping facilities are usually filled to capacity. The effect of a single fire on recreational usage therefore will probably lead to an equal amount of change in net recreational usage. There is no unused capacity for the displaced recreationist to move to. Commercial timber impacts are a smaller percentage of the total net value change. Water quality standards are violated in all years only at PL_1, and air quality standards are violated from 2 to 22 days, depending upon year and program level.

Table 17—*Net value change on the Tonto National Forest by fire year, resource category, and program level (PL_1 lowest)*

Fire year and resource category	Net change[1]			
	PL_1	PL_2	PL_3	PL_4
	Thousand dollars			
A:				
Commercial timber	5	1	[2]	[2]
Commercial forage	[2]	[2]	[2]	[2]
Water use	3	1	[2]	[2]
Water storage	[2]	[2]	[2]	[2]
Wildlife habitat	5	3	2	2
Recreation	6	[2]	[2]	[2]
Structures	1,593	1,232	627	627
Total	1,596	1,229	625	625
B:				
Commercial timber	1	1	[2]	[2]
Commercial forage	1	[2]	[2]	[2]
Water use	2	1	1	1
Water storage	[2]	[2]	[2]	[2]
Wildlife habitat	22	9	5	5
Recreation	7	2	1	1
Structures	202	210	11	7
Total	185	203	6	2
C:				
Commercial timber	92	10	[2]	1
Commercial forage	-1	1	1	1
Water use	-2	2	1	1
Water storage	[2]	[2]	[2]	[2]
Fish habitat	1	[2]	-	
Wildlife habitat	50	-32	15	-14
Recreation	114	59	55	54
Structures	61	18	14	14
Total	215	52	52	53

[1]Columns may not add due to rounding.
[2]Less than \$0.5 thousand.

CONCLUSIONS

The results of this study should be interpreted only within the context of several important limitations of the study method. First, this was a marginal analysis of the fire management program. The C + NVC efficiency criterion by its nature is a measure of marginal efficiency. It measures the economic efficiency of the added program increment but it does not give a measure of the efficiency of the total program to which the increment is being added.

Second, this was a partial, as opposed to a total analysis. The cost of most, but not all, of the program inputs were measured and the net value change of most, but not all, of the resource and structural impacts of fires was measured. Some fire effects, such as violations of air and water quality standards, were measured only in physical terms. The only major direct fire effects excluded were human life and soil productivity. Secondary impacts were excluded. These added impacts must somehow be added to the C + NVC estimate before a final decision on the best fire management program can be reached.

Third, the analysis covered only a sample of the possible conditions that fire management programs face nationwide. The six Forests encompassed a wide range of fuel, weather, resource, and fire occurrence conditions, but other combinations exist. The selection of 3 historical years of varying fire severity is also a small sampling of the full range of fire severity conditions which can exist.

Last, the analysis included variations in only the initial attack and aviation components of the fire management program on the Forest. Changes in these program components have impact on the efficiency of the other components of the fire management program and on the efficiency of resource programs on the Forest. They also affect the use of fire management inputs shared among several Forests, such as smokejumpers. To the extent that the cost of inputs used beyond the Forest's fire management program were not included in this analysis, this study method will lead to a suboptimum solution that is biased toward a smaller Forest-level fire management program.

Some limitations encountered in this study must eventually be overcome before a more complete economic analysis of alternative fire management programs can be constructed. First, estimates of effectiveness of program alternatives for all five major components of the fire management program (prevention, detection, initial attack, escaped fire suppression, and fuel treatments) must be incorporated within a single model construct. Only then can trade-offs between the components be measured effectively. The high suppression cost and low net value change in the Tonto case study, for example, indicates that a joint analysis of alternative initial attack programs and suppression strategy is needed. This analysis of initial attack and aviation alone has the potential of leading to severe suboptimization even within the fire management program.

Second, the analysis should be expanded to include the fire management program inputs which are shared among individual forests. Smokejumpers, air tankers, and some helicopters fall into this class. The size and composition of the pool of shared inputs was held constant in this study at all Forest program levels.

Third, the range of the program levels tested should be wider than the program range in this study to ensure that the minimum C + NVC is located. The most efficient program level in this study was one of the two end points (PL_1 or PL_4) in 13 of the 17 years studied. Under these conditions, there is no assurance that the overall program level which minimizes the C + NVC was found.

Fourth, alternative fire management program compositions or program mixes should be evaluated separately at each program level. The results for the Deschutes and San Bernardino Forests demonstrate that the program mix or balance influences economic efficiency much as the program level does. It is unlikely that judgment and intuition alone can lead directly to the most efficient program mix any more than judgment alone can lead directly to the most efficient program level. Both level and mix must be varied in a structured and systematic way to locate the jointly optimum combination.

Fifth, the stochastic element must be more completely incorporated throughout the entire analysis. The random variations in fire occurrence and fire weather variations must be translated into a probability distribution of resource effects and C + NVC itself. The most efficient long-run program can then be identified. The expected value C + NVC and the risk associated with an expected value decision could also be more clearly calculated from a full C + NVC probability distribution than from the three points represented in this study by the varying fire severity years.

Last, even though the preliminary sensitivity analysis in this study demonstrated that errors in the fire effects and resource value estimates would not materially affect the economic efficiency answers in most instances, the accuracy of much of the fire effects data and some of the resource value data is still suspect. More thorough sensitivity analyses should be completed with a prototype analysis model which contains the additional attributes described here. The results of that sensitivity analysis will help establish priorities for future data acquisition.

The fire management analysis and planning model being used on individual National Forests (U.S. Dep. Agric., Forest Serv. 1980c) contains some of these model improvements, such as incrementing the program level until the minimum C + NVC is located, and calculating the expected value fire weather and fire occurrence input rather than evaluating the fire program options against the fire conditions of selected historical years. Similarly, Mills and Bratten (1981) describe the conceptual design of a probabilistic fire economic evaluation system (FEES) which addresses most of these suggested analysis improvements. In particular, FEES evaluates fire program mixes, which include fuel treatments, initial attack and aviation, and large fire suppression components. It also produces the C + NVC probability distribution as well as its expected value. The full probability distribution permits a much more complete analysis of risk.

REFERENCES

Bratten, Frederick W.; Davis, James B.; Flatman, George T.; Keith, Jerold W.; Rapp, Stanley R.; Storey, Theodore G. **FOCUS: a fire management planning system—final report.** Gen. Tech. Rep. PSW-49. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1981. 34 p.

Gorte, Julie K.; Gorte, Ross W. **Application of economic techniques to fire management—a status review and evaluation.** Gen. Tech. Rep. INT-53. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1979.

Mills, Thomas J. **Calculation of financial return and determination of budget levels for fire protection programs.** 1979. Unpublished draft.

Mills, Thomas J. **Economic evaluation of alternative fire management programs.** Proceedings of the symposium on Fire Control in the 80's; 1979 Oct. 30-Nov. 1; Missoula, MT: Intermountain Fire Counc. and Soc. Amer. Foresters.; 1980; 75-89.

Mills, Thomas J.; Bratten, Frederick W. **Conceptual design of a fire economics evaluation system: FEES.** 1981. Unpublished draft.

Nelson, Thomas C. **Fire management policy in the National Forests—a new era.** J. For. 77(11):723-725; 1979 November.

U.S. Congress. **Conference report on Department of Interior and related agency appropriation bill.** Washington, D.C. 1978; Rep. 95-1672.

U.S. Department of Agriculture, Forest Service. **National forest fire report, 1973.** Washington, D.C. 1973; 50 p.

U.S. Department of Agriculture, Forest Service. **Evaluation of fire management activities on the National Forests** [Policy Analysis Staff]. Washington, D.C. 1977; 127 p.

U.S. Department of Agriculture, Forest Service. **National forest fire report, 1978.** Washington, D.C. 1978a; 53 p.

U.S. Department of Agriculture, Forest Service. Forest Service manual; Title 5100 Fire Management, Chapter 5130 Fire Suppression. Washington, D.C. 1978b.

U.S. Department of Agriculture, Forest Service. **Preliminary estimates of RPA regional resource values** [Resources Program and Assessment Staff]. Washington, D.C. 1978c.

U.S. Department of Agriculture, Forest Service. **Budget object class reports** [Program Development and Budget Staff]. Washington, D.C. 1979a.

U.S. Department of Agriculture, Forest Service. **Land areas of the National Forest System as of September 30, 1979.** Washington, D.C. 1979b; Rep. FS-348. 75 p.

U.S. Department of Agriculture, Forest Service. **Budget object class report** [Program Development and Budget Staff]. Washington, D.C. 1980a.

U.S. Department of Agriculture, Forest Service. **National Forest System fire management budget analysis, 1980** [Aviation and Fire Management Staff]. Washington, D.C. 1980b. 29 p.

U.S. Department of Agriculture, Forest Service. **Fire management analysis and planning handbook (draft).** Washington, D.C. 1980c; Forest Serv. Handb. 5109.19. 100 p.

U.S. Senate. **Report on Department of Interior and related agency appropriation bill.** Washington, D.C. 1978; Rep. 95-1063.

APPENDIX

Following are examples of the presuppression fire program activities charged to each major Forest Service budget line item.

111 Forest Fire Prevention

Includes the expenditures primarily incurred for fire prevention activities which are intended to help prevent the occurrence of fires. Examples would be installation and maintenance of effective prevention display facilities; publicity, exhibits, lectures, and other educational activities; issuance of camping and campfire permits; spark arrestor inspections of chain saws, and registration of visitors; enforcement of closed area restrictions; patrols; caution of visitors and users, fire law enforcement including fire origin investigation and preparation and distribution of circular letters on fire and other fire prevention material.

112 Forest Fire Detection

Includes the expenditures primarily incurred for the detection of forest fires. This includes fixed and mobile detection, infrared detection, electronic detection, and both ground and aerial observers whose primary job is to look for and report the occurrence of forest fires. Includes aircraft costs involved in the use of aerial detection.

113 Forest Fire Attack Forces

Includes the expenditures primarily incurred to maintain manpower, equipment (other than aircraft) and supplies in a state of readiness for the immediate suppression of forest fires. It also includes those additional preplanned forces held in reserve to be activated when initial attack fails to control a fire—such as interregional crews, hotshot crews, and specialized equipment which are available for use on a region or nationwide basis. Travel and transportation costs to move attack forces in behind other attack forces that were dispatched on initial attack will be charged here. Includes payments to State agencies and private associations under fire protection agreements. Mobilization of initial attack forces to a staging area in anticipation of fire will be charged here.

114 Forest Fire Aviation Operations

Includes the expenditures primarily incurred to provide the aviation portion of initial attack and the support items for aviation operations which will be used in fighting forest fires except aerial detection (function 112) and retardant plants (function 116). Includes items such as non-WCF pilots, aircraft specialists, airbase fees, airbase operations, aircraft availability, WCF-fixed ownership rate, safety equipment and aircraft inspection, contract payments, and other related costs.

115 Forest Fuels Management

Includes the expenditures primarily incurred to dispose of, reduce, manipulate, and/or modify forest fuels to meet fire management objectives.

The Forest Service of the U.S. Department of Agriculture

...Conducts forest and range research at more than 75 locations from Puerto Rico to Alaska and Hawaii.

...Participates with all State forestry agencies in cooperative programs to protect and improve the Nation's 395 million acres of State, local, and private forest lands.

...Manages and protects the 187-million-acre National Forest System for sustained yield of its many products and services.

The Pacific Southwest Forest and Range Experiment Station

...Represents the research branch of the Forest Service in California, Hawaii, and the western Pacific.

Schweitzer, Dennis L.; Andersen, Ernest V.; Mills, Thomas J. **Economic efficiency of fire management programs at six National Forests.** Res. Paper PSW-157. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 29 p.

Two components of fire management programs were analyzed at these Forests: Francis Marion (South Carolina), Huron-Manistee (Michigan), San Bernardino (California), Tonto (Arizona), and Deschutes and Willamette (Oregon). Initial attack and aviation operations were evaluated by the criterion of minimizing the program cost plus the net value change of resource outputs and structures resulting from fire (C + NVC). Four alternative program or budget levels were investigated at each Forest for each of 3 years of varying fire severity. The program levels ranged from 20 percent below the 1979 funding level to 40 percent above that level. The most economically efficient levels were −20 percent at four Forests, +20 percent at one Forest, and +40 percent at another Forest. Results suggested that increased fire year severity may not mean that a higher program level is more efficient. Commercial timber and structural losses contributed most to net value change, which was a small percent of the C + NVC in most of the years evaluated.

Retrieval Terms: fire economics, initial attack, aviation operations, fire suppression, marginal analysis, economic efficiency, risk

United States
Department of
Agriculture

Forest Service

**Pacific Southwest
Forest and Range
Experiment Station**

Research Paper
PSW-158

Mapping Pine Mortality by Aerial Photography, Umstead State Park, North Carolina

Clarence J. DeMars   Garey W. Slaughter   Lula E. Greene   John H. Ghent

Authors:

CLARENCE J. DEMARS is a research entomologist with the Station's research unit investigating the biology and control of forest insects in California, headquartered at Berkeley, California. He received a bachelor's degree (1953) in forestry from the University of Georgia and a doctorate (1966) in entomology from the University of California, Berkeley. **GAREY W. SLAUGHTER** is a staff research associate, Department of Plant Pathology, University of California, Berkeley, and a Station cooperator. He received a bachelor's degree (1973) in forestry from the University of California. **LULA E. GREENE** is a research entomologist with the Station's biology and control of forest insects research unit. She earned a biology degree (1969) at Shaw University. **JOHN H. GHENT** is an entomologist with the Forest Pest Management Staff, Southeastern Area State and Private Forestry, Forest Service, U.S. Department of Agriculture, Asheville, North Carolina. He has a forestry degree (1974) from Catawba College and a master of forestry degree (1976) from Duke University.

Acknowledgments:

We thank the following persons for their contributions to this study: *Chester T. Gray*, North Carolina State Highway Department, for aerial photography by his staff; *Coleman Doggett*, North Carolina State Forest Service, for use of aerial survey data; *Fred P. Hain, William T. McClelland,* and *Michael S. Stringham,* all of the Department of Entomology, North Carolina State University, for ground checks of the aerial photography; *William L. Hafley*, School of Forest Resources, North Carolina State University, and *Richard L. Welch*, Southeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture, for their advice on mensuration; *James R. Cartwright, Michael J. Gialdini,* and *Robert N. Colwell,* all of the College of Natural Resources, University of California, Berkeley, for their help in developing the mapping system; *David L. Wood* and *Marian V. Merrill,* Department of Entomology and Parasitology, University of California, Berkeley, for their administrative assistance; *Robert C. Aldrich*, Rocky Mountain Forest and Range Experiment Station, Forest Service, *William H. Clerke*, Southeastern Area, State and Private Forestry, Forest Service, *William M. Ciesla*, Methods Application Group, Forest Pest Management Staff, Forest Service, *William H. Klein*, also of that Staff, and *Fred P. Hain*, for their helpful reviews of the manuscript.

The research reported herein was supported by the U.S. Department of Agriculture program entitled the Expanded Southern Pine Beetle Research and Applications Program.

Cover: Sequential aerial photography can be viewed stereoscopically on a hand-held field board.

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

February 1982

Mapping Pine Mortality by Aerial Photography, Umstead State Park, North Carolina

Clarence J. DeMars Garey W. Slaughter Lula E. Greene John H. Ghent

CONTENTS

IN BRIEF . . .

DeMars, Clarence J.; Slaughter, Garey W.; Greene, Lula E.; Ghent, John H. **Mapping pine mortality by aerial photography, Umstead State Park, North Carolina.** Res. Paper PSW-158. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 14 p.

Retrieval Terms: Dendroctonus frontalis, southern pine beetle, *Pinus*, Coleoptera: Scolytidae, damage surveys, detection, volume losses, economic impact, ecologic impact

Southern pine beetle (*Dendroctonus frontalis*) infestations were large and wide spread in North Carolina during 1973-1976. Infestations at the 2170 hectare (5362 acre) William B. Umstead State Park were selected for study because of their proximity to research and airport facilities at Raleigh and of the "no control" policy of the Park.

Color infrared photography (1:8,000 scale) was used to detect and map tree mortality accumulated up to October 1975 and sequential photography (1:12,000 scale) was used at monthly intervals from March to July 1976 to detect and map subsequent tree mortality. Total number, volume, and value of the killed trees were estimated and the economic and ecologic impacts assessed.

Photos were interpreted stereoscopically at four-power magnification, and all detected tree mortality spots were delineated. On the October 1975 photos, the area of each tree mortality spot was measured, and standing dead trees in selected 1-ha circular plots were counted. Total tree mortality was estimated from these measurements.

Photos taken subsequently in spring 1976 were interpreted for only the recently faded trees, those faded treees that still had healthy foliage on the previous photos. The trees were counted, mapped and a sample, or all, were ground checked. Ground checks used a stereo field viewing board to locate individual trees on the ground. The trees were examined and species, size, crown color, and beetle life stage were recorded. A random sample of measured tree heights was used to correct the estimated tree heights. Total numbers of beetle killed trees were estimated for each photo date. Metric volumes were estimated by regresssion, converted to cubic feet and cords, and the dollar values determined. The ecologic impact on stand composition was assessed.

A photo interpretation data management system PISYS-1 using FORTRAN IV language was developed to assist mapping and cross comparison of photo detected tree mortality. The main elements of the system were a photo base map, a control point network, coordinate digitization, mathematical fitting, accuracy tests, and map plotting.

More than 20,500 trees on 137 ha (339 acres) were killed between 1973-1975 having a volume of 7427 cords and a value of over $236,000. This tree mortality had a significant impact on vegetation types converting 63 ha from pine and mixed species stands to hardwood forests.

Subsequent tree mortality during 1976 was much less, amounting to 248 trees detected at 120 spots in March, 24 trees detected at 13 spots in April, 18 trees detected at 5 spots in May, 2 individual trees detected in June and finally 9 trees detected at 6 spots in July. The total of 301 trees had a volume of 109 cords valued at $3,667. This loss was scattered and caused no changes to vegetation types. Total loss during the outbreak was 20,851 trees containing 7546 cords valued at $240,581.

The PISYS-1 mapping system performed well, fitting control points with an average accuracy on the ground of 12 ± 5 m (40 ± 16 ft). This resulted in tree mortality maps with a ground accuracy of 16 ± 5 m (53 ± 17 ft) with mean errors for individual photos ranging from 1 to 30 m (3 to 99 ft).

The population of southern pine beetle collapsed as the study was getting underway, therefore, we were unable to obtain the within-tree population data necessary to make area wide population estimates. However, the study does illustrate the procedures necessary to incorporate aerial photographic detection, mapping, and estimation of successive cohorts of bark beetle infested trees into population dynamics studies. Such mapping is essential in describing the distribution and abundance of bark beetles.

The southern pine beetle (*Dendroctonus frontalis* Zimm.) has a dichotomous effect on its host plant—an attacked tree is either killed or it survives without apparent damage. Evaluating trends in the beetle population and trends in the damage it causes requires an area-wide measurement of beetle density and pine mortality.

Aerial photography has proved to be an effective tool in detecting beetle-caused pine mortality. Ciesla and others (1967) detected 66 percent of the beetle-killed trees by using 1:3,960-scale color infrared transparencies. Heller and others (1974) reported that imagery recorded on color infrared film, over a range of scales (1:12,000 to 1:32,000), permitted the detection of virtually all large tree mortality spots (greater than 25 trees) caused by the mountain pine beetle (*D. ponderosae* Hopk.). For smaller spots, larger scale (1:4,000 to 1:8,000) photos were required. At the largest scale, 95 percent of the spots with four to six trees and 70 percent of the spots with one to three trees were detectable.

Aerial photo studies to date of trees killed by the southern pine beetle have used photos taken on a single occasion to measure the tree mortality that accumulated over an extended period of time (Ciesla and others 1967, Heller and others 1959). Heller (1974) reported annual assessments of the ponderosa pine mortality caused by the mountain pine beetle, and Klein (1979) mapped trends in mortality in lodgepole pine stands caused by that insect over a 4-year period by using 35-mm color aerial photographs. Sequential aerial photography was also used by Caylor and Thorley (1970) and DeMars and others (1980) to study ponderosa pine mortality in relation to the population dynamics of the western pine beetle (*D. brevicomis* Lec.)

With the sequential approach, photos are taken at intervals and interpreted to measure the change in photo-detectable tree mortality occurring during each interval. In this manner, the rate of tree mortality can be related to the rate of bark beetle survival. Analysis of the relationship between these two rates is the basis of any system to predict trends in beetle populations and the associated tree mortality over large areas.

In late 1975 and early 1976, we used sequential color infrared aerial photography to study pine trees killed by southern pine beetle in central North Carolina.[1] The study area was 2170 hectares (5362 acres) of the William B. Umstead State Park, which lies directly east of the Raleigh-Durham airport. The Park forest includes pine, hardwood, and mixed pine-hardwood stands. The pines are species typical of the Piedmont, including loblolly (*Pinus taeda* L.), short leaf (*P. echinata* Mill.), and Virginia (*P. virginiana* Mill.)—all hosts of the southern pine beetle.

This paper reports estimates of the number and volume of pine trees killed by the southern pine beetle at the Umstead State Park in 1973-1976, and of the ecological and economic effects of that mortality on stand type and resource value.

METHODS

Photo Imagery

The study area was photographed in October 1975, by using color infrared film at a scale of 1:8,000 to locate and catalogue the background of pine mortality that occurred before fall 1975. We chose color infrared film for use in the study because it is superior to normal color film in haze penetration and differentiation of hardwoods from conifers (Ciesla and others 1967).

The Park was photographed from the air at monthly time intervals from March to July 1976. The schedule attempted to synchronize the photography with the beetle generations, so that each set of photographs would image primarily the faded crowns of pines associated with one beetle generation. Medium-scale (1:12,000) photography was taken to provide mapping coverage of the entire study area, and still have reasonably few photos to interpret. Medium scale photography is typically used by the Forest Service, U.S. Department of Agriculture, to map tree mortality over large areas. Concurrently, large scale

[1]The study was done concurrently with a study of southern pine beetle population dynamics by Fred P. Hain, North Carolina State University, and a study of biometeorology by James Taylor, Southeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture.

(1:6,000) photography was used to cover selected areas to provide more accurate individual tree counts at the beetle population sampling spots than could be made on the medium-scale photos.

The processed rolls of film were cut into individual frames, and each was placed into a clear, 8-mil vinyl envelope to protect the film from dust, moisture, and scratching. Photos were labeled with the date, scale, and numbered by flight line and photo number.

The photos were examined stereoscopically at four-power magnification. The transparencies were back lighted by using fluorescent light tables having a split top, translucent, white plastic viewing surface (*fig. 1*). The stereoscopic image was scanned for the presence of pine mortality spots. On color infrared photos, healthy conifers have a dark red-brown appearance, while the fading crowns of dead and dying pines have a pink, white, or yellow-orange image, depending on how long they have been dead (Ciesla and others 1967). This difference corresponds to the normal spectrum color progression from healthy green to yellow-green, yellow, orange, and finally orange-red. When the dead needles fall off, the remaining snag appears blue-gray to gray.

New mortality spots were circled and serially numbered in black ink on clear acetate templates, one for every other photo. The templates were labeled and registered by marking the four camera fiducial points. Nine well distributed control points were transferred from a photo base map to each photo template. These control points were used to fit the photo interpretation data on tree mortality to the photo base map.

The October 1975 photos were taken to provide a baseline of older mortality from which accurate interpretation of subsequent pine mortality could be made. Consequently, these photos were interpreted somewhat differently than were later photo sets. All photo-detected pine mortality on the October photos was circled, but not counted. These dead trees ranged from the oldest snags to the most recent faders. The area of each pine mortality spot was measured.

Each subsequent photo set, starting with March 1976, was interpreted for the presence of newly faded pine crowns. Any faders suspected of being new mortality spots were checked against previous photo sets to ensure that each dead pine was recorded only once and only on the first photo set on which that tree showed a faded crown.

Tree Count Estimates

The October 1975 photography was not ground checked on a statistical basis. Trees with faded crowns were inspected on the ground only to locate centers of current beetle infestation. The total number of dead pines was estimated as follows: a 1-ha area was circled on several of the large tree mortality spots, all dead pine trees detected on the photo were counted, and the mean and standard deviation of the counts were computed and multiplied by the total area of mortality for the study area.

A probability-proportional-to-size (Cochran 1963) sample of five spots was used to estimate the total dead pines detected on the March 1976 photos. For the later photos, all spots detected were ground-checked, and all dead trees were counted.

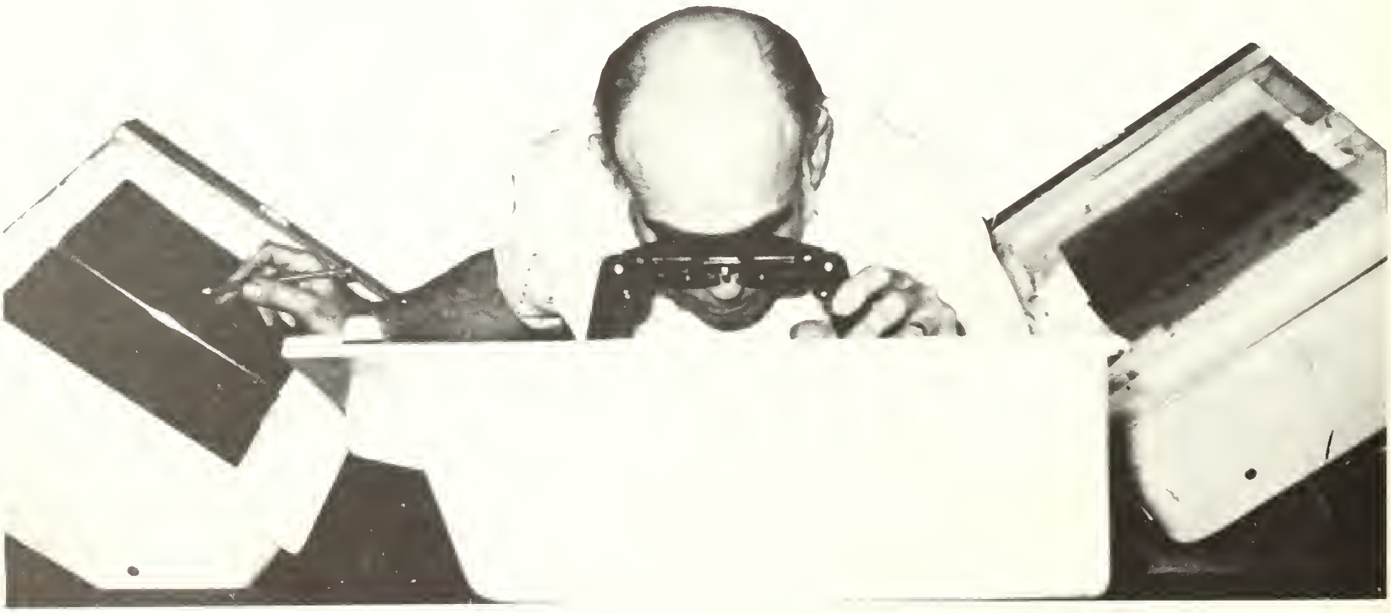


Figure 1—Aerial photographic transparencies are examined on back lighted split topped fluorescent light tables. The several tables permit cross checking dying trees to determine the earliest date fading was visible.

Ground Check Procedures

Tree mortality spots were visited by first locating the exact faded trees on site, using the photos as a guide, and collecting the desired data. A hand held field-board, using the sun as a light source, permitted stereo-viewing of the transparencies and greatly facilitated accurate location of mortality spot for ground checking.

All trees checked were labeled with a numbered metal tag nailed to the tree, inspected, and recorded, as to:

- Tree species
- Diameter at breast height, 4.5 ft (d.b.h.)
- Estimated total height (ETH)
- Crown color—ground and photo
- Cause of death
- If southern pine beetle killed, predominate lifestage present
- Height to base of infestation (HBI)

The heights of all trees at each spot were estimated and one randomly selected tree was measured by a clinometer. A simple linear regression model was developed to correct the estimated tree heights for all spots and provide an average height (HGT).

Volume and Value Estimates

The total volume killed in each time period during 1976 was calculated by using an equation that is generally applicable to loblolly pine growing on average quality sites in the Piedmont:[2]

Total volume $(m^3) = 0.37 \text{ d.b.h.}^2 \times \text{HGT} \times \text{no. trees}$

The average volume per tree killed in 1976 was computed by dividing the total volume by the number of trees. Assuming that the trees killed during 1973-1975 were the same average size as those killed in 1976, the total volume killed in those years was estimated by multiplying the average volume per tree by the number of trees killed in each of those years. These metric estimates were scaled, first to obtain cubic feet ($35.61 \ ft^3/m^3$), and then cords ($76 \ ft^3/cd$).[3]

The average price per cord for each year reported by Hutchins (1977) was applied to the volume estimates to derive an estimate of the value of the timber killed. Summing these values provided an estimate of the effect on beetle infestations on park resources during the 1973-1976 outbreak.

[2]Personal communication from William L. Hafley, School of Forest Resources, North Carolina State University, June 20, 1980.

[3]Personal communication from Richard L. Welch, Southeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture, July 15, 1980.

Figure 2—Print of a small-scale (1:78,000), high-altitude, black-and-white photo used as a base map to establish geometrical control of photo-detected tree mortality.

Tree Mortality Mapping

A photographic interpretation system called PISYS-1 was developed to provide computer assisted tree mortality mapping and data management in support of the work conducted at the Park (DeMars 1980). With this FORTRAN IV language system, the position of any previously observed point may be quickly located on the current photo and attributes compared as in back-checking tree mortality spots.

The main elements of PISYS-1 are these:

Photo base map—A photo base map with scale small enough to cover the entire test area is required. A high-altitude, black-and-white aerial photograph, from the Geological Survey, U.S. Department of Interior, dated 23 March 1973 was selected (*fig. 2*). The original scale of the photo was 1:78,000; we enlarged it four times to a scale of 1:19,500. The flying height (38,000 ft above mean ground elevation) and the 6 inch focal length lens, combined with the flat terrain at the study area, produced a photograph relatively free of planimetric distortion. This enlarged photo provided an accurate base map which is vital to the mapping system because of the infinite amount of unique detail available for establishing a control point net as compared to that available on a drafted map.

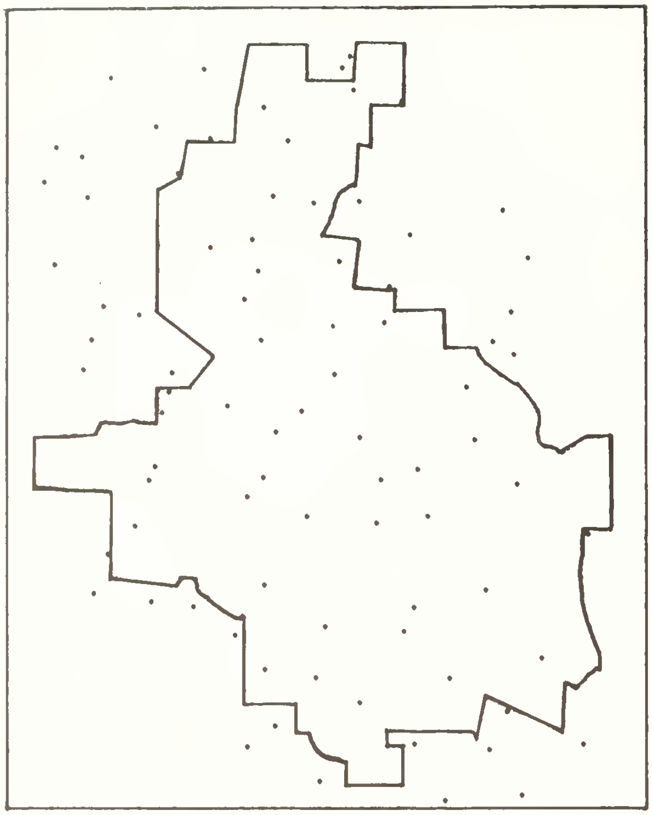


Figure 3—Control point net established for Umstead State Park, North Carolina, as an overlay to the photo base map.

Control points—Each aerial photo required nine well distributed points common to both the interpretation photo and the photo base map. These points were used to fit mathematically points of interest on each photograph to the base map. The control points were selected by choosing points which were readily observable on both the large-scale color infrared photos and the smaller scale photo base map (road intersections, buildings, large trees, bends in a stream, and other geographical features) (*fig. 3*). The chosen points were marked and numbered on both the photo interpretation template and the photo base map.

Digitization—The Cartesian coordinates of all information annotated on the templates of the 9- by 9-inch, large-scale, color infrared photos were digitized using a graphics calculator (*fig. 4*). This information included the locations of the template corners, fiducial marks, photo center, control points, and the centers of tree mortality spots. The coordinates of the control points as plotted on the 1:19,500 scale photo base map were also digitized.

Mathematical fitting—Six of the nine control points on each template were selected to calculate the transformation coefficients needed to fit the unknown point locations (tree mortality spots) to the photo base map. The coefficients were determined by simultaneously solving a pair of bivariate linear regression equations. A FORTRAN IV computer routine called FITIT was used to calculate the coefficients and predict the map positions of the points using the coefficients in the equations:

$$X_{map} = b_0 + b_1 X_{photo} + b_2 Y_{photo}$$

$$Y_{map} = b'_0 + b'_1 X_{photo} + b'_2 Y_{photo}$$

The effect of the coefficients in transforming the data are illustrated in *figure 5*.

Accuracy—The accuracy of the tree mortality spot mapping is determined by the fit of an independent set of control points (generally three or more). These additional points were not used in calculating the coefficients used to fit that photo to the base map. The accuracy established by these independent control points for each photo is, by inference, the accuracy with which the tree mortality spots are mapped. The predicted X-Y coordinates for each spot

Figure 4—Location coordinates of control points and tree mortality spots were digitized by using a Numonics Graphics Calculator interfaced with an ASR-33 teletype, stored on punched paper tape, then transmitted to a large computer for analysis.

may be visualized as the center of a circle that probably contains the spot location depending upon its radius. A radius of x + 2.76 σ of the accuracy has a 97.5 percent chance of containing the spot at the 95 percent confidence level.

Plotting—The data files created by FITIT were plotted by using the routine GRAF to produce the maps and map overlays. Files of labeled coordinates are retained in plotter inches. For convenience, errors are multiplied by the photo scale so that accuracy is expressed as ground meters. The base map is retained at the scale of 1:19,500 but for this report, all maps have been reduced by 50 or 75 percent to scales of 1:39,000 or 1:78,000.

Vegetation Type Maps

The type boundaries from the 1973 vegetation type map in the Master Plan for the park were transferred by hand to an overlay fitting the photo base map.

The considerable southern pine mortality which occurred at the park between 1973-1975 caused significant changes in the vegetation types. This mortality was delineated on the October 1975 aerial photography. When this mortality was in spots 1 ha or larger, the type boundaries were modified to encompass this updated information on the 1976 type map.

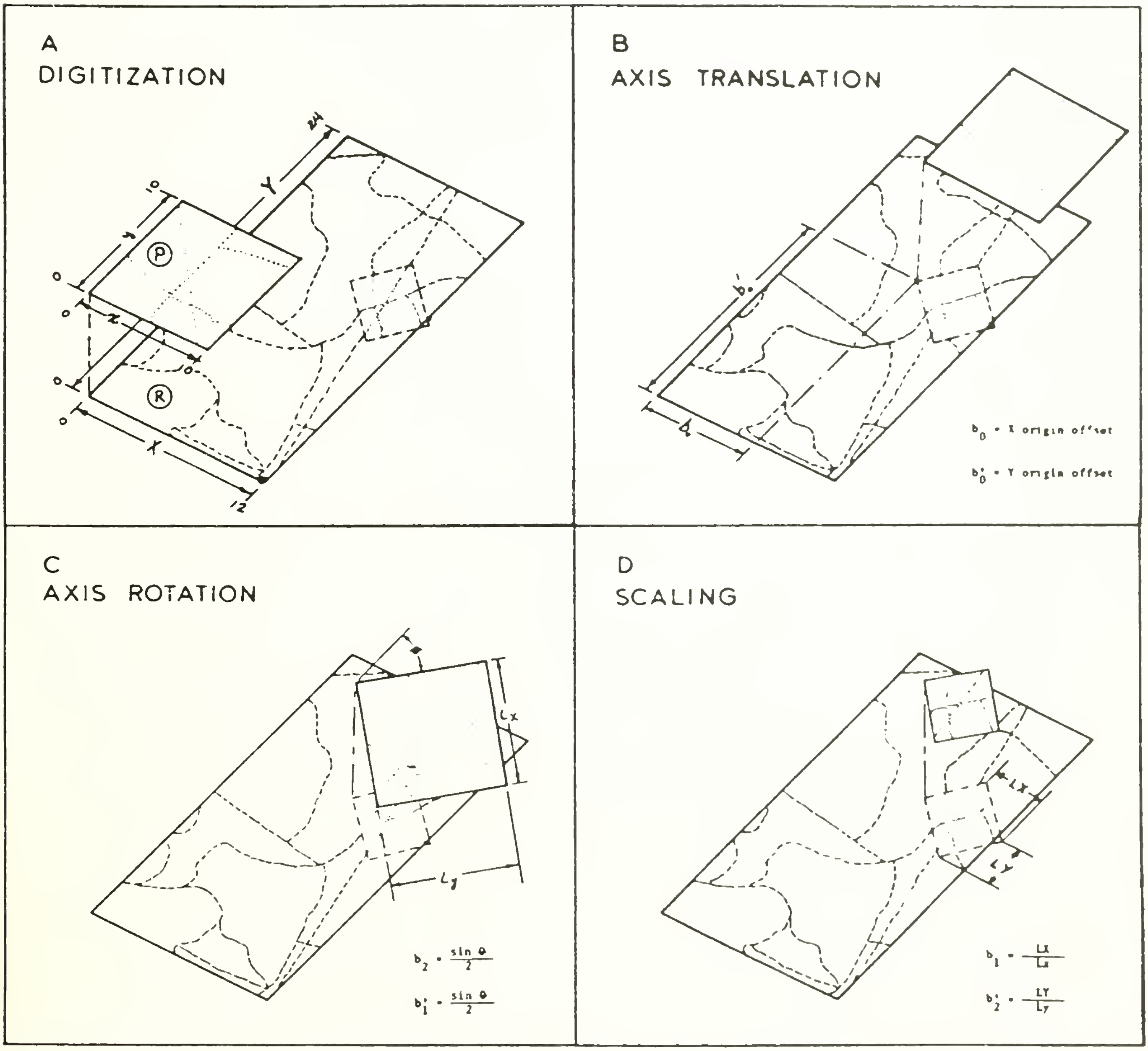


Figure 5—Effects of the affine transformation coefficients in mapping tree mortality data: (*A*) initial digitization, (*B*) translation of X and Y axes, (*C*) rotation of axes, (*D*) scaling.

RESULTS AND DISCUSSION

Tree Mortality 1973-1975

Extensive pine mortality occurred at the Park during the period 1973-1975. Most of the southern pines in 350 infestations occupying 137 scattered ha (339 acres) were killed. This mortality was detected and mapped from color infrared aerial photography taken on October 20, 1975 (*fig. 6*). Observed spot size frequency classes, where size refers to the number of hectares covered with standing dead pines, were computed (*table 1*). We estimated that there were 150 ± 16 dead pines per hectare of photo detected mortality, for a total of 20,550 ± 2,192 dead trees. This is a conservative estimate since it is based on photo counts only, which are generally lower than ground counts. Although no systematic ground check was undertaken, checks made at some of the larger mortality spots indicated that the beetle was responsible for virtually all of the pine mortality recorded on the October photos. The 21 largest spots (greater than 1.3 ha) accounted for only 3 percent of the spots, but accounted for 57 percent of the total tree mortality.

In 1973, the forest at the Park was composed of pine type (4.4 percent), mixed pines and hardwoods (59.3 percent), mixed hardwoods (34.5 percent), and water (5.8 percent) (*table 2, fig. 7*). By October 1975, this proportion had changed significantly owing to the high level of pine mortality during that period. A new type map reflected these changes (*fig. 8*). The area in each vegetation type polygon was computed (*table 3*) and totals were summarized (*table 2*).

The area of hardwood forest showed a net increase of 63 ha caused primarily by the conversion of mixed stands to hardwood. Eleven hectares of pine were converted to mixed or hardwood stands. Thus 4.5 percent of the pine and mixed stands existing in 1973 had been converted to hardwood by 1975. The revised type map and the October 1975 tree mortality map provided an accurate base line for the interpretation of the pine mortality recorded on subsequent aerial photography.

Tree Mortality 1976

A major decrease in the rate of pine mortality was already evident on the October 1975 photos. Mortality spots were composed primarily of snags, with only a few dead pine crowns still retaining faded needles.

Table 1—*Tree mortality 1973-1975, by spot size class at Umstead State Park, North Carolina, from October 20, 1975 photographs*

Spot size class		Spots	Cumulative proportion	Total		Cumulative proportion
ha	acres			ha	Trees	
0.04	0.1	179	0.51	7.2	1,080	0.05
.04- 0.08	.1- 0.2	1	.51	.1	15	.05
.08- 0.16	.2- 0.4	63	.69	6.5	975	.10
.16- 0.32	.4- 0.8	33	.79	7.9	1,185	.16
.32- 0.65	.8- 1.6	27	.87	12.7	1,905	.25
.65- 1.30	1.6- 3.2	26	.94	25.1	3,765	.43
1.30- 2.59	3.2- 6.4	9	.97	13.7	2,055	.53
2.59- 5.18	6.4-12.8	8	.98	28.2	4,230	.74
5.18-10.36	12.8-25.6	2	.99	12.9	1,935	.83
10.36-20.72	25.6-51.2	2	1.00	22.7	3,405	1.00
Total		350	1.00	137.0	20,550	1.00

Table 2—*Vegetation type map summaries for Umstead State Park, North Carolina, 1973 and 1976*

Types	Area						Tree species
	ha		acres		percent		
	1973	1976	1973	1976	1973	1976	
Pine	95	84	234	206	4.4	3.9	Loblolly, shortleaf
Mixed	1287	1235	3180	3052	59.3	56.9	Mixed pine, hardwoods
Hardwood	749	812	1850	2006	34.5	37.4	Mixed hardwoods
Lakes	39	39	98	98	1.8	1.8	
Total	2170	2170	5362	5362	100.0	100.0	

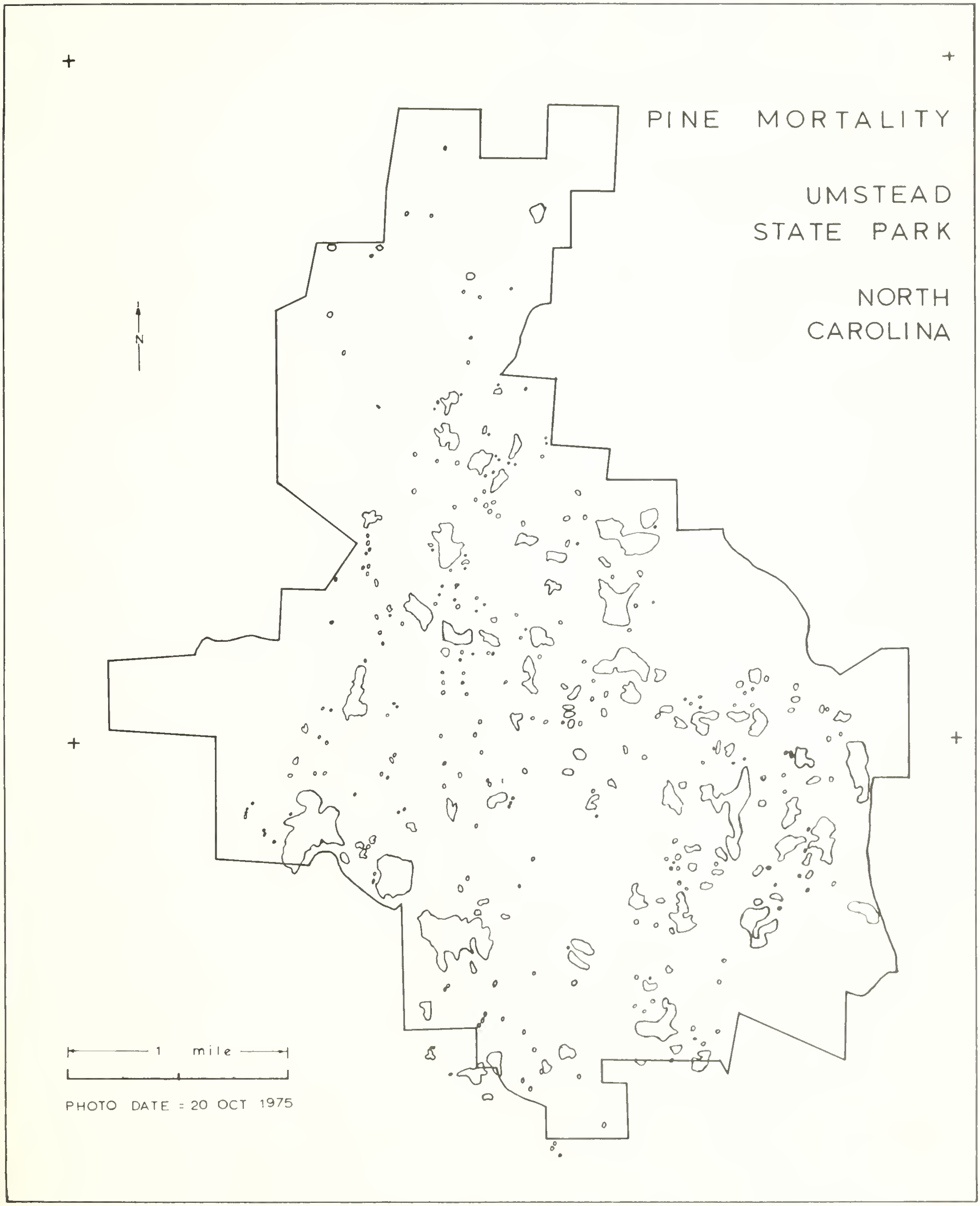


Figure 6—Pine mortality on 137 hectares (339 acres) was detected on color aerial photographs taken on October 20, 1976. Scale of map depicted is 1:39,000.

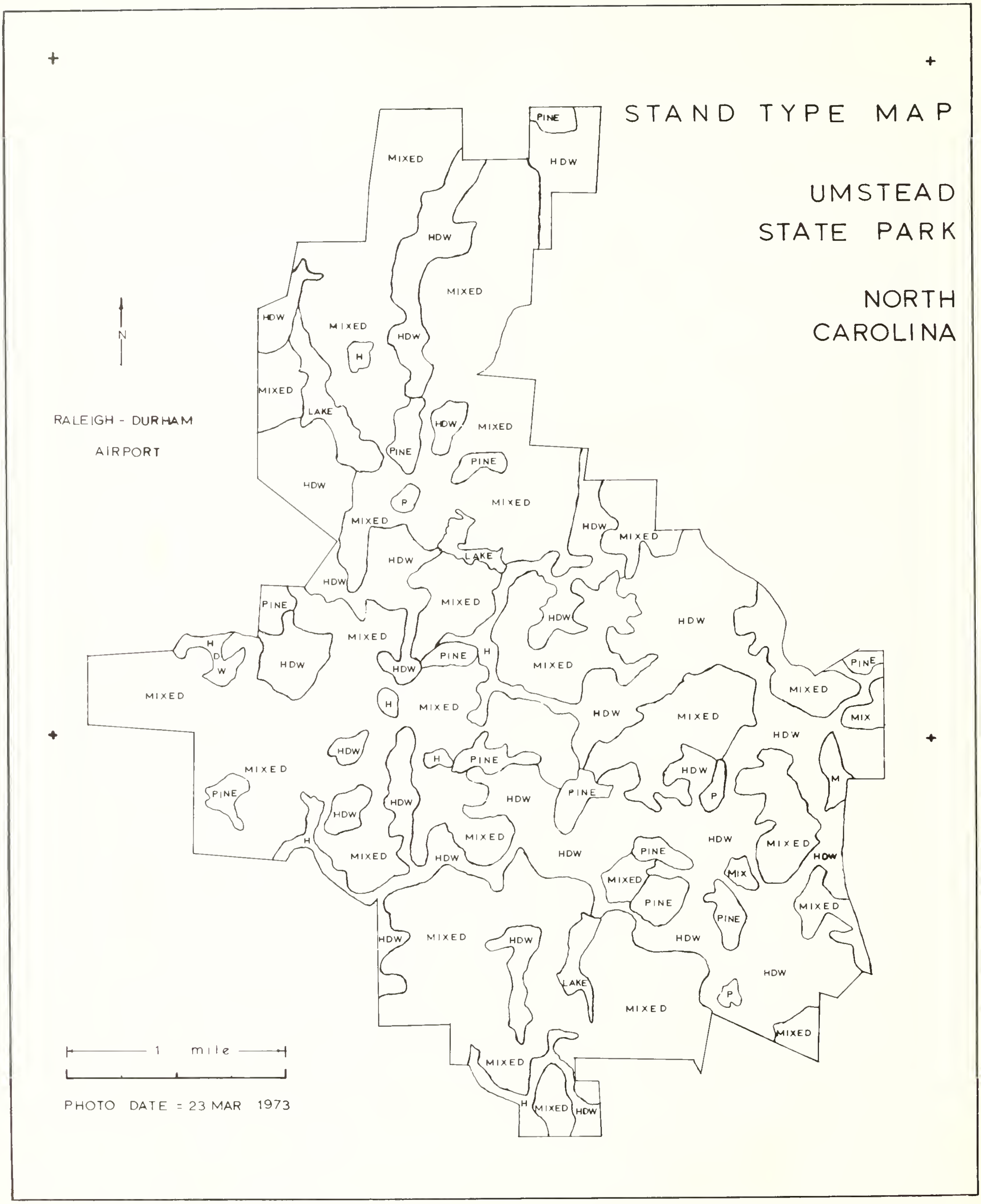


Figure 7—Umstead State Park, photographed in 1973, was composed chiefly of mixed pines and hardwoods, mixed hardwoods, and pine types. Scale of map depicted is 1:39,000.

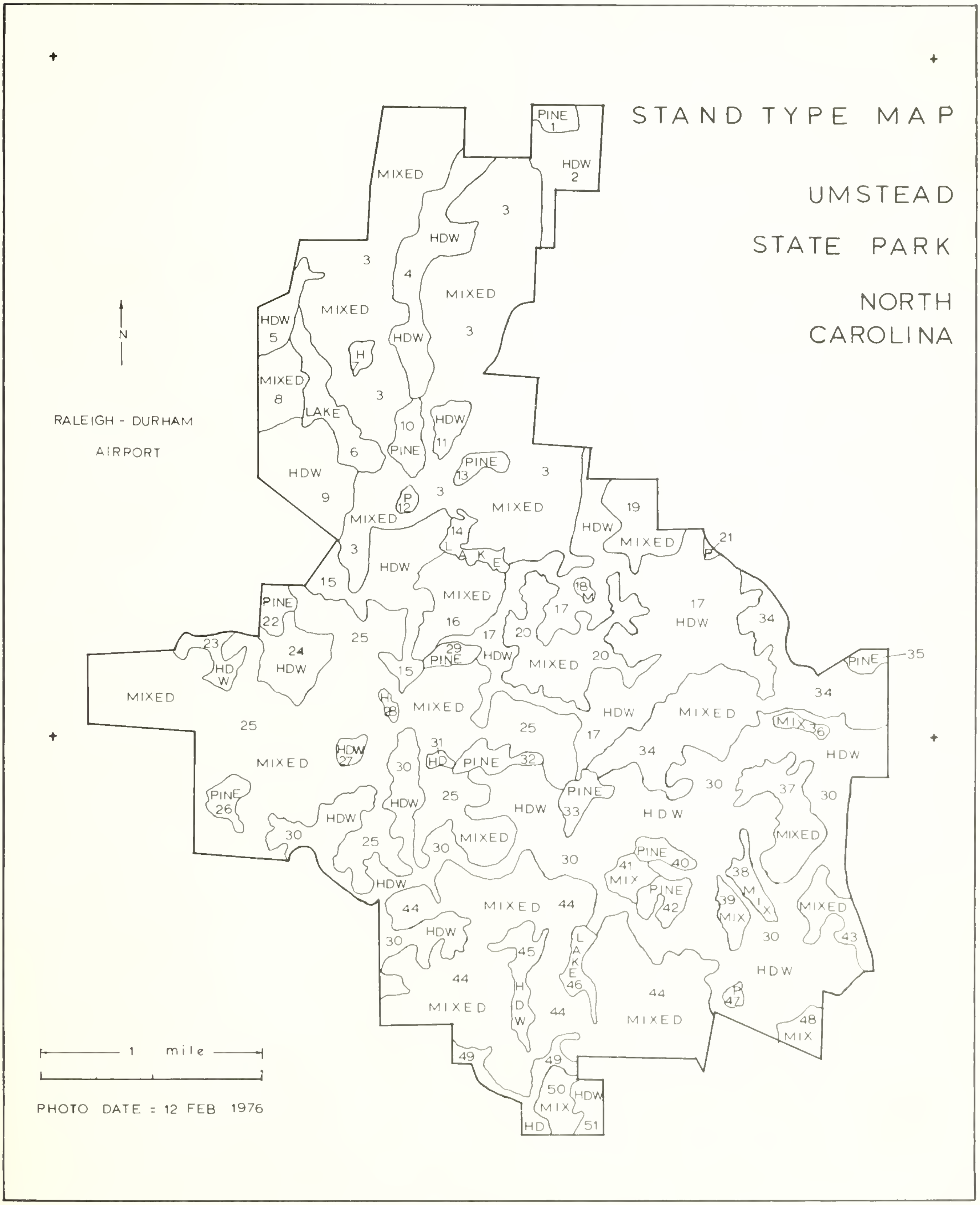


Figure 8—Vegetation type at Umstead State Park in 1976 had changed from that recorded in *figure 7* because of the extensive pine mortality. Scale of map depicted is 1:39,000.

Table 3—*Stand type polygon information, Umstead State Park, North Carolina, 1976*

Polygon	Stand type	Area (ha)	Polygon	Stand type	Area (ha)
1	Pine	6	27	Hardwood	4
2	Hardwood	28	28	Hardwood	2
3	Mixed	358	29	Pine	5
4	Hardwood	43	30	Hardwood	381
5	Hardwood	12	31	Hardwood	2
6	Lake	23	32	Pine	9
7	Hardwood	3	33	Pine	8
8	Mixed	18	34	Mixed	102
9	Hardwood	40	35	Pine	4
10	Pine	10	36	Mixed	4
11	Hardwood	7	37	Mixed	30
12	Pine	2	38	Mixed	8
13	Pine	5	39	Mixed	7
14	Lake	8	40	Pine	6
15	Hardwood	48	41	Mixed	8
16	Mixed	31	42	Pine	9
17	Hardwood	172	43	Mixed	16
18	Mixed	2	44	Mixed	227
19	Mixed	23	45	Hardwood	14
20	Mixed	49	46	Lake	8
21	Pine	1	47	Pine	2
22	Pine	7	48	Mixed	8
23	Hardwood	9	49	Hardwood	17
24	Hardwood	22	50	Mixed	11
25	Mixed	335	51	Hardwood	8
26	Pine	8			

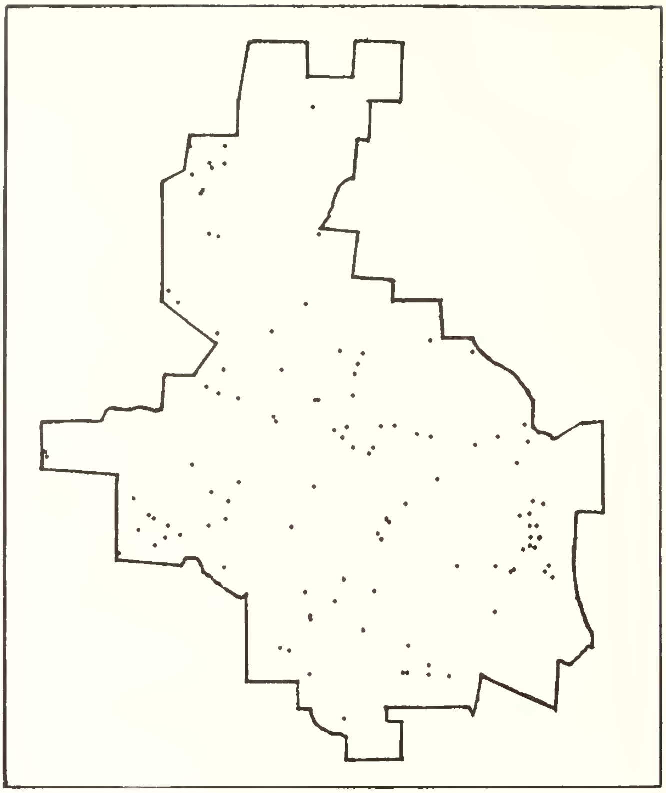


Figure 9—Aerial photography taken on March 17, 1976, shows the extent of pine mortality from southern pine beetle infestations. Scale of map depicted is 1:78,000.

Table 4—*Number and stand type for trees killed by southern pine beetle, Umstead State Park, North Carolina, spring and summer 1976*

Julian date	Spots detected	Trees		Stand type		
		Checked	Killed	Pine	Mixed	Hardwoods
				percent		
76077	120	13	[1]248	8	80	12
76117	13	28	24	0	86	14
76142	5	20	18	0	95	5
76176	2	2	2	0	0	100
76198	6	9	9	11	44	44
Total	146	72	301	—	—	—

[1]Probability proportional to size estimate of 248 ± 187.

March 1976 Photography

Pine trees with crowns fading between 20 October 1975 and 17 March 1976 were recorded on the March photography. We detected 120 separate mortality spots, and counted 225 newly dead pines since the October photos were interpreted. Among these spots, 45 were scheduled to be ground checked, but only 5 were because of a shortage of time and staff. All trees at these spots had been infested by southern pine beetles. We estimated that a total of 248 ± 187 pines had been killed by the southern pine beetle (*table 4, fig. 9*).

Some spots occurred along the margins of large, older mortality spots detected in October, but most of them were small and scattered throughout the study area. This difference suggests that the southern pine beetle populations as well as the size of the pine mortality spots had declined. While there were many spots in excess of 100 dead trees evident in October, the largest spot detected in March contained only 8 trees. This mortality produced negligible effects on the vegetation type, and no type lines on the map were modified.

Spring, Summer 1976 Photography

The spring and summer photo interpretation data for the months of April through July continue to show a drastic decline in newly killed pines associated with southern pine beetle (*table 4*).

A complete ground check of the April photo-detected spots showed 24 beetle-killed trees. A computer plotted map illustrates their distribution. Five spots were detected on the May photos, with 18 beetle-killed trees (*table 5,6*). Only two new spots were found in June, each with one beetle-killed tree. July photos showed six spots with nine beetle-killed trees. The spots were all small (less than 0.08 ha) and scattered, occurring almost entirely in mixed and hardwood type stands. No changes in the vegetation map were required.

Table 5—*Pine mortality at Umstead State Park, North Carolina, mapped from photos taken May 21, 1976*

Spot	Coordinates X	Coordinates Y	Faded crowns[1] Total	Yg	Og	Rd	Stand type	Ground check	Beetle-killed trees	Source photos
4101	2.52	4.42	2	—	2	—	Mixed	Yes	4	1-3
4103	2.13	8.57	1	—	—	1	Mixed	Yes	4	1-7
4201	4.05	2.43	1	—	—	1	Hard-wood	Yes	1	2-3
4302	5.40	4.43	1	—	1	—	Mixed	Yes	6	3-4
4303	4.36	6.58	4	—	4	—	Mixed	Yes	3	3-6

[1]Colors: Yg = yellow-green, Og = orange, Rd = red.

Table 6—*Ground check data from tree mortality spots at Umstead State Park, North Carolina detected on photos taken May 21, 1976*

Spot	Tree	D.b.h. (mm)	Height (m)	Crown color Ground	Crown color Photo	Insect Species[1]	Insect Stage	HBI[2] (m)	Tree species
4101	931	311	23	Snag	Orange	SPB	Aban	0.0	Short leaf
4101	932	274	25	Snag	Orange	SPB	Aban	.0	Short leaf
4101	933	285	27	Snag	Orange	SPB	Aban	.3	Short leaf
4101	986	137	16	Snag	Orange	SPB	Aban	.0	Short leaf
4103	916	434	26	Snag	Orange	SPB	Aban	.3	Loblolly
4103	917	370	23	Snag	Orange	SPB	Aban	.3	Loblolly
4103	978	343	20	Snag	Orange	[3]—	—	—	Loblolly
4103	979	250	17	Snag	Orange	SPB	Aban	.6	Loblolly
4103	980	202	17	Snag	Orange	SPB	Aban	.3	Loblolly
4201	915	435	31	Snag	Orange	SPB	Aban	.3	Short leaf
4302	923	338	24	Snag	Orange	SPB	Aban	.0	Short leaf
4302	924	208	18	Snag	Orange	SPB	Aban	.0	Short leaf
4302	925	234	17	Snag	Orange	SPB	Aban	.0	Short leaf
4302	926	265	20	Snag	Orange	SPB	Aban	.0	Short leaf
4302	927	325	22	Snag	Orange	SPB	Aban	.3	Short leaf
4302	975	238	17	Snag	Orange	SPB	Aban	7.2	Short leaf
4303	936	271	16	Snag	Orange	SPB	Aban	.3	Short leaf
4303	937	267	21	Snag	Orange	SPB	Aban	.3	Short leaf
4303	938	250	18	Snag	Orange	SPB	Aban	.3	Short leaf
4303	976	139	13	Snag	Hidden	—	—	—	Short leaf

[1]SPB = Southern pine beetle.
[2]Height to base of infestation.
[3]— = unknown.

Table 7—*Number and dimensions of trees killed by southern pine beetle, Umstead State Park, North Carolina, spring and summer 1976*

Julian date	Killed trees	D.b.h. X	D.b.h. SD	HBI[1] X	HBI[1] SD	Height[2] X	Height[2] SD	Total[3] volume
		mm		*m*				m^3
76077	248	300	82	0.45	0.49	19.5	3.8	186.00
76117	24	326	100	.30	.25	21.1	3.5	23.28
76142	18	283	77	.28	.36	21.0	4.4	12.96
76176	2	311	12	.60	.00	21.5	2.1	1.54
76198	9	292	90	.91	.93	24.8	8.0	8.37
Total	301							232.15

[1]Height to base of infestation.
[2]Total tree height estimated by regression.
[3]Volume (m^3) = 0.37 × d.b.h.^{2} × HGT × no. trees.

Because of the collapse of the beetle population and the resulting decline in pine mortality at Umstead State Park, we discontinued sequential photographic coverage.

Tree Heights

Estimated tree heights (25.6 ± 5.3 m) did not differ significantly from measured heights (24.0 ± 5.7 m) (*table 7*). The relationship is characterized by the linear regression:

$$Y = 2.08 + 0.86\,X$$

in which

Y = measured tree height

X = estimated tree height

Volume and Value

To estimate the volume of trees killed, we prorated the 20,550 trees killed in the 3 earlier years (1973-1975) by using the proportion of spots detected by the North Carolina State Forest Service in the surrounding area of Wake County during the infestation period occurring in a given year. On that basis, the estimated number of trees killed, by year, was 4932 in 1973, 7398 in 1974, and 8220 in 1975 (*table 8*). We then estimated the total volume of trees killed each year by applying the average cubic volume per tree killed in 1976 (0.77 m^3). By scaling to obtain round wood equivalents, we computed the volume, in cords, by year: 1785 in 1973, 2677 in 1974, 2975 in 1975, and 109 in 1976 (*table 8*). By applying the average round wood prices for each year (Hutchins 1977), we estimated that the value of trees killed during the outbreak was $240,581.

Mapping Tree Mortality

Predicted map coordinates for tree mortality spots detected on the March through July 1976 photography were plotted on the 1:39,000-scale maps (*fig. 9,10*).

Table 8—*Amount and value of trees killed by southern pine beetle, Umstead State Park, North Carolina, 1973-1976*

Year	Trees killed[1]	Volume killed		Price	Total value
		m^3	[2]*cords*	[3]*dollars/cd*	*dollars*
1973	4,932	3797.6	1784.9	28.20	50,333
1974	7,398	5696.5	2677.4	32.80	87,817
1975	8,220	6329.4	2974.8	33.20	98,764
1976	301	232.2	109.1	33.60	3,667
Total	20,851	16,055.7	7546.2	—	240,581

[1]Prorated by proportion of tree mortality spots detected by the North Carolina Forest Service in Wake County, N.C. for the years 1973-1975 (personal communication from Coleman Doggett, North Carolina State Forest Service, July 12, 1980).

[2]Based upon 76 ft^3/cord of roundwood and 35.61 ft^3/m^3.

[3]Hutchins (1977).

The mapping system performed well, providing tree mortality maps with an average ground accuracy of 12 ± 5 m (40 ± 16 ft) (*table 9*). The accuracy of the fit of tree mortality spots, inferred from the fit of the independent set of control points (ATR), averaged 16 ± 5 m (53 ± 17 ft) and ranged from 1 to 30 m (3 to 99 ft). Mortality spot comparisons between sequential photos were aided by machine comparison of location information rather than solely by the ocular comparisons of the photo interpreter. Analysis of the distance between nearest neighbor trees infested by the southern pine beetle is also possible.

CONCLUSIONS

Tree mortality information from this study provide a coherent data base to relate to the other southern pine beetle studies which have been conducted at Umstead State Park. The original plan was to provide complete tree mortality data for an area to combine with within-tree beetle population estimates, in order to produce estimates of the total beetle population over a wide area. The total beetle population equals the average beetle density per unit of bark × the average number of infested bark units per tree × the number of trees (Stephen and Taha 1979a, 1979b).

Population sampling was discontinued (due to the population decline) at Umstead State Park before sufficient data were collected to make these estimates.

The procedures made available here illustrate the type of data which can be collected with the aid of aerial photography and some of the factors to be considered in planning such an effort. Such products provide the type of information vital in evaluating both natural southern pine beetle populations and the results of experimental controls.

The value of trees lost to beetle infestation was estimated at more than $240,000. The economic meaning of this dollar value may be subject to question. In a strict

Table 9—*Average accuracy of fit of control points (CTR) and test points (ATR) obtained with the PISYS-1 photo information mapping system for Umstead State Park, North Carolina, 1976*

Julian date	CTR				ATR				Units
	X	SD	Range		X	SD	Range		
76077	45	17	80	14	59	20	99	35	(feet)
	14	5	24	4	18	6	30	11	(meters)
76117	35	9	59	28	47	11	30	8	(feet)
	11	3	18	9	14	3	9	2	(meters)
76142	38	8	55	26	40	12	56	19	(feet)
	12	2	17	8	12	4	17	6	(meters)
76176	26	9	39	15	51	12	64	35	(feet)
	8	3	12	5	16	4	20	11	(meters)
76198	51	20	84	26	68	15	59	4	(feet)
	16	6	26	8	21	5	18	1	(meters)
Overall	40	16	84	14	53	17	99	4	(feet)
accuracy	12	5	26	4	16	5	30	1	(meters)

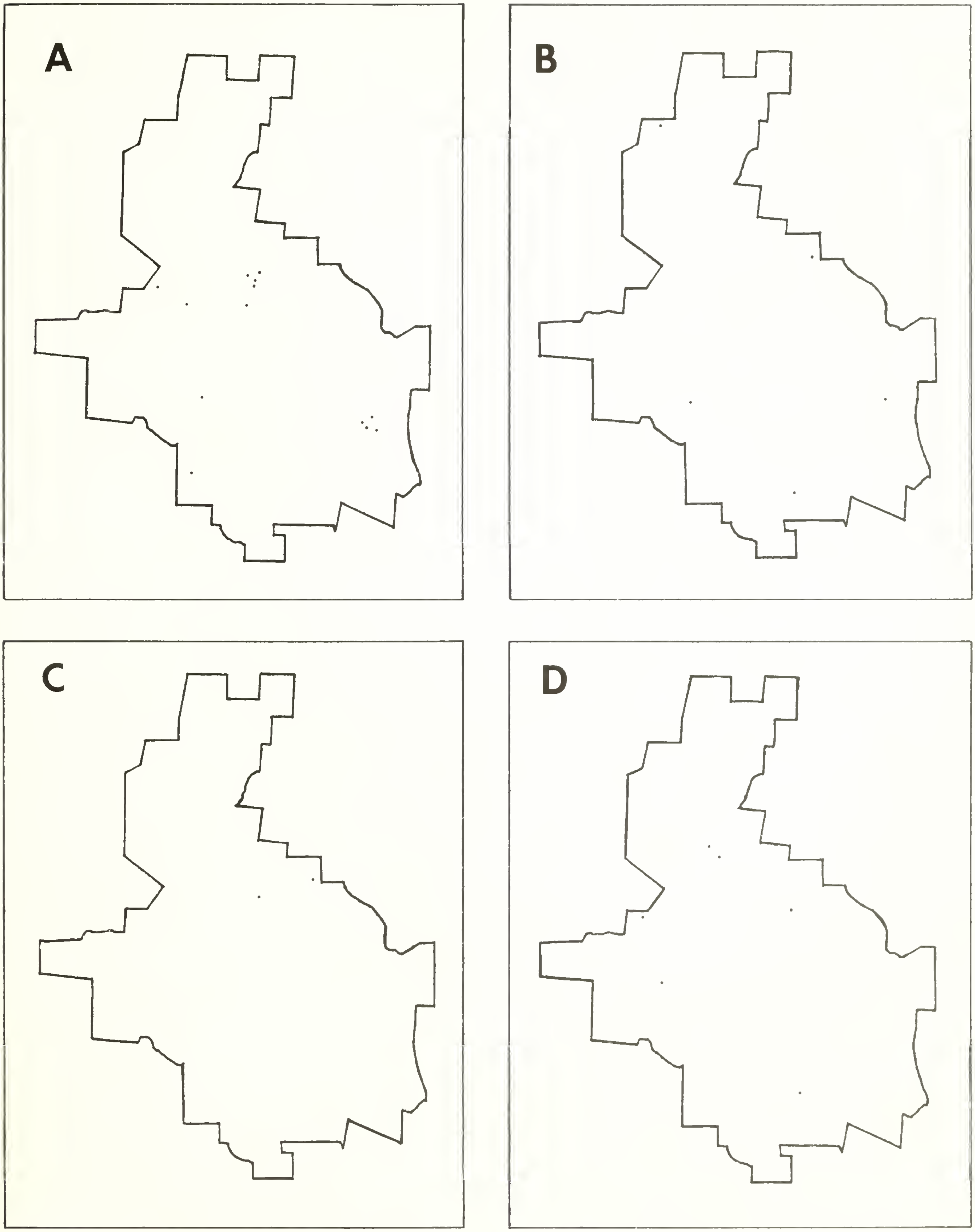


Figure 10—Spots showing trees killed by the southern pine beetle were detected on photographs taken on (*A*) April 26, 1976; (*B*) May 21, 1976; (*C*) June 24, 1976; and (*D*) July 16, 1976. Scale of maps depicted is 1:78,000.

sense, the tree mortality is not an economic loss, because the policy of the Park is to treat the area as an unmanaged "natural forest" and logging green trees, or even the salvage of killed trees, is not a possibility. An alternative view however, is to consider the $240,581 as an investment, or cost, of environmental protection.

The procedures developed to map and compare tree mortality should be applicable to many studies of bark beetle damage assessment and population dynamics. The specifics on impact are more limited, but are probably typical of other parks and natural areas in the Southeast where timber stands are unmanaged.

REFERENCES

Caylor, J.A.; Thorley, G.A. **Sequential aerial photography as an aid in the evaluation of bark beetle population trends in westside Sierra forest.** In: Stark, R.W.; Dahlsten, D.L., eds. Studies on the population dynamics of the western pine beetle, *Dendroctonus brevicomis* LeConte (Coleoptera: Scolytidae). Berkeley, CA: University of California. Division of Agricultural Sciences; 1970:8-32.

Ciesla, W.M.; Bell, J.C., Jr.; Curlin, J.W. **Color photos and the southern pine beetle.** Photogramm. Engr. 33(8):882-888; 1967 August.

Cochran, William, G. **Sampling techniques.** 2d ed. New York: John Wiley and Sons, Inc.; 1963. 413 p.

DeMars, C.J. **Managing tree mortality location data with a desk-top minicomputer.** Heller, Robert C.; Ulliman, Joseph J.; Hall, William B., eds. Proceedings of remote sensing for natural resources, an international view of problems, promises and accomplishments; 1979 September 10-14; Moscow, ID. Moscow, ID: Univ. Idaho; 1980; 69-77.

DeMars, C.J.; Slaughter, G.W.; Bedard, W.D.; Norick, N.X.; Roettgering, B. **Estimating western pine beetle-caused tree mortality for evaluating an attractive pheromone treatment.** J. Chem. Ecol. 6(5):853-866; 1980 September.

Hain, F.P.; McClelland, W.T.; Pope, D.N.; Pulley, P.E.; Foltz, J.L.; Coulson, R.N. **Standardized within-tree sampling of *Dendroctonus frontalis*.** Environ. Entomol. 7(1):157-164; 1978 February.

Heller, Robert C.; Aldrich, R.C.; Bailey, W.F. **An evaluation of aerial photography for detecting southern pine beetle damage.** Photogramm. Engr. 25(9):595-606; 1959 September.

Heller, R.C. **Remote sensing as an inventory tool for forest insect surveys.** Cunia, Timberius, ed. Proceedings, monitoring forest environment through successive sampling; 1975 June 24-26; Syracuse, NY. Syracuse, NY: State Univ. New York; 1974; 321-343.

Hutchins, Cecil, C. **Pulpwood prices in the Southeast, 1976, and 5-year trend.** Res. Note SE-253. Asheville, NC: Southeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture; 1977. 4 p.

Klein, William H. **Measuring damage to lodgepole pine caused by the mountain pine beetle.** Waters, William E., ed. Current topics in forest entomology. (Selected papers from the XV International Congress of Entomology Washington, D.C., August 1976). Gen. Tech. Rep. WO-8. Washington, DC: Forest Service, U.S. Department of Agriculture; 1979; 35-42.

Stephen, F.M.; Taha, H.A. **Tree mortality, infested bark area, and beetle population measurements as components of treatment evaluation procedures on discrete forest management units.** Coster, Jack E.; Searey, Janey L., eds. Evaluating control tactics for the southern pine beetle. Symposium proceedings; 1979 January 30-February 1; Many, LA. Tech. Bull. 1613. Washington, DC: U.S. Department of Agriculture; 1979a; 45-53.

Stephen, F.M.; Taha, H.A. **Area-wide estimation for southern pine beetle populations.** Environ. Entomol. 8(5):850-855; 1979b October.

DeMars, Clarence J.; Slaughter, Garey W.; Greene, Lula E.; Ghent, John H. **Mapping pine mortality by aerial photography, Umstead State Park, North Carolina.** Res. Paper PSW-158. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 14 p.

In 1975-1976, pine trees killed by the southern pine beetle (*Dendroctonus frontalis* Zimm.) in a 2170-hectare (5362-acre) area at the William B. Umstead State Park in central North Carolina, were monitored by sequential color infrared aerial photography. From 1973 through summer 1975, beetles in 350 infestation spots killed more than 20,500 pines on 137 hectares (339 acres). From October 1975 to July 1976, an additional 301 dead pines were detected at 146 tree mortality centers. Southern pine beetles were associated with 98 percent of these dead trees. Pine mortality dropped rapidly from 248 trees killed in fall and winter at 120 spots to 9 trees killed in July at six spots. The volume of timber killed during the outbreak exceeded 16,000 m^3 (7500 cords) of roundwood valued at more than $240,000. Strictly speaking, this is not an economic loss because the Park's management goal is to maintain a "natural forest."

Retrieval Terms: Dendroctonus frontalis, southern pine beetle, *Pinus*, Coleoptera: Scolytidae, damage surveys, detection, volume losses, economic impact, ecologic impact

United States
Department of
Agriculture

Forest Service

**Pacific Southwest
Forest and Range
Experiment Station**

Research Paper
PSW-159

Computer Simulation for Integrated Pest Management of Spruce Budworms

Carroll B. Williams, Jr. Patrick J. Shea

Authors:

CARROLL B. WILLIAMS, JR., is a pioneer scientist studying integrated management systems for forest insect pests and diseases, with headquarters in Berkeley, Calif. He is a University of Michigan graduate (B.S., 1955; M.S. 1957; and Ph.D., 1963, in forestry). He joined the Forest Service in 1957. **PATRICK J. SHEA** is in charge of the Station's field evaluation of chemical insecticides research unit, with headquarters at Davis, Calif. He joined the Forest Service and the Station staff in 1967. He earned degrees (B.S., 1962; M.S., 1972) in entomology at the University of California, Berkeley.

Acknowledgment:

We are grateful to D. Gordon Mott, Northeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture, for assistance in the development of the ideas expressed in this paper and for services in computer programming.

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

July 1982

Computer Simulation for Integrated Pest Management of Spruce Budworms

Carroll B. Williams, Jr.   Patrick J. Shea

CONTENTS

IN BRIEF . . .

Williams, Carroll B., Jr.; Shea, Patrick J. **Computer simulation for integrated pest management of spruce budworms.** Res. Paper PSW-159. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 11 p.

Retrieval Terms: spruce budworms, insecticides, parasites, integrated pest management

System simulation can be used to develop a decision support system for scientists and forest managers in suppressing populations of forest insect pests. Information from the literature describing the effects of insecticides on the western budworm (*Choristoneura occidentalis* Freeman) and its major parasites, and models from population research on the spruce budworm (*C. fumiferana* Clem.) were used in a trial of the method. A simple model was developed to describe budworm-parasite systems which differed according to the hypothetical effectiveness of the parasites. Computer simulations described the survival of these systems when subjected to different levels of control by insecticides, and also described possible cost-benefits associated with different levels of control for the various budworm-parasite systems defined in the model. The primary components of the model for the simulations were

1. Mathematical models of the population dynamics of the pest insect and its parasites.
2. Mathematical functions for impact of different population levels of the pest insect on generalized forest product yields or values.
3. Estimates of the effectiveness of various "control" factors (parasites, insecticides) in suppressing and in preventing high populations of the pest insect.
4. The economic framework for cost-benefit analyses of the various control options.

Computer simulation of the model produces both stable and oscillating average population densities over time, depending on the parasite's searching efficiency or attack effectiveness. In general, as the parasite's effectiveness increases, the budworm-parasite systems become more stable, and the average or steady density of the budworm decreases with increased parasite effectiveness.

In the simulations, when insecticide is applied to the oscillating system, the amplitude of the density oscillations increases at the lowest levels (control rates). However, at higher insecticide levels, amplitude decreases until a level of control is reached where the system becomes stable. The level of control at which the oscillations attain maximum amplitude increases with increasing parasite effectiveness. The level of control which produces a steady system decreases with increasing parasite effectiveness.

Similarly, in stable budworm-parasite systems, as insecticide control rates increase, the host density increases, then decreases at high insecticide rates. The control rate which produces the maximum density level increases as parasite effectiveness increases.

The simulations revealed that the level of budworm population suppression in stable or steady density budworm-parasite systems is not proportional to the amount of control applied in that insect generation. Only when very high control rates (insecticide dosages) are applied is much effect produced on the budworm population. Cost-benefit analyses showed that under these conditions, very high investments are worthwhile but moderate investments produce little effect.

A steady density budworm-parasite system (budworm density of 2150 without insecticides) was simulated to illustrate through cost-benefit comparisons the most economical pest population level achievable in control efforts. A variety of linear and curvilinear relationships between pest density and the value of damage were depicted for this system. If pest density was reduced from 2150 to some smaller value, a variety of costs were incurred and a number of gains were possible, depending upon the initial relation between pest or budworm density and the value of the damage.

Broadly, this study showed that the process of constructing a mathematical systems model serves to define the kinds of information required for understanding the biological structure and dynamics of the system. The study also demonstrated the usefulness of computer simulation experiments with these models to predict system behavior under different conditions and the consequences of various management decisions.

The development of ecologically acceptable management methods for forest insect pest populations is a complex problem. It requires for its solution data from many investigations of the insect populations and the crops they affect, the efficacies of various control methods, and the economic and social systems in which all of the activities take place. The currently popular terms "integrated control" and "systems approach" indicate an increased awareness by biologists and resource managers of the complexities of pest-crop systems and the need to understand them in order to develop viable management techniques.

Many of these systems for forest pest management have been presented as generalized diagrams and flow charts *(fig. 1)*, in which the forests (crops), the pests and other system components, and their hypothetical relationships are illustrated (Campbell 1972, 1973; Waters 1976; Waters and Ewing 1976). Less commonly, systems analysis and computer simulation have been used to illustrate the structure and dynamics of the system, the linkages between system components and the consequences of various management decisions on the dynamics of the system (Watt 1959, 1961, 1964, 1968; Miller 1959; Holling 1963, 1964, 1966; Berryman and Pienaar 1974; Mott 1973). A thorough historical account of the development of the concepts and realities in forest pest management was provided by Waters and Stark (1980).

A great advantage of computer simulation is that it permits experimentation with mathematical representations of real-world systems which would be risky, difficult, and expensive with actual systems. For example, a prime requirement in the development of most management systems for forest defoliating insect pests is the evaluation of the effects of insecticide applications on these pest populations and their parasites, and of the amount of protection such applications may offer to various forest product yields and values. Field experimental programs designed to examine these interests are difficult and expensive to run, but they provide quantitative estimates for various system parameters that allow us to evaluate the effects of insecticide treatments on the actual pest-forest system.

Field studies of the effects of pesticides on the spruce budworms (*Choristoneura* sp.) and their parasites have shown severe suppression of host (budworm) populations and increased parasitism after treatment (Eaton and others 1949, MacDonald 1959, Williams and others 1969, Carolin and Coulter 1971). Parasite survival was enhanced by moderate reduction (50-70 percent) of the host population;

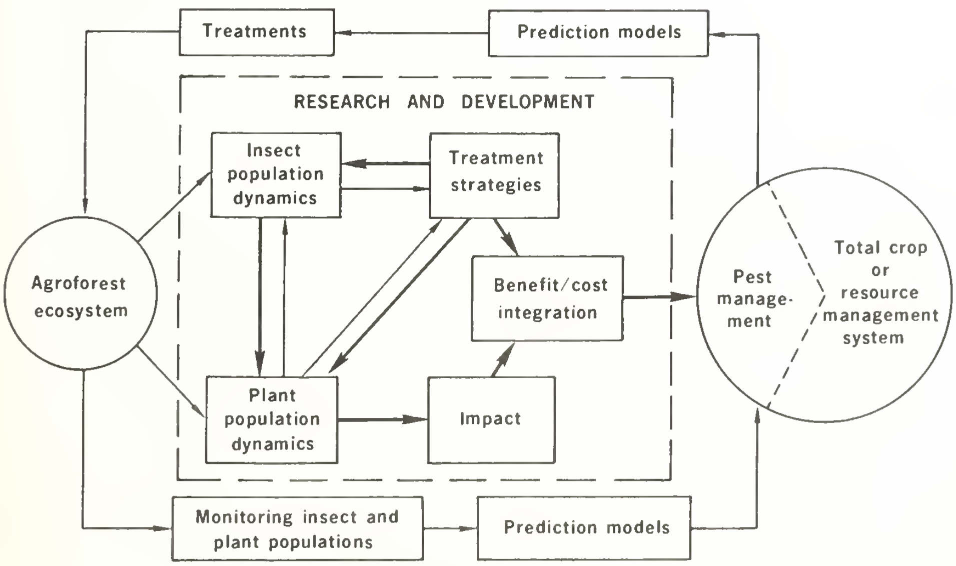


Figure 1—Model structure of an insect pest management system, with research and development components and action sequence (Waters and Ewing 1976).

increased parasitism under these conditions lasted for several years (Williams and others 1979).

In contrast, reports of spray programs to control agricultural insect pests have frequently described the initial severe suppression of the pest, but the virtual elimination of the natural enemies of the pests, followed by a resurgence of the pest populations; subsequent damage to crops is often higher than before pesticide treatments (Van den Bosch 1970, Kilgore and Doutt 1967, and Pickett and MacPhee 1965). The conflicting results of these two sets of studies are partly explained by the nature of the pest insect-crop system and the frequency of insecticide applications. Such conflicts indicate, however, a role for computer simulations as an aid in forecasting the biological consequences of applying different levels of insecticide control on the pest populations and their parasites.

This paper demonstrates the applicability of computer simulation to research and management through the construction and use of system models in integrated forest pest management. A mathematical systems model can indicate what kind of information is required for understanding the biological structure of the system and prediction of system behavior with and without regulation. We examine the interactions among parasites and host (pest) densities and survival of host-parasite systems subjected to different levels of control by insecticides. We also examine cost-benefit functions associated with different levels of control.

Although the concepts used in these simulation studies are taken from field insecticide trials on western spruce budworm (*Choristoneura occidentalis* Freeman), and data from population research on the eastern spruce budworm (*Choristoneura fumiferana* Clem.) were used to describe the interaction; we do not suggest that the simulations mimic population dynamics of either budworm. Rather, we describe a very simple and general process that may pertain to other defoliators, with the aim of demonstrating the potential of simulation studies as aids in decisionmaking in forest insect pest management problems.

COMPONENTS OF THE PEST MANAGEMENT SYSTEM

Ideally a pest management system can be envisioned as a large model composed of different components or submodels. These components describe various biological and socio-economic processes and are linked in a manner to show the primary pathways of information flow that lead to decisionmaking. The nature of the linkages is important because inputs from one submodel can be the parameters for another.

The generalized forest pest management system model shown in *figure 1* has two structures—an inner research and development core and an outer "management" structure. Our computer simulations focus on four components of the research and development core:

- Mathematical models of the population dynamics of the pest insect and its parasites.
- Mathematical functions for impact (usually damaging) of different population levels of the pest insect on generalized forest product yields or values.
- Estimates of the effectiveness of various control factors (parasites, insecticides) in suppressing and in preventing high populations of the pest insect.
- An economic framework for cost-benefit analyses of the various control options.

Our simulations do not include the forest stand dynamics component because it adds more complexity than we desire or need for our purpose. However, we will discuss this component below along with the others because it provides the linkage between the pest population dynamics and impact components. The impact and control components provide direct inputs into cost-benefit analyses required for decisionmaking on pest management activities within the forest resource management system. A more detailed description of these system components is given by Waters and Stark (1980).

Population Dynamics

Generally, models of population dynamics of pest insect species show how insect mortality is affected by population densities and forest conditions and identify key mortality agents. These models may indicate which mortality agents have the greatest potential for biological control. Generally these agents—parasites, predators, or disease-causing organisms—are density-dependent; that is, they respond to population changes of the pest insect species. Their potential can be enhanced occasionally by management actions, and although they may not adequately suppress epidemic pest populations, they may be effective in regulating low or endemic pest populations. Models of population dynamics may indicate how natural enemies of the pest may be made more effective. Perhaps some of the potentially more effective parasites are themselves regulated by alternate hosts or hyperparasites.

These models show whatever relationships may exist between insect survival and forest stand variables such as size and age of host trees, forest composition or habitat types, crown levels, stand densities and basal area, aspect, and topography. Consequently, the models serve to indicate the stand management or silvicultural treatments that may produce forest conditions less favorable to population increases of the pest insect. The models are also designed to mimic the effects of various kinds and dosages of chemicals. In particular, they describe the influence of these chemicals on the effectiveness of parasites, predators, and disease-causing organisms in controlling pest insect populations.

Forest Stand Dynamics

Models of stand dynamics and biomass production portray the ecological impact of pest population density levels, and of the duration of feeding injuries, on a variety of forest conditions or habitat types.

For example, defoliating insects consume the leaves of forest trees. If this activity is severe and sustained, it can lead to growth reduction, stem dieback, stunted and deformed trees, and eventually tree mortality over small or large areas. Defoliation can also reduce competition among surviving forest trees, however, and thus result in increased tree growth. The residual stand may actually be more productive than it would have been without the insect activity. Defoliation can increase the fall of nutrient-rich litter, stimulate the activity of decomposer organisms, and increase light penetration to the forest floor, thereby increasing the survival of seedlings, and the production of forage, or both. Defoliation can also increase water yield from the area.

Whether a particular level of insect activity is beneficial or injurious depends on the forest management objectives and plans of different ownership and user groups, the costs of effective control, the costs of alternative management plans if current plans are made unfeasible, and the vagaries of the market place. Economic impact models serve to determine values (losses and gains) affected by insect activities within the forest stand in relation to specific forest management plans.

Economic Impact

A model of economic impact describes both the values produced by forests under specific management plans and procedures and the influence of insect pest populations on this value production. Little or no economic damage may be caused by heavy defoliation over a short period of time, or severe damage may result from moderate defoliation over an extended period of time. The direct and indirect economic effects of defoliation by a forest insect pest species may be immediately obvious or may not be measurable until the end of the rotation period. Under certain conditions we may occasionally find that low to moderate pest population levels add value to forest stands by the end of the rotation period.

Economic impact models guide decisionmaking for control activities by establishing a means of benefit-cost analysis, leading to more efficient use of resources. The concept of "economic threshold" is a useful part of any benefit-cost analysis, and may be defined as the level at which the loss caused by the pest insect population just exceeds in value the cost of the control measures available (Geier and Clark 1961). Obviously, economic impact models must encompass the costs and effectiveness of various control strategies, including no control, and the short- and long-term value saved or lost by different control strategies initiated at different population densities and different times during the outbreak.

Control Systems

The effectiveness of the various materials, organisms, and techniques of vegetation management that either directly suppress insect pest populations or inhibit further population increase may be modeled as a control system. Materials applied include insecticides, microbials, and behavioral chemicals. Computer simulation of the control system can help in the evaluation of the effectiveness of various dosage levels of different materials on the pest insect and nontarget organisms.

Insecticides differ in their uses, properties, advantages, and restrictions. Predictions of the fate of each insecticide in various environments and effects on target and nontarget organisms can be made on the basis of the correlation of toxicological, chemical, and physical properties for each insecticide with the physical and biological environment and the representative phylum and order of organism treated. Computer simulation can aid the development of control systems that will allow the resource manager to use those insecticides that are currently available more intelligently and judiciously to avoid serious problems, and will help the researcher to develop more ecologically acceptable insecticides.

Direct control of insect pests by chemicals tends to be least expensive in the short run compared to other kinds of controls. If used repeatedly, however, chemical control decreases in effectiveness as pest populations become more resistant and economic and environmental costs increase. Direct control by certain biological organisms tends to be expensive in the short run, but if the organisms subsequently become established and effectively keep pest population levels below the economic threshold, then this control method becomes least expensive in the long run. Environmental costs associated with most forms of biological control are small.

If we include the environmental costs in with the economic costs of control, then some combination of biological and chemical control could be part of an optimal pest management program. To achieve this, information on the interaction of chemicals and various biological organisms such as parasites would be required. Modeling these interactions and the economic costs of control may allow us to devise optimum control strategies and policies for use of chemicals and other controls.

An optimal pest management program would distribute available controls (singularly or in combination) so that costs associated with forest product damage, controls, and environmental damage due to controls are minimized. An example of how the methods of optimal control theory can be applied to the problems of pest management and the results which may be expected has been described by Vincent (1975).

STRUCTURE OF THE MODEL

The basic structure of the model used for the present simulation is

$$N_{t+1} = N_t SC_t SG_t (1 - RP_t) F_t$$

in which

N_{t+1} = number of pest insects at time t + 1
SC_t = survival rate for the exposed population, N_t, from insecticidal applications during the interval from t to t + 1
SC_t = survival rate for the exposed population, N_t, from other factors during the interval t to t + 1
RP_t = mortality rate for N_t from parasitism during the time interval
F_t = reproductive rate for N_t during the time interval.

The following general assumptions are made:

1. The pest host insect-parasite system is closed, with neither immigration nor emigration.
2. Generation survival (SG) is a constant.

These assumptions are unrealistic. Many unconsidered factors affect system dynamics. For example, death results from weather and from predation, disease, and accident. In real systems, many of these mortality agents are density dependent. Also, the intensity of many of them is determined by extrinsic or accidental events which affect population levels at various stages of an insect generation.

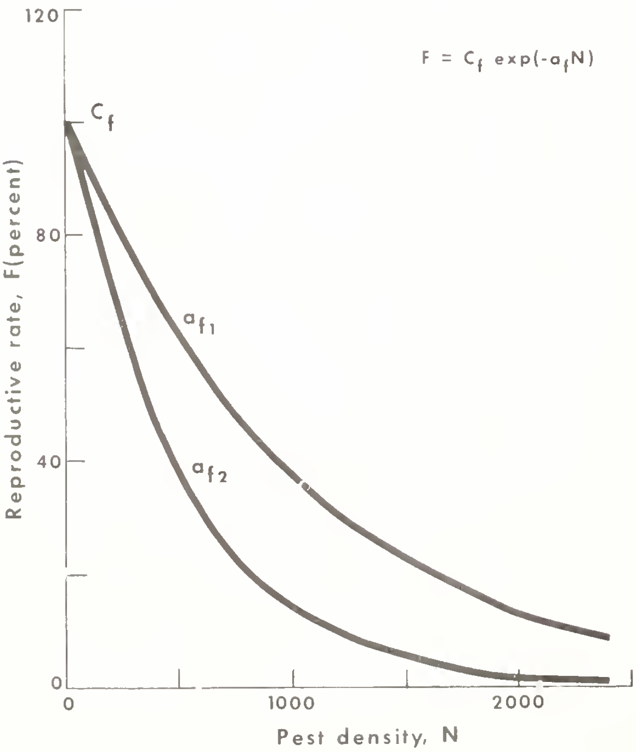


Figure 2—Fecundity function $F = C_f \exp(-a_f N)$; $C_f = 100$.

These two assumptions are necessary, however, because our intention here is to study certain simple effects. Our main rationale is that these merit attention before studies of compound effects.

3. SC—survival of pest insect under insecticidal control—is a constant in each simulation run, for a given case (set of system values), but varies from case to case.

4. F—reproductive rate—varies in response to density, N. It is assumed *(fig. 2)* that F has an upper limit (C_f) when density approaches zero, and that F diminishes exponentially at a rate a_f as N increases, such that

$$F = C_f \exp(-a_f N)$$

F is not permitted to decrease at very low population density as a result of mating failure or other phenomena affecting the reproductive process. The general form of this relation closely resembles natural events, however, and it is an acceptable approximation for our present purpose.

5. Parasite attack and adult parasite population dynamics are as defined by Watt (1959):

$$NA_t = P_t K[1 - \exp(a_p N_t P_t^{1-b_p})]$$

in which

NA_t = number of host insects attacked in generation t
P_t = number of adult parasites present in generation t
a_p and b_p = constants for parasite effectiveness
K = maximum attacks per parasite

For a complete discussion of the derivation of this model, see Watt (1959); for examples of its application see Miller (1959) and *figure 3*. The constant a_p describes the parasite's searching ability in the absence of competition, and b_p describes competition among parasites for opportunities to attack hosts.

Briefly, the attack rate per parasite, NA/P, can attain a maximum, K, and diminishes as the ratio of hosts per parasite, N/P, diminishes.

We assume that parasite attack occurs early in the host's generation, that the survival of the parasite and that of the host are identically affected by the mortality factors, except for the insecticide applied, and that, after emergence, parasites are subject to an additional mortality factor (C_p, see assumption 7) before attacking the next generation of host insects.

6. Natural control of the pest host insect population results from reductions in reproductive rate (F) and from the effects of parasites, RP.

When some insecticides are applied against some forest pests, particularly immature stages of the spruce budworms containing developing parasites, differential mortality occurs among parasitized and nonparasitized insects (Eaton and others 1949; MacDonald 1959; Carolin and Coulter 1971; Williams and others 1969, 1979). The sur-

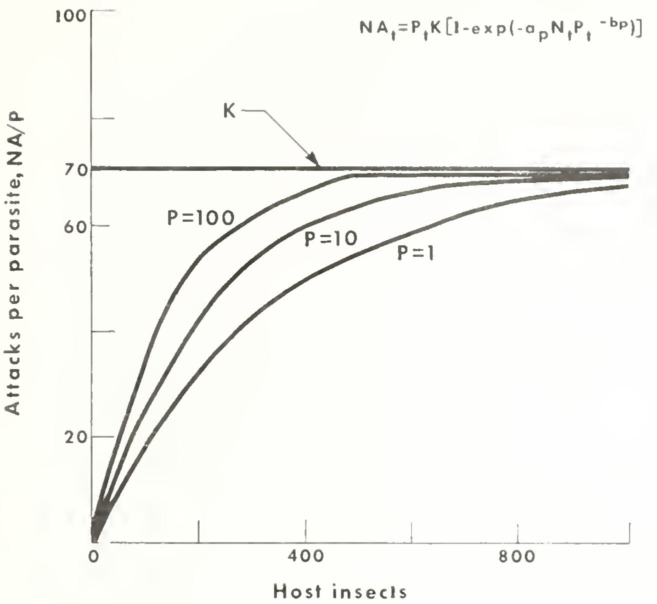


Figure 3—Number of attacks per parasite, NA/P as host-parasite ratio varies. $NA_t = P_tK[1 - \exp(-a_pN_tP_t^{1-b_p})]$

vival rate of the relatively inactive, moribund parasitized larvae is higher because they are less exposed than the nonparasitized insects to other mortality factors, such as the insecticide spray droplets. This interpretation is particularly relevant for 5th and 6th instar western spruce budworm larvae parasitized by *Apanteles fumiferanae* Viereck and *Glypta fumiferanae* Viereck (Williams and others 1969, 1979). These parasites attack the 1st and 2d instars of the budworm, and except for some early emergence of *A. fumiferanae* from the 4th instar, their progeny emerge from 5th and 6th instars. A 5th- to 6th-instar budworm containing a fully developed parasite about to emerge is usually inactive and moribund. These host larvae are probably not as much exposed to insecticide droplets and residues as normal, highly mobile, actively feeding 5th to 6th instars.

We included this phenomenon in our model by making the insecticide more effective, by factor E, against nonparasitized than parasitized insects *(fig. 4)*. The following relations then hold:

If

PP = proportion of insects parasitized before spraying
PN = proportion not parasitized before spraying
RP = proportion parasitized after spraying
SC = survival rate of total insect population from spraying
LP = survival rate of parasitized insects from spraying
LN = survival rate of nonparasitized insects from spraying
E = ratio of LP to LN

then

$$LP - (E\,LN) = 0$$

$$(LP\,PP) + (LN\,PN) = SC$$

and

$$E(PP + PN) = \frac{SC}{LN}$$

$$RP = \frac{LP\,PP}{SC}$$

Solving for LP, LN, and RP yields

$$LN = \frac{SC}{1 + (E - 1)PP}$$

$$LP = E\,LN$$

$$RP = \frac{E\,PP}{1 + (E - 1)PP}$$

The relation between RP and PP for various values of E is shown in *figure 4A*. Analyses of data from Williams and others (1979) support our contention that E is dependent on SC. If this relation is valid, E is certainly dependent on the timing, method and quality of insecticide application, the type and physical properties of the insecticide, and the specific host-pest-parasite system under consideration.

We chose the relation $E = e^{a_e SC}$ *(fig. 4B)* because it is based on observed fact (Williams and others 1979) and logical reasoning. Experiments to test this hypothetical relation are particularly needed because the phenomenon has a profound effect on the results of simulation of insecticide applications in an integrated control program.

7. Our model component for changes in parasite populations subjected to insecticide treatments while in the host budworms reflects the differential survival of parasitized budworms over nonparasitized budworms, as well as other factors previously described.

$$P_{t+1} = C_pN_tSC\,RP = C_pN_tSC\left(\frac{E\,PP}{1 + (E - 1)PP}\right)$$

in which

C_p = parasite mortality in adult stage, and

$$PP = \frac{NA_t}{N_t}$$

8. An element in the system to be simulated is the degree of damage to the resource. We assume that each year the pest population produces some damage to the resource—damage that will occur either in the year of attack, or in some future year—for example, growth reduction in a perennial crop; or proportional mortality in an annual crop. Several cases are discussed below.

9. The following relations were used to derive the cost function: First, a relation usually exists between the dos-

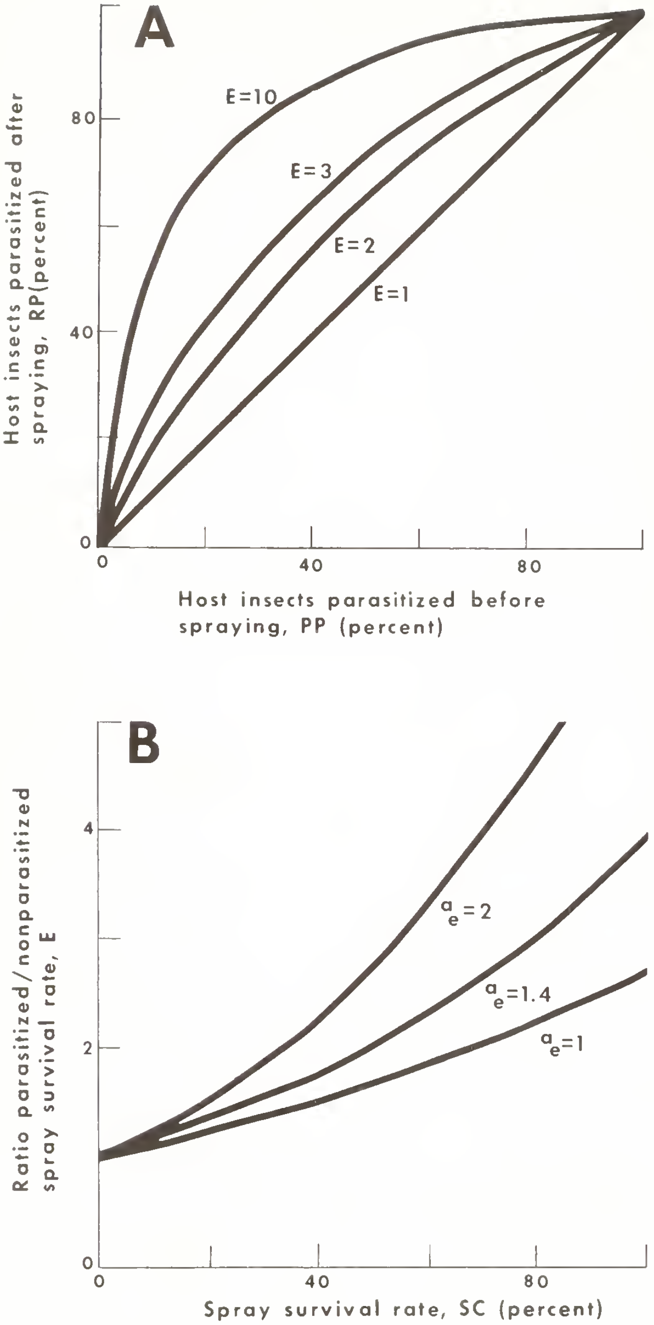


Figure 4—*(A)* Relationship between RP and PP as factor E varies. E is the ratio of the survival rate of the parasitized insects from spraying to that of the nonparasitized insects from spraying. *(B)* Relationship between E and SC for various values of a_e, a constant representing rates of increase ($E = e^{a_e SC}$).

age of any insecticide and the proportional mortality secured. Conventionally, a probit mortality, logarithmic dosage transformation produces an approximately linear relationship (Goldstein 1964, Finney 1971). We assumed a simpler relationship, that of an asymptotic exponential. The result assumes a greater effectiveness for insecticides at low dosages than is ordinarily obtained, and thus, a lower cost for any specified level of control below 50 percent. For the purposes of this study we will exclude any environmental or social cost of using insecticides.

The function for cost was obtained as follows:

$$(1 - SC) = e^{-a_c INS}$$

in which

a_c = constant which establishes proportionality between units—that is, numbers or percent of insects killed and pounds of insecticide applied

INS = amount of insecticide.

Solving the above for INS, we obtain

$$INS = \frac{\ln SC}{-a_c}$$

or solving for mortality $(1 - SC)$, we obtain

$$1 - SC = \frac{INS}{a_c}$$

For applying insecticide, as in aerial spraying, the costs incurred are fixed costs (FX) plus a variable amount proportional to the amount of insecticide applied (including application cost, cost of insecticide and so forth). Thus

$$COST_t = FX + C_c\left(\frac{\ln SC}{-a_c}\right)$$

in which C_c = variable cost per unit of insecticide.

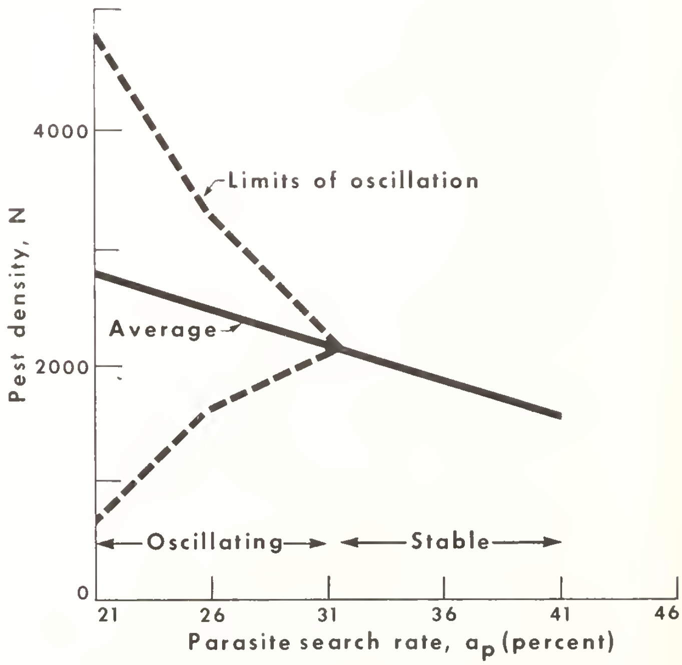


Figure 5—Result of varying parasite effectiveness constant a_p after 200 generations.

SIMULATIONS

To demonstrate the applicability of system simulation in integrated pest management in forestry, we conducted simulation runs using data drawn from the literature and analytic procedures developed from our study of the problem. The results of these simulations serve to illustrate certain basic points:

1. Intelligent multiple-use forest resource management (with respect to pest control) requires the development and early application of analytic methodology such as that represented by the simulations.

2. Forest insect population biologists must provide information in the form required by the analytic methodology referred to in 1, above.

3. The nature of the pest-forest interaction, and the estimated value of the damage caused to specific forest products by different population levels of the pest insect, must be known if the simulation is to be useful.

The values used in the experimental simulations were obtained from Miller (1959):

SG (generation survival from factors other than insecticides) = 0.4
C_f (upper limit of reproductive rate) = 0.100
a_f (rate that F diminishes exponentially) = 0.001
K (maximum attacks per parasite) = 0.70
b_p (constant for parasite effectiveness) = 1.8
C_p (added mortality factor for parasite after emergence) = 0.1
FX (fixed cost of insecticide) = 0.50
C_c (variable cost per unit of insecticide) = 0.50
a_c (constant for proportionality between units of insects killed and amounts of insecticide applied) = 0.001

Variation in Parasite Search Rate (a_p)

The model produces both stable and oscillating population densities after 200 generations, depending upon the value of a_p, the constant representing the parasite's searching efficiency. *Figure 5* depicts these results. In general, as a_p increases, the system becomes more stable, and the average or steady density decreases with increased parasite attack effectiveness. These results demonstrate that pest management can be obtained by improving parasite effectiveness, either by increasing the vulnerability of the host insect or the searching effectiveness of the parasite, or by finding new parasites with more effective searching abilities. Studies are needed, however, to test the feasibility of such efforts. The costs and benefits of the studies themselves must be investigated, with reference to their net effects on the host-parasite system. The accuracy of the model must also be tested, by examination of the effects of varying its parameters. Subsequently, additional biological studies are needed to estimate the costs of modifying promising parameters.

Variation in Insecticide Survival Rate (SC)

The results of modifying both SC and a_p are shown in *figure 6A*. First, the intercept values on the y axis represent the values plotted in *figure 5*. Note that there is a separate curve for each value of a_p, relating pest density to SC. SC decreases from left to right—that is, mortality due to insecticide increases from left to right.

Two types of cases are possible. The first type includes those in which a_p has values which permit the system to oscillate. In these cases, a two-branched curve shows the limits of the oscillation. The second type includes those in which the values of a_p produce a stable system. In the oscillating system, as insecticide is applied at increasing levels, the amplitude of the oscillations changes. At the lower insecticide levels, amplitude increases; at higher levels, it decreases until a level is reached where the system becomes stable. The level at which the oscillation attains maximum amplitude increases with increasing parasite effectiveness. The level which produces a steady system decreases with increasing parasite effectiveness.

Similarly, in steady density systems, as insecticide levels increase, the steady density increases, then it decreases. The level which produces the maximum density increases as parasite effectiveness increases.

These results illustrate the need for a relevant framework for the development of methods for controlling insect population and minimizing forest pest impact. From the cases described by these simulations, it is evident that since damage is related to insect density, it may be more profitable to leave the system alone than to attempt control with low insecticide dosage rates.

A particularly important result is shown in *figure 6B*. The degree of steady density reduction obtained by increasing levels of control is plotted against the mortality rate. Clearly, the level of population suppression obtained is not proportional to the amount of control applied in the generation. Only when very high control rates or insecticide dosages are applied is much effect produced in the population. It appears that very high investments are worthwhile but moderate investments produce little effect.

A final important result from these simulations is the indication that parasites become extinct when sufficient insecticide is applied (SC = 0.13) to cause 87-percent mortality. At this point each host-parasite system behaves in the same way in response to the insecticide dosage, and all curves in *figure 6A* coalesce. In a real system, the presence of alternate hosts and invasion of parasites from surrounding untreated areas may maintain or reestablish the parasite population.

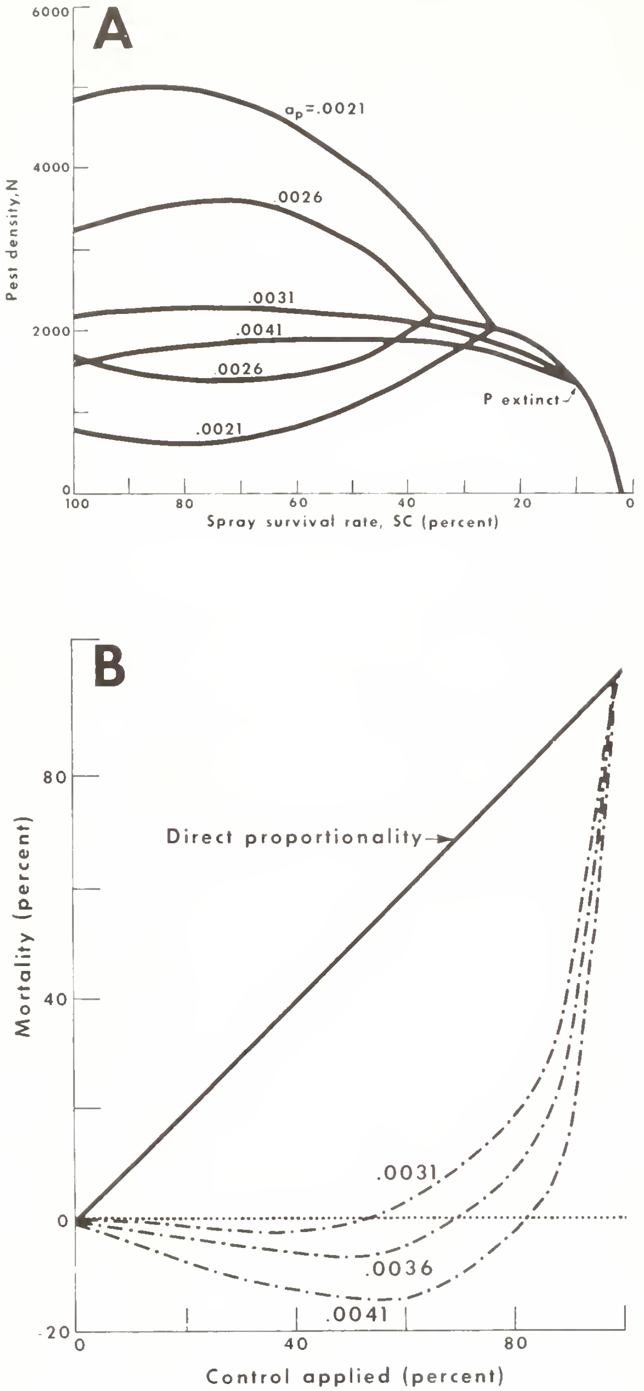


Figure 6—*(A)* Relationships between pest density and SC for various values of a_p. *(B)* Relationship between percent control applied with insecticides and actual reduction in population level for various values of a_p after 200 generations.

OPTIMIZING PEST MANAGEMENT

The preceding discussion suggests that the behavior of the pest-parasite population system under insecticidal control is complex; suppression of the pest is not proportional to insecticide dosage rate.

The most economical pest population level achievable through control can only be determined through cost-benefit analyses of the impact of pest insect populations on forest product values. First consider a simple example of the relation between damage value and pest density. We know that without insecticidal control our pest population has a density that depends on the parameters of the model, and that if $a_p = 0.0031$, the steady density is 2150. In *figure 7A* three similar cases are depicted in which there are simple linear relationships between the value of damage to different forest product values and pest density. Consider case A with pest density 2150 and value of damage about 350 units. If pest density is reduced to 0, all of this value will be gained. A linearly proportional gain occurs at intermediate pest densities. In case B, the maximum gain is greater—about 50 units, and in case C, a very high gain is possible.

In *figure 7B* these three gain curves are described as a function of pest density. The cost of obtaining this pest density, calculated as explained above, is also shown. Clearly, in case A, any insecticidal control operation will yield a net loss—the gain function is always less than the cost function. In case B, pest control does not become profitable until pest density is reduced to about 700; then there is a region of increasing net gain to a maximum, followed by a region of decreasing net gain to a point beyond which control rates that result in very low densities are again unprofitable.

In case C, in which there is a very rapid increase in gain as pest density declines, it will be maximally profitable to practice the highest possible rate of control because the point at which the gain function curve exceeds the cost function curve the most (point of maximum net gain) is in the vicinity of the intercept. Otherwise, some lower rate of population suppression is maximally profitable.

This simplified example demonstrates several fundamental points:

1. The cost and gain functions are necessary to determine optimal control rates.

2. The cost function cannot be derived without a thorough knowledge of the consequences of attempting population control. Results may not be those expected. In more realistic cases—where there are compound interactions among the mortality sources, or where integrated control through manipulation of several factors of mortalities or control methods is to be attempted—it will be necessary to observe and analyze system response in far greater detail than can be shown here.

3. The best control decision is based on the form of both he gain function and the cost function. The gain function lepends on the relation between damage value and pest lensity in this case. This relationship, of course, is an mportant problem in insect impact studies. In this examble we are concerned with the relation between insect densities and damage values. More generally, we must be concerned about relationships which depend on density, ime of attack relative to the development of values in the ree species, physical location of attacks in timber, the nteraction between pest control activities and the yield of other forest resource values, and so forth. Ultimately, we must be able to compute real cost and real gain in the system.

Consider an additional factor which complicates the simple linear density example. In *figure 8A* a threshold effect has been added to the previous linear case. Two different threshold densities, below which no damage occurs, are introduced. The consequences *(fig. 8B)* are that the point of maximum net gain is always less than complete control.

In additional simulation runs, we added more complexity to our examples by showing a curvilinear relationship between the amount or value of damage and pest density in order to represent a situation where low insect populations or densities provide some benefit in forest value production. In *figure 8C,* the lower curve represents a situation in which there is actually some gross gain (a negative damage) from a low pest density. Clearly *(fig. 8D),* high control rates would not be selected. On the other hand, the upper curve in *figure 8C* would indicate a very high control rate.

In summary, we have clearly shown the kinds of data required for determining insect control strategies in timber management. The primary requirements are

- A thorough knowledge of the pest system, including effectiveness of natural control agents, and the consequences of introducing various degrees or rates of control into that system.
- The effectiveness and costs of alternative methods of control required to obtain various degrees of population reduction.
- An understanding of the relationship between pest population levels and units of damage.
- Knowledge of the value of the resource and units of damage.
- Ability to develop the cost and gain functions necessary to determine optimal control rates.

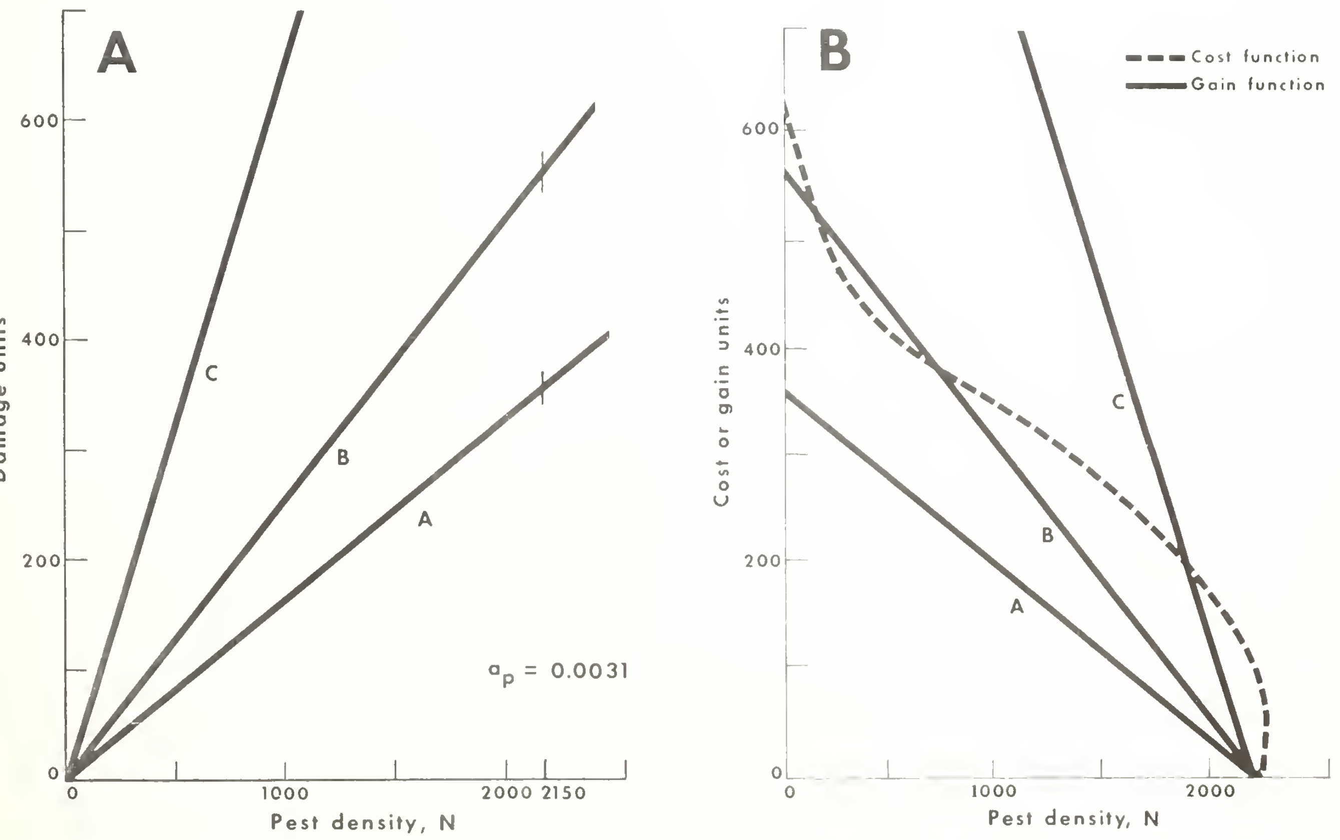


Figure 7—*(A)* Linear relation between the amount or value of damage and pest density for three cases of the parasite-host-pest system, with $a_p = 0.0031$. The steady density of the pest population is 2150. *(B)* Relationships between the gain curves of three cases or situations and pest density for the parasite-pest system: $a_p = .0031$, and cost curve for the amount of control required to reduce the pest density from 2150 to 0.

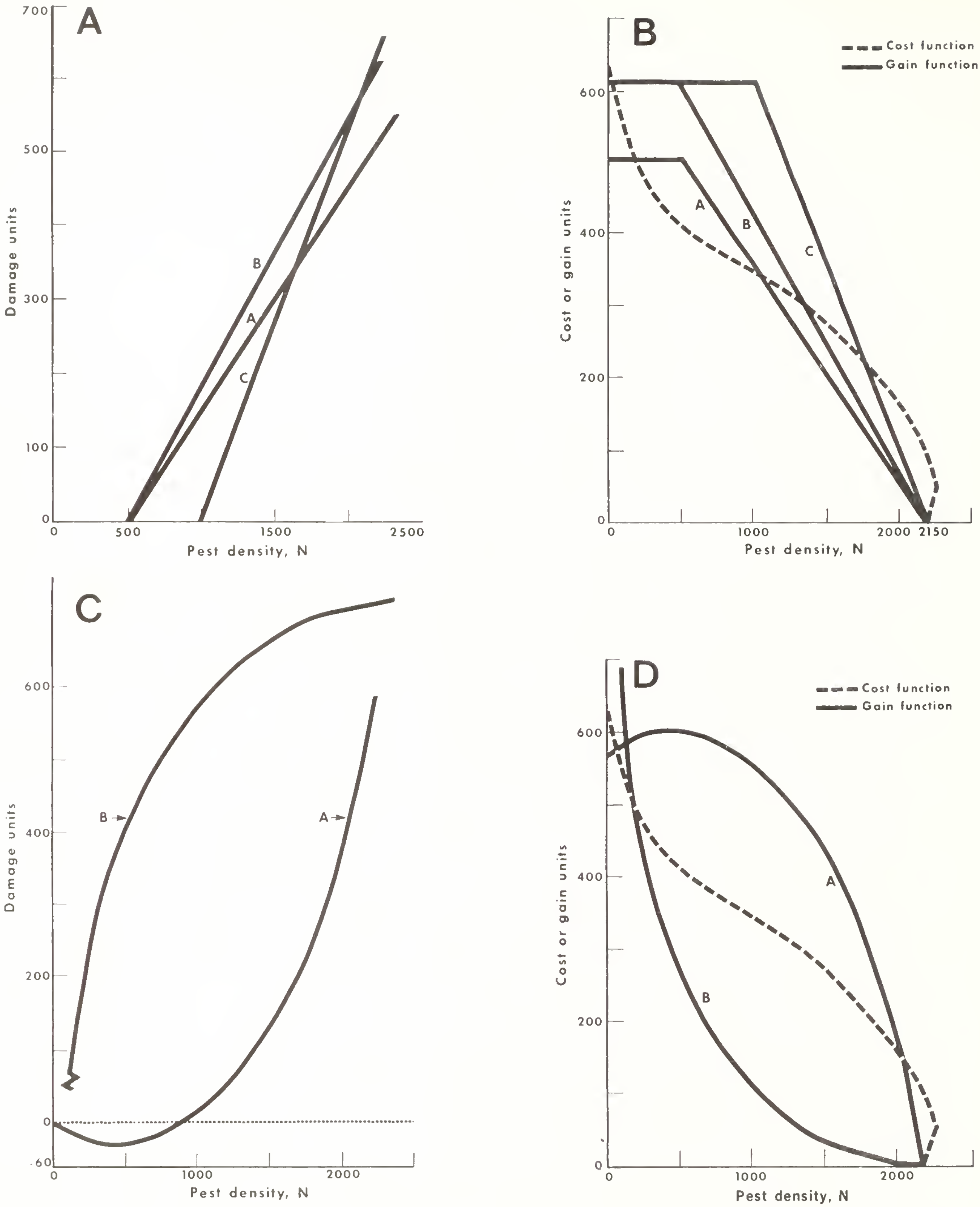


Figure 8—*(A)* Relationships between the amount or value of damage for the parasite-pest system (a_p = .0031) where no damage occurs until the pest population density reaches 500 (cases A and B) and 1000 (case C). The steady density for the pest population is 2150. *(B)* Relationship between the gain functions of cases A and B with a pest density threshold of 500 and case C with a pest density threshold of 1000, and cost curves for the amount of control required to reduce pest density of the parasite-pest system (a_p = .0031) from 2150 to 0. *(C)* Curvilinear relationship between the amount or value of the damage and pest density for the parasite-pest system: a_p = .0031. The steady density of the pest population is 2150. Situation A represents small gains (negative damage) at pest densities from 0 to 800. *(D)* Relationship between the gain functions of cases A and B, pest density for the parasite-pest system: a_p = .0031, and cost curve for the amount of control required to reduce the pest density from 2150 to 0.

Perhaps the most important points that we have demonstrated are the analytical methodology necessary to determine the relationship between certain kinds of information required in decisionmaking for pest control, and the usefulness of computer simulation in experimenting with mathematical representatives of real world systems to predict the consequences of various management decisions.

REFERENCES

Berryman, A. A.; Pienaar, L. V. **Simulation: a powerful method of investigating the dynamics and management of insect populations.** Environ. Entomol. 3(2):199-207; 1974 April.

Campbell, Robert W. **Developing a pest population management system.** Proceedings of the Tall Timbers conference on ecological animal control by habitat management; 1971 February 25-27; Tallahassee, FL. Tallahassee, FL: Tall Timbers Res. Stn; 1972; 9-20.

Campbell, Robert W. **The conceptual organization of research and development necessary for future pest management.** In: Stark, R. W.; Gittens, A. R., eds. Pest management for the 21st century. Nat. Res. Series 2. Moscow, ID: Idaho Res. Found., Inc.; 1973: 23-38.

Carolin, V. M.; Coulter, W. K. **Trends of western budworm and associated insects in Pacific Northwest forests sprayed with DDT.** J. Econ. Entomol. 64(1):291-297; 1971 February.

Eaton, C. B.; Beal, J. A.; Furniss, R. L.; Speers, C. F. **Airplane and helicopter spraying with DDT for spruce budworm control.** J. For. 47(10):823-827; 1949 October.

Finney, D. J. **Probit analysis.** 3d ed. London: Cambridge University Press; 1971. 333 p.

Geier, P. W.; Clark, L. R. **An ecological approach to pest control.** Proceedings of the 8th technical meeting of the International Union for Conservation of Nature and Natural Resources, 1961; Warsaw, Poland. 1961; 10-18.

Goldstein, Avram. **Biostatistics. An introductory text.** New York: Macmillan Publishing Co., Inc.; 1964. 272 p.

Holling, C. S. **An experimental component analysis of population processes.** Memoirs Entomol. Soc. Can. 32:22-32; 1963.

Holling, C. S. **The analysis of complex population process.** Can. Entomol. 96(1-2):335-347; 1964 January-February.

Holling, C. S. **The functional response of invertebrate predators to prey density.** Memoirs Entomol. Soc. Can. 48:3-86; 1966.

Kilgore, W. V.; Doutt, R. L. **Pest control, biological, physical and selected chemical methods.** New York: Academic Press; 1967. 447 p.

MacDonald, D. R. **Biological assessment of aerial forest spraying against spruce budworm in New Brunswick III: Effects on two overwintering parasites.** Can. Entomol. 91(6):330-336; 1959 June.

Miller, C. A. **The interaction of the spruce budworm, *Choristoneura fumiferana* (Clem.), and the parasite *Apanteles fumiferanae* Vier.** Can. Entomol. 91(8):457-477; 1959 August.

Mott, D. Gordon. **Future pest management systems.** In: Stark, R. W.; Gittens, A. R., eds. Pest management for the 21st century. Nat. Res. Series 2. Moscow, ID: Idaho Res. Found., Inc., 1973; 73-92.

Pickett, A. D.; MacPhee, A. W. **Twenty years experience with integrated control programs in Nova Scotia apple orchards.** Proceedings of the 12th International Congress on Entomology. London; 1971. 597 p.

Van den Bosch, R. **Pesticides: prescribing for the ecosystem.** Environment 12(3):20-25; 1970 April.

Vincent, Thomas L. **Pest management programs via optimal control theory.** Biometrics 31:(1)1-10; 1975 March.

Waters, William E. **Evaluation of insect impacts on forest productivity and values.** Proceedings of the XVI IUFRO World Congress, Group 6; 1976 June 24; Oslo, Norway. Moscow, ID: University of Idaho; 1976; 15-18.

Waters, William E.; Ewing, Bland. **Development and role of predictive modeling in pest management systems—insects.** Tummala, Ramamohan L.; Haynes, Dean L.; Croft, Brian A., eds. USA/USSR Symposium on long-term and short-term prediction models of insects, phytopathogens, and weed populations as they relate to crop loss; 1974 July 16-18. East Lansing, MI: Michigan State Univ.; 1976; 19-27.

Waters, William E.; Stark, Ronald W. **Forest pest management: concept and reality.** Ann. Rev. Entomol. 25:479-509; 1980.

Watt, K. E. F. **A mathematical model for the effect of densities of attacked and attacking species on the number attacked.** Can. Entomol. 91(3):129-144; 1959 March.

Watt, K. E. F. **Mathematical models for use in insect pest control.** Can. Entomol. Suppl. 19; 1961. 62 p.

Watt, Kenneth E. F. **Computers and the evaluations of resource management strategies.** Amer. Sci. 52(4):408-418; 1964 December.

Watt, Kenneth E. F. **Ecology and resource management.** New York: McGraw Hill Book Co.; 1968. 450 p.

Williams, Carroll B., Jr.; Walton, Gerald S.; Tiernan, Charles F. **Zectran and naled affect incidence of parasitism of the budworm *Choristoneura occidentalis* in Montana.** J. Econ. Entomol. 62(2):310-312; 1969 April.

Williams, Carroll B., Jr.; Shea, Patrick J.; McGregor, Mark D. **Effects of aerially applied mexacarbate on western spruce budworm larvae and their parasites in Montana.** Res. Paper PSW-144. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1979. 14 p.

Williams, Carroll B., Jr.; Shea, Patrick J. **Computer simulation for integrated pest management of spruce budworms.** Res. Paper PSW-159. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 11 p.

Some field studies of the effects of various insecticides on the spruce budworm (*Choristoneura* sp.) and their parasites have shown severe suppression of host (budworm) populations and increased parasitism after treatment. Computer simulation using hypothetical models of spruce budworm-parasite systems based on these field data revealed that (1) effective parasites produce greater stability in budworm populations than ineffective ones and are more resistant to changes induced by insecticides; and (2) the level of budworm population suppression in most budworm-parasite systems is not proportional to the amount of insecticide applied. Only high insecticide dosages produce any effect on the budworm population. Cost-benefit analyses showed that very high investments are worthwhile, but moderate investments produce little effect. The study demonstrated that the computer simulation process helps to define kinds of information needed for understanding the budworm-parasite system, and can predict system behavior under varying conditions.

Retrieval Terms: spruce budworms, insecticides, parasites, integrated pest management

United States
Department of
Agriculture

Forest Service

**Pacific Southwest
Forest and Range
Experiment Station**

Research Paper
PSW-160

Xylem Monoterpenes of Some Hard Pines of Western North America: three studies

Richard H. Smith

Author:

RICHARD H. SMITH is in charge of this Station's research on the biology, ecology, and control of destructive forest insects, with headquarters in Berkeley, California. He holds B.S. (1942) and M.S. (1947) degrees from New York State University, College of Forestry, and a Ph.D. degree (1961) from the University of California, Berkeley. He has been with the Station since 1955.

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

August 1982

Xylem Monoterpenes of Some Hard Pines of Western North America: three studies

Richard H. Smith

CONTENTS

IN BRIEF...

Smith, Richard H. **Xylem monoterpenes of some hard pines of Western North America: three studies.** Res. Paper PSW-160. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 7 p.

Retrieval Terms: xylem monoterpenes, *Pinus ponderosa, P. coulteri, P. jeffreyi, P. torreyana, P. sabiniana, P. montezumae, P. hartwegii, P. rudis, P. pseudostrobus, P. durangensis, P. cooperi, P. engelmannii*

Copious production of xylem resin is characteristic of pines. The terpene fraction of this resin is suspected of being a defense mechanism in some pines; it also appears to be under strong genetic control. Thus, investigations of it can be useful for information on both genetics and host relationships. Studies were made to determine (1) the within-tree monoterpene composition of single stems, forks, and grafts; (2) the monoterpene composition of seven species of pines from Mexico growing in California; and (3) the number of trees required in a plot for estimates of local variation, and the comparative accuracy of short- and long-column gas chromatographic analysis.

All analyses were of normalized monoterpene composition of xylem resin using a thermal conductivity gas chromatograph and pentane solutions of whole resin.

Within-tree studies showed negligible and insignificant variation with varying vertical location in both single and forked stems of 40-year-old Jeffrey and Coulter pines and in forked stems of ponderosa pine. Within-tree constancy of single stems of ponderosa pine was reported earlier. Much of the intertree variation in Jeffrey pine is found only in heptane, which varies from 85 to 96 percent; the remainder of the composition is small amounts of nonane, α-pinene, camphene, β-pinene, 3-carene, sabinene, myrcene, limonene and β-phellandrene. All of these vary from less than 1 percent to 3 percent but with β-phellandrene as high as 6 percent. Coulter pine, however, has significant intertree variation: α-pinene (29 to 48 percent), sabinene (2 to 5 percent), myrcene (5 to 23 percent), limonene (2 to 10 percent), β-phellandrene (24 to 35 percent), and terpinolene (0 to 5 percent); five other components—heptane, nonane, camphene, β-pinene, α-phellandrene—are usually less variable and less than 5 percent. Ponderosa pine had a large intertree range in the percent of α-pinene, β-pinene, 3-carene, myrcene, and limonene. Hybrids of Jeffrey × ponderosa also showed little intratree variation in single stems and forks.

Analysis of 20-year-old grafts of Jeffrey on ponderosa and Digger on ponderosa (with graft unions at about 2 m) showed negligible variation in the monoterpene composition of the scion, but the root stock had monoterpene characteristics of both species. The effect of the scion on the root stock diminished with distance below the graft union. A graft of ponderosa on Jeffrey was quite different in that both scion and root stock showed only monoterpene characteristics of ponderosa. A graft of Torrey on ponderosa was made near the ground line. The scion showed only Torrey pine characteristics and variation was negligible; samples could not be obtained from the root stock.

Seven species of pines from Mexico were studied using 6-year-old trees growing in the nursery at the Institute of Forest Genetics near Placerville, California. Of these seven, only *P. durangensis* showed little intertree variation; but only two trees were available and both had about 96 percent α-pinene. Three of the remaining six species showed large intertree variation in α- and β-pinene as follows: *P. engelmannii*—α-pinene 49 to 94 percent, β-pinene 3 to 49 percent; *P. cooperi*—α-pinene 26 to 96 percent, β-pinene 2 to 69 percent; *P. montezumae*—α-pinene 76 to 98 percent, β-pinene 1 to 22 percent. The other three showed large variation in four or more components as follows: *P. hartwegii*—α-pinene 2 to 94 percent, β-pinene 1 to 60 percent, 3-carene 0 to 80 percent, limonene 0 to 64 percent; *P. rudis*—heptane 0 to 32 percent, α-pinene 6 to 79 percent, β-pinene 0 to 69 percent, 3-carene 0 to 33 percent, sabinene 0 to 30 percent, limonene 0 to 76 percent, terpinolene 0 to 19 percent; *P. pseudostrobus*—heptane 0 to 42 percent, nonane 2 to 10 percent, α-pinene 22 to 98 percent, β-pinene 1 to 37 percent, 3-carene 0 to 30 percent, limonene 0 to 34 percent. In addition to this variation in individual components, there is considerable range in types of composition.

This study does little to resolve the problem of the taxonomy of the pines of Mexico, but it does point out the large variation in monoterpene composition and the need for further study.

More than 1500 trees were used in a study of the local variation of the types of monoterpene composition of ponderosa pine in northeastern California. The results suggest that 80 trees are adequate for determining average composition, but are inadequate for determining the distribution and abundance in types of individual tree composition. About 350 trees are necessary for this last determination.

A short-column analysis (about 3 min) was found to be almost as accurate as a long-column analysis (about 12 min). The short-column analysis was based on converted peak height values. When a code system was used to express total monoterpene composition of a tree, the short column was 97 percent correct in determining individual code values and 86 percent correct for determining the types of composition of a five-component mixture. Thus, the short column is suitable for screening large numbers of trees in localized areas.

Copious production of xylem resin is a distinctive characteristic of the genus *Pinus*. The composition of the terpene fraction of the resin appears to be under fairly strong genetic control, and information about it can be useful, therefore, in genetic studies. Knowledge of monoterpene composition is also valuable in investigation of the role of the resin in general, and the terpenes in particular, as a defense mechanism in the ecology of pine (Smith 1972).

This paper reports results of several studies and relates them to earlier work. The first study examined within-tree variation in monoterpene composition of several California pine species. Evidence that xylem monoterpene resin is constant with varying positions within the tree would have application to both genetic theory and the design of biological studies. Both constancy and variation have been found in pines; for example, ponderosa (*Pinus ponderosa* Doug. ex Laws.) is constant in both time and place within a tree (Smith 1968); slash pine (*Pinus elliottii* Engelm.) is variable in certain trees (Squillace 1976).

The second study was an analysis of the monoterpene composition of 6-year-old trees of seven pine species growing at the Institute of Forest Genetics near Placerville, California, from seed collected in Guatemala and Mexico.

The third study examined two elements of procedure in the study of monoterpene composition: sample plot size and chromatographic analysis.

GENERAL PROCEDURES

Some of the procedures used to obtain, process, and analyze resin samples were similar in all three studies, and are described here. Procedures specific to a particular study are noted in the report of results.

Sample Collection

Resin was obtained in one of two ways depending on the size of the tree. Trees greater than 10 cm d.b.h., which included all the California species, hybrids, and grafts, were tapped with a 1.41 cm bit and brace. The hole was drilled, at a slight upward slant, through the outer bark and phloem and 0.6 to 1.3 cm into the xylem. The hole was cleared of debris, and a 5-cm^3 vial was placed in the hole so that the lip was past the phloem tissue. Except where noted in studies which sampled trees at varying heights, all taps were made 1.0 to 1.3 m above the ground. The vial was removed 6 to 24 hours after tapping. Up to 0.5 cm^3 of fresh resin was placed in a half-dram screw-cap vial with an approximately equal volume of chromatographic quality pentane. The vial was agitated to produce a homogeneous clear liquid ready for chromatographic analyses.

The resin sample from the Mexican pines, which were 6 to 7 years old, was obtained by cutting the tree off in the third internode back from the tip. A ring of cortex about 6 mm wide was removed from the wood just below the cut to prevent contamination of the xylem resin by cortex resin. The cross sectional surface was made clean and smooth by careful removal of a thin slice of about 0.5 mm of wood; the cut also increased resin flow. Within minutes resin began to exude onto the surface of the cross section. Within an hour or two after the cut was made, a drop of this resin was carefully picked up with a clean glass rod and placed in a half-dram vial. An approximately equal volume of pentane was added to the vial and agitated. The tightly sealed vials were held at about 3° C for periods as long as 4 to 6 months before analysis.

Chromatographic Analysis

All samples were analyzed by gas liquid chromatography using a thermal conductivity detector. Operating temperatures were 135° to 145° C on the injector, 60° to 70° C on the column, 145° to 155° C on the detector. There was a flow of helium of 30 to 40 ml per minute at the outlet port. All columns were stainless steel with a diameter of 3.1 mm; the short columns were 1.7 m in length and the long columns 4.0 m. All columns had a solid phase of 100 to 110 Chromosorb W AW and a liquid phase of 5 percent b,b'-oxydipropionitrile. None of these variables was associated with any differences in the results of qualitative or quantitative analysis. The standard analysis required 12 to 15 minutes on the long column; the short analysis required about 3 minutes on the short column.

Peak areas of the standard chromatogram were used for quantitative analysis; these were derived from disk integrator values and then normalized for each sample to express each monoterpene component as a percentage of the total monoterpene content.

For the short column analyses, peak heights with appropriate conversion factors were used to obtain the percent composition (Smith and Greene 1971). The short column chromatogram was also used to guide and check the standard analysis.

WITHIN-TREE VARIATION IN COMPOSITION

Five groups of trees growing at the Institute of Forest Genetics, Placerville, California, were studied by sampling at different vertical positions on the main stem. The internode length varied from about 30 to 45 cm. Trees sampled were 8 Coulter pines (*P. coulteri* D. Don.) 35 years old; 10 Jeffrey pines (*P. jeffreyi* Grev. & Balf.) 35 years old; 3 Jeffrey × ponderosa pine hybrids 30 years old; 10 forked trees (7 ponderosa, 2 Jeffrey, 1 Jeffrey × ponderosa hybrid); and four 20-year-old grafts of Jeffrey, ponderosa, Digger (*P. sabiniana* Dougl.), and Torrey (*P. torreyana* Parry) pines.

The monoterpene composition of all species and hybrids examined is quite constant with differing locations within a tree (*table 1, fig. 1*). This result closely resembles findings for ponderosa pine (Smith 1968) and several other pines (Squillace 1976). The evidence now points to constancy rather than variation in this characteristic in many pines, although some pines do have variation (Squillace 1976) past the juvenile stage.

Considerable change in composition was seen in the grafts, depending on the point of sampling and the species (*table 2*). In all grafted trees, the scion held true to the general species composition, but the root stock was affected by the scion. This was also found for slash pine (*P. elliottii*) (Squillace and Fisher 1966). In Digger or Jeffrey pine grafts on ponderosa, the samples from the ponderosa root stock within 1 m of the union had all the characteristics of Jeffrey or Digger but none of ponderosa. More than 1 m below the union, however, the composition was a mixture of both scion and stock. This condition suggests possible movement of precursors from the scion to the stock, or the slow movement of scion resin across the union; in 20 years the scion resin had moved about 1 to 2 m. The fact that there was no evidence of root stock resin less than 1 m below the union suggests possible slow loss and replacement of resin over long periods.

Table 1—*Normalized percent monoterpenes in xylem resin by species from within-tree vertical samples selected to represent the trees studied*[1]

Tree and internode[2]	Heptane	Nonane	α-pinene	Camphene	β-pinene	3-carene	Sabinene	α-phellandrene	Myrcene	Limonene	β-phellandrene	γ-terpinene	Terpinolene
							Percent[3]						
							Coulter pine						
1-12	0.4	0.5	34.3	0.5	3.9		2.7	0.9	15.6	6.7	32.5		2.0
24	0.6	0.7	30.6	0.7	3.9		2.7	0.9	17.4	5.8	34.7		2.0
36	1.1	1.1	29.2	0.7	4.9		2.0	0.6	18.5	5.8	34.5	t	1.7
6-12	0.7	0.5	44.7	0.5	3.5		4.8	0.7	5.3	6.7	28.0		4.6
24	0.6	0.5	48.5	0.5	3.6		3.4	0.4	5.6	10.2	24.3		2.3
36	0.2	0.2	46.3	0.8	3.5		4.0	0.6	5.0	10.3	26.6		2.6
8-12	0.2	0.2	36.7	0.5	3.2		0.5	0.4	23.2	2.2	32.7		
24	0.4	0.4	37.7	0.7	3.4		0.5	0.4	21.1	2.7	32.6		
36	0.4	0.4	36.5	0.7	4.1		0.3	0.4	21.5	2.5	33.1		
							Jeffrey pine						
2-12	93.2	1.1	1.1	0.1	1.1	0.1	t		0.4	t	3.0		
24	93.0	1.4	0.6	0.2	1.4	0.3	t		0.3	t	2.9		
36	93.3	1.4	0.5	0.1	1.2	0.4	t		0.3	t	2.9		
6-24	83.7	1.1	1.0	0.3	3.4	1.2	0.9	t	1.6	0.6	6.1		
36	88.2	1.3	0.6	0.3	3.0	0.9	0.4	t	0.9	0.4	3.9		
7-12	96.5	0.2	0.2	0.1	0.9	0.1	0.1		t	0.5	1.6		
24	96.8	0.3	0.1	0.1	0.8	0.1	0.1		t	0.3	1.6		
36	96.4	0.5	0.2	0.1	0.8	0.1	0.1		t	0.4	1.6		
							Jeffrey × ponderosa pine[4]						
1-10	30.0	1.0	8.0		21.0	24.0			7.0	5.0	1.0	t	2.0
30	35.0	1.0	6.0		18.0	21.0			8.0	6.0	1.0	t	1.0

[1]Three of 8 Coulter pines, 3 of 10 Jeffrey pines, and 1 of 3 Jeffrey × ponderosa hybrids.

[2]Internodes are counted from the terminal.

[3]t = trace.

[4]Two percent undecane was found for both internodes.

The mixing pattern did not hold true in grafts of ponderosa pine on Jeffrey. Here, there was no evidence of the Jeffrey root stock resin even nearly 1.7 m below the union; both scion and stock had only ponderosa characteristics. Because the union of the Torrey pine scion with ponderosa stock was just above the ground line, it was not possible to get a sample of the stock. Above the union it was fully Torrey pine. Unfortunately, these trees were cut before sampling and analysis could be made to check on any changes in these conditions.

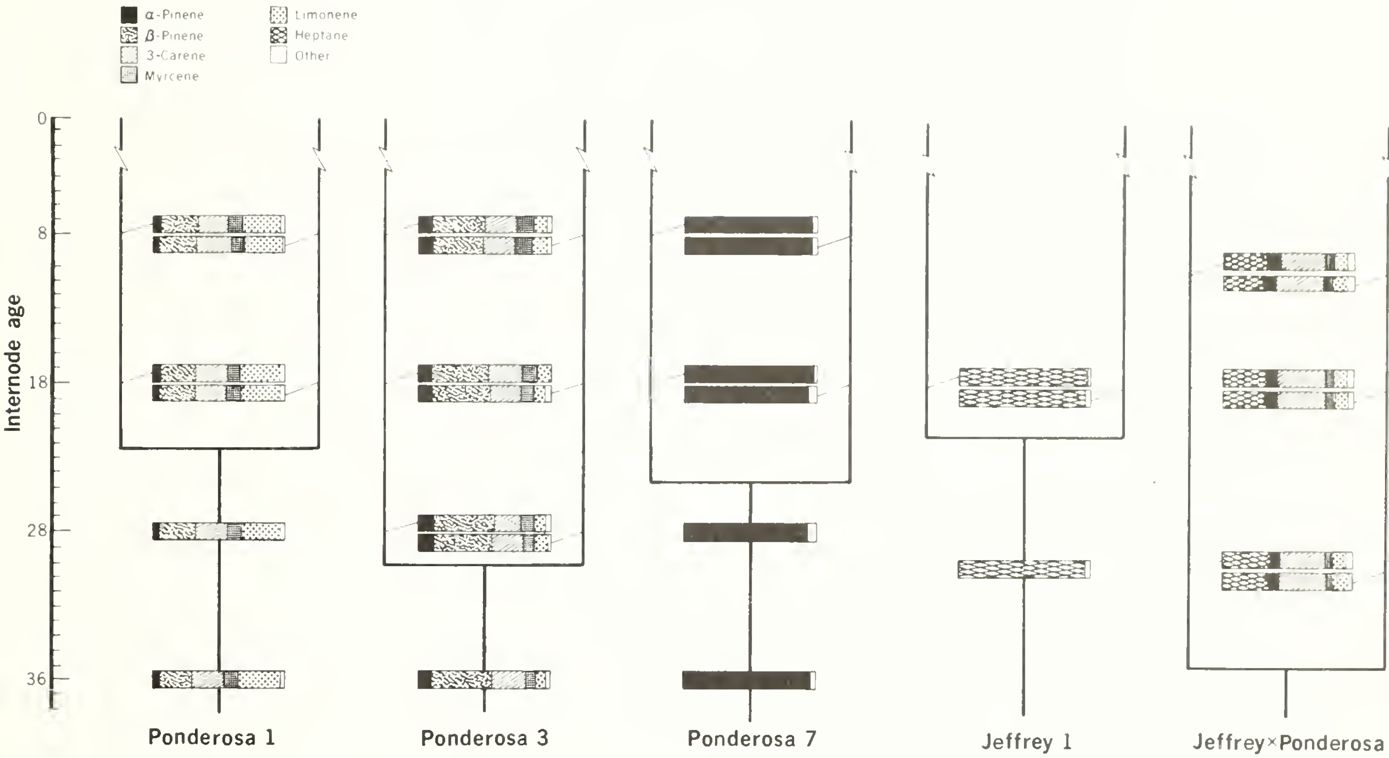


Figure 1—Normalized monoterpene composition of the xylem resin at different heights of forked trunks of selected pines. Each multishaded bar equals 100 percent of the monoterpenes.

Table 2—*Normalized xylem monoterpene composition of within-tree samples taken at specified distances above the ground on four 20-year-old grafts (arrow shows location of graft union)*

Monoterpene	Jeffrey on ponderosa				Ponderosa on Jeffrey					Digger on ponderosa				Torrey on ponderosa	
	5.0 m	3.3 m	2.0 m	0.7 m	7.0 m	5.0 m	3.3 m	2.0 m	0.7 m	5.0 m	2.8 m	2.0 m	0.7 m	2.0 m	0.7 m
	Percent[1]														
Heptane	98	98	↓94	70				↓		99	99	↓97	81		↓
α-pinene	t	t	t	2	8	8	8	8	8	t	t	t	1	3	3
Camphene	t	t	t	t	29	29	29	29	29	1	1	1	1	10	9
β-pinene	t	t	2	10	50	49	49	50	49			1	4	2	
3-carene	t	t	2	12	7	7	7	7	7			1	8	1	
Myrcene	2	2	2	4	3	3	3	3	4			8	2	4	4
Limonene	t	t	t	2	1	t	1	1	t			t	3	81	85
β-phellandrene		t	t	t	t	t	t	t	t				8		
γ-terpinene			t	t											
Terpinolene			t	t	2	3	3	3	3						

[1]t = trace.

MONOTERPENES IN HARD PINES OF MEXICO

Earlier studies of some of the Mexican pines did not establish the value of the terpenes in resolving their taxonomy. In a preliminary study of the monoterpenes of Mexican pines (Mirov 1961), samples were obtained by open-faced collection, often bulked for several trees in order to obtain sufficient resin for analysis, which did not include gas chromatographic procedures. Later, gas chromatographic analysis provided reports on *P. hartwegii* Lindl. (Williams and Bannister 1962); on *P. durangensis* Martinez, *P. montezumae* Lamb, and *P. pseudostrobus* Lindl. (Manjarrez and Guzman 1964); and on *P. engelmannii* Carr. and hybrids of ponderosa with *P. engelmannii* and with *P. montezumae* (Smith 1967).

The present study made use of the five species mentioned above, with the addition of *P. rudis* Endl. and *P. cooperi* E. E. Blanco. All were grown in the 1966 and 1967 nursery of the Institute for general study. The identification of the seed-bearing parents is based on determinations by qualified botanists. Seed was collected in 1963 and 1964 from trees growing in Mexico; some additional seed of *P. pseudostrobus* was collected in Guatemala. Six-year-old plants were analyzed for monoterpenes in 1972-73 as a preliminary study of the species.

Xylem resin samples were obtained (see general procedures) from the 3-year-old internode of 182 6- to 7-year-old trees. Samples were analyzed on a short column for guidance and on the standard long column for calculations. For concise summary for each species, data were averaged in certain obvious appropriate groupings of composition.

The types of composition that could be identified by inspection for each species (*table 3*) showed a fairly narrow range of values for a given assigned value for a component. The data in this preliminary study do not seem sufficient to justify listing of standard deviations. Some examples of the range of values for an assigned value are as follows:

Species (n):	Component	Assigned value	Range
P. engelmannii (5)	α-pinene	94	90-97
	β-pinene	3	1-7
P. cooperi (7)	α-pinene	47	38-54
	β-pinene	49	42-60
P. hartwegii (9)	α-pinene	30	20-40
	myrcene	3	1-4
	limonene	64	45-75

Two general observations can be made from the data in *table 3*. First, there is a wide range in composition and compositional types, despite the relatively small number of trees sampled, particularly in *P. hartwegii*, *P. rudis*, and *P. pseudostrobus*, which show large variations within a single State and from State to State. Second, the previously reported composition types were found and were fairly common in every species. However, many distinctly new types of composition were found for six of the species: *P. engelmannii*, 1; *P. cooperi*, 2; *P. montezumae*, 1; *P. hartwegii*, 6; *P. rudis*, 14; *P. pseudostrobus*, 11.

Five types of composition are of particular note:

1. A large percentage of limonene was found in several trees of *P. hartwegii*, *P. rudis*, and *P. pseudostrobus*. Some of these types also have moderate amounts of α-pinene, and are much like those found in a few ponderosa pines in Arizona.

2. Two high sabinene types were found in *P. rudis*, in a total of six trees. Again, similar types were found in several ponderosa pines in southeastern Arizona. The approximate one-to-one relation between sabinene and terpinolene, which has been noted for ponderosa pine (Smith 1977), prevailed in one set of these trees (13 to 15); in the other set, the relation was about one and one-half to one (30 to 19).

3. A number of trees of *P. rudis* and *P. pseudostrobus* had heptane and nonane along with several terpenes. This type might be expected of a hybrid of Jeffrey and ponderosa pine from southeastern Arizona, or a cross between ponderosa pine and *P. montezumae* reported by Smith (1967).

4. All species except *P. rudis* have trees which can be termed high in α-pinene (greater than 94 percent α-pinene).

5. Five of the species, *P. engelmannii*, *P. cooperi*, *P. hartwegii*, *P. rudis*, and *P. pseudostrobus*, have trees with nearly equal amounts of α-pinene and β-pinene, with small amounts of other terpenes.

The pines of Mexico are rich in variety of composition types, but until further and more detailed studies are made, the value of monoterpenes in clarifying the taxonomy of these pines remains uncertain.

Table 3—*Normalized monoterpene composition of the xylem resin of assigned types of composition of seven hard pines native to Mexico*

Pinus species	Trees[1]	Heptane	Nonane	α-pinene	Camphene	β-pinene	3-carene	Sabinene	Myrcene	Limonene	β-phellandrene	Terpinolene	Seed source[2]
		Percent[3]											
P. engelmannii	5(m,s)			94	1	3		t	1	t	t		Ca
	1			49	t	49			1	1	1		Ca
P. durangensis	2(m,mg)			96	1	1		t	t	1	1		Ca
P. cooperi	7(m)			47	1	49	1	t	1	1	1		D
	2			26	t	69		t	1	1	2		D
	1			96	1	2			1	1	t		D
P. montezumae	23(m,mg)			98	1	1	t	t	t	t			MS
	3			76	1	22			1	1	t	1	MS
P. hartwegii	9(m)			30	1	2			3	64		t	MS,NL
	8(w)			12	t	1	80		2	1	t	5	MS
	7			32	t	1	43		3	19	t	2	NL
	6			66	1	3		2	2	26	t	t	MS,NL
	4			39	1	2	53		1	t	t	3	MS,NL
	4			34	t	60	3		1	1	1	t	NL
	2			94	1	2		t	3				MS,P
	2			18		1	57		4	17	t	3	MS
P. rudis	15(m)			28	1	69			1	1	1		NL,T,P
	4			34	1	6	t	30	5	4	t	19	NL
	3	9	3	79	1	3	2		3				NL
	2	2	3	13	1	50	2		2	26			NL
	2(m)	11	4	13	2	14		13	2	28	1	15	NL
	1	4	2	60	1	t	4		1	24			NL
	1	9	1	57	2	28			3	t	t		NL
	1	32	2	57	2	5			1				MS
	1			55	1	2			t	42			NL
	1			50	1	1	33		2	11	1	2	NL
	1	20	1	29		45	4		1		1		NL
	1			21	2	5			2	70	t		NL
	1			17	3	45	2		2	30	1	t	NL
	1	14	2	11	1	3	9		4	54		t	NL
	1	8	4	6	2	t	t		4	76			NL
P. pseudostrobus	23	38	7	49	t	3	1		1	t	t		O,P,Mi
	9(m)			98	1	1			t	t			Cs,G
	6			61	t	37	1		t	t	t		Ca,Cs G, Mi, P
	6	27	6	47	t	18			1	t	t		O,P
	4	10	6	75	t	7	1		1		t	1	O,P
	4	36	5	26	3	5	1	t	1	23			P
	2	14	8	44	t	5	30		2	t	t	1	Mi,P
	2	20	3	26		16			1	34			P
	1(mg)			90	t	10							G
	1	42	10	25	t	23			1	t	t		T
	1	21	2	24		9	28		1	14			Mi
	1	47	7	22		4	18		1			1	P

[1]This approximate composition type has been reported as noted: m = Mirov (1961); w = Williams and Bannister (1962); s = Smith (1967); mg = Manjarrez and Guzman (1964).

[2]States in Mexico are Ca, Chihuahua; D, Durango; MS, Mexico State; NL, Nuevo Leon; O, Oaxaca; T, Tlaxcala; P, Pueblo; Mi, Michoacan; Cs, Chiapas. G is Guatemala.

[3]t = trace.

RESEARCH PROCEDURE STUDIES

Sample Plot Size

In an earlier report (Smith 1977), the relation of plot size to frequency distribution of the percentages of the five major monoterpenes of ponderosa pine—α-pinene, β-pinene, 3-carene, myrcene, and limonene—was examined. No appreciable change in distribution was found between a plot of 78 trees and one of 641 trees. The conclusion was that an 80-tree plot was adequate for determining the average level of occurrence for these components. Because the number of compositional types was slightly larger for the larger plot, however, additional data were gathered from three more plots to test the earlier conclusion. These plots, containing 366, 377, and 94 trees, were in the same general forest area near Adin Summit on the Modoc National Forest, California, as the two plots sampled earlier.

Chromatographic analysis was designed to allow comparison of results with the earlier work, and also to test the comparative accuracy of short-column analysis as opposed to the standard long-column method (see below). Resin samples from the 78-tree plot had been analyzed on the long column, and those from the 641-tree plot on the short column. Samples from the new plots were analyzed on the short column; in addition, the first 72, 79, and 76 samples from the new plots were analyzed on the long column as well. All analyses were expressed in code form, according to a system defined in the original study (Smith 1977).[1] The normalized percent frequency of each coded type was determined for each plot—that is, the number of trees of each compositional type was expressed as a percent of the total number of trees in the plot. Plots were compared by regression analysis of these normalized values.

The occurrence of composition types in the five plots is given in *figure 2*. All five are correlated with each other between 0.5 and 0.9 (r^2):

Number of trees in plot:	Coefficient of determination (r^2)				
	n = 78	n = 641	n = 366	n = 377	n = 94
78		0.69	0.62	0.55	0.48
641			0.64	0.54	0.55
366				0.89	0.49
377					0.58

Figure 2—Normalized distribution of the compositional types of xylem monoterpenes of 1556 ponderosa pines in five plots near Adin Summit, Modoc National Forest. The sum of the bars for each plot equals 100 percent of the trees in that plot.

There is an evident increase in the types of composition with increase in the number of trees in a plot (*fig. 2*). However, the three largest plots had about the same number of types of composition—between 35 and 38. Thus, it appears that about 350 trees is the optimum size of a plot in this type of forest. But each of these three

[1]Intervals for the code value of each component are as follows (Smith 1977): α-pinene, 0 = 0 to 17.4 percent, 1 = 17.5 to 64.4 percent, 2 = 64.5 to 100 percent; β-pinene, 0 = 0 to 4.4 percent, 1 = 4.5 to 35.4 percent, 2 = 35.5 to 100 percent; 3-carene, 0 = 0 to 15.4 percent, 1 = 15.5 to 35.4 percent, 2 = 35.5 to 100 percent; myrcene, 0 = 0 to 2.4 percent, 1 = 2.5 to 15.4 percent, 2 = 15.5 to 100 percent; limonene, 0 = 0 to 2.4 percent, 1 = 2.5 to 17.4 percent, 2 = 17.5 to 100 percent.

plots has a slightly different array of the kinds and the frequency of tree types. This could be caused by accumulation of three small variations: actual composition in the tree, the gas chromatographic analysis, and the coding procedure.

In the course of the plot study, an effort was made to find trees having the apparently rare high limonene composition type. Three were found (coded as 10022 or 11022, *fig. 2*): one in the first original plot of 78 trees, one more in the second plot, containing 641 trees, and one more in the 366-tree plot. (None was found in the 377-tree plot.) The frequency is thus about one in 500.

Chromatographic Analysis on Short Column

In the plot-size investigation, the use of short column analysis (Smith and Greene 1971) was also tested for rapid surveys of large numbers of trees from the same area. In this testing, the code values derived from the long column analysis were considered the correct values.

The accuracy of the short column, with respect to the long column, was determined on two points: coding of individual component and coding of tree composition. Of the 1135 components (5 components for each of the 227 trees) coded from the short column analysis, 1103 or 97 percent were coded correctly. Of the 227 trees coded from the short column analysis, 195 or 86 percent were coded correctly (*table 4*). This slight inaccuracy is acceptable for rapid survey and classification of a large number of trees in an area. The savings in analysis time can be as much as 20 hours per hundred trees. The coefficient of determination (r^2) between the two types of analyses was greater than 0.9. Most of the incorrectly coded components were either limonene or myrcene. This is to be expected since the chi-square values obtained with previous work were lower for these two than for α-pinene, β-pinene, and 3-carene. The short-column results for two of the plots—about 98 percent correct for components, and about 90 percent correct for composition types—were noticeably better than the results for the third plot at 95 percent and 78 percent respectively.

An inspection of the incorrectly coded components showed all falling a percent or two outside the limit of a code class. Thus, a shift of about 2 percent in the short-column values would have made nearly all analyses correct. One might expect to get differences of somewhat similar magnitude between repeated analyses of the same sample on the same column.

Table 4—*Accuracy of short column analysis as compared to long column, in determining coded monoterpene values and composition types for ponderosa pine*

Trees in sample	Components[1]	Component values correct		Composition types correct	
		Number	Percent	Number	Percent
72	360	354	98	66	92
79	395	386	98	70	89
76	380	363	95	59	78
			$\bar{x}$ 97		$\bar{x}$ 86

[1]There were five monoterpene components for each sample.

REFERENCES

Manjarrez, A.; Guzman, A. **Composicion de aguarrases obtenidos de pinos del Stado de Michoacan.** Bol. inst. quim. univ. nal. auton. Mex. 16:20-26; 1964.

Mirov, N. J. **Composition of gum turpentines of pines.** Tech. Bull. 1239. Washington, DC: U.S. Department of Agriculture; 1961. 158 p.

Smith, Richard H. **Monoterpene composition of pine species and hybrids ... some preliminary findings.** Res. Note PSW-135. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1967. 14 p.

Smith, Richard H. **Intratree measurements of the monoterpene composition of ponderosa pine xylem resin.** Forest Sci. 14(4):418-419; 1968 December.

Smith, Richard H. **Xylem resin in the resistance of the Pinaceae to bark beetles.** Gen. Tech. Rep. PSW-1. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1972. 7 p.

Smith, Richard H. **Monoterpenes of ponderosa pine xylem resin in Western United States.** Tech. Bull. 1532. Washington, DC: U.S. Department of Agriculture; 1977. 48 p.

Smith, Richard H.; Greene, L. E. **Use of peak heights from a fast column for rapid approximation of the normalized monoterpene composition of pine resin.** J. Chromatogr. Sci. 9:755-756; 1971 December.

Squillace, A. E. **Analyses of monoterpenes of conifers by gas-liquid chromatography.** *In:* Miksche, J. P., ed. Modern methods in forest genetics. Berlin: Springer-Verlag; 1976:120-157.

Squillace, A. E.; Fisher, Gordon S. **Evidences of the inheritance of turpentine composition in slash pine.** Pauley, Scott S.; Nienstaedt, Hans, chairmen. Joint proceedings, second genetics workshop of the Society of American Foresters and the seventh Lake States forest tree improvement conference; 1965 October 21-23; Hickory Corners, MI. Res. Paper NC-6. St. Paul, MN: North Central Forest Experiment Station, Forest Service, U.S. Department of Agriculture; 1966; 53-60.

Williams, Allette L.; Bannister, M. H. **Composition of gum turpentines from twenty-two species of pines grown in New Zealand.** J. Pharm. Sci. 51(10):970-975; 1962 October.

Smith, Richard H. **Xylem monoterpenes of some hard pines of Western North America: three studies**. Res. Paper PSW-160. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 7 p.

Monoterpene composition was studied in a number of hard pine species and results were compared with earlier work. (1) Intratree measurements showed strong constancy of composition in both single-stemmed and forked trees of ponderosa, Jeffrey, Coulter, and Jeffrey × ponderosa pines. In grafts of these and other pines, the scion influenced the root stock, but not the reverse. (2) Large intertree variation in composition was found in a small sample of seven hard pines native to Mexico; the value of monoterpenes in clarifying taxonomy of these pines remains uncertain. (3) An 80-tree plot of ponderosa is adequate to determine average monoterpene composition. For the best estimate of the kinds and abundance of types of composition, a 350-tree plot is needed. Short-column chromatographic analysis is acceptably accurate for rapid classification of a large number of samples.

Retrieval Terms: xylem monoterpenes, *Pinus ponderosa*, *P. coulteri*, *P. jeffreyi*, *P. torreyana*, *P. sabiniana*, *P. montezumae*, *P. hartwegii*, *P. rudis*, *P. pseudostrobus*, *P. durangensis*, *P. cooperi*, *P. engelmannii*

Research Paper PSW-161
is available on microfiche
located in cabinets behind
information desk on third
level.

Research Paper PSW-162
in out of print and no
longer available to our
library.

United States
Department of
Agriculture

Forest Service

**United States
Department of
Agriculture**

Research Paper
PSW-163

Optimum Use of Air Tankers in Initial Attack: selection, basing, and transfer rules

Francis E. Greulich William G. O'Regan

The Authors:

FRANCIS E. GREULICH is an associate professor of forestry, University of Washington, Seattle. He earned bachelor's degrees in forestry (1965) and mathematics (1965) at Oregon State University, and master's (1967) and doctoral (1976) degrees in forestry at the University of California, Berkeley. **WILLIAM G. O'REGAN** was, until his retirement in 1977, Station biometrician and a lecturer at the College of Natural Resources, University of California, Berkeley, where he earned bachelor's (1949) and doctoral (1962) degrees in agricultural economics.

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245
Berkeley, California 94701

December 1982

Optimum Use of Air Tankers in Initial Attack: selection, basing, and transfer rules

Francis E. Greulich **William G. O'Regan**

CONTENTS

IN BRIEF . . .

Greulich, Francis E.; O'Regan, William G. **Optimum use of air tankers in initial attack: selection, basing, and transfer rules.** Res. Paper PSW-163. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 8 p.

Retrieval Terms: air tanker model, initial attack, resource allocation

The air tanker is an extremely effective fire suppression resource when used during the early stages of fire growth, but it is also expensive. Cost-effective allocation of this resource relies on two interrelated decisions: selection of particular air tankers for the season, and their assignment to home bases. Also, the possibility exists of daily reassignment of air tankers in anticipation of fire occurrence.

This paper reports a study to develop a mathematical model that would assist fire managers in assigning air tankers throughout the fire season.

The solution to this resource allocation problem is a mixed integer linear program consisting of two types of variables—integer and continuous. Integer variables represent the assignment of particular air tankers to specific home bases. Continuous variables define the probabilities of assigning specific air tankers to specific air bases contingent upon fire conditions for a given day.

Fire information that controls daily air tanker transfer and allocation decisions is viewed as a Markov process. The data may be derived from any number of relevant sources, such as National Fire Danger Rating values, lightning counts, and the number of on-going fires.

Air tanker output for a specific assignment may be specified by the model user. These output estimates will be based in part on the given fire-day conditions. The objective of the model, therefore, is to maximize the output of the entire air tanker system over the fire season.

This seasonal output of the air tanker system is limited by several constraints, foremost of which is the annual budget. The cost of contracting and operating a fleet of air tankers must not exceed available funds. Steady state conditions are also imposed. Included among these conditions are normalization and non-negativity constraints. The restrictive character of these steady state constraints lessens as length of fire season increases. Other constraints may be imposed to further control budget and air tanker allocations.

The computerized model was tested by using the air tanker system of District 1, California Division (now Department) of Forestry. This district, headquartered in Santa Rosa, includes all of northern coastal California. Three air bases serve as home bases for air tankers, from which initial attack sorties may be made on fire: Rhonerville, in Humboldt County; Ukiah, in Mendocino County; and Sonoma County, at Santa Rosa. The model uses a fourth air base to represent release from standby condition. The air tanker system consists of five aircraft available for contract: two F7F's and three TBM's. These aircraft have different costs and outputs associated with their use, and differ in their possible home base assignments. The expected period of air tanker use is 107 days, from July 1 through October 15.

The model was tested at nine annual budget levels, of which one level—for $152,000—was examined in detail. The results verified the mathematical structure of the model. They also showed that the computer programs needed to generate the data structure, solve a mixed integer linear program, and interpret the solution can be written and executed. The results also suggest the adequacy of the model in describing and solving a real-world situation. The model permits a more general and realistic portrayal of the decision process within an air tanker program than has been heretofore possible.

Chemical retardants dropped from air tankers can be effective in fire suppression—especially during the early stages. But the maintenance and operation of aircraft are expensive. To use air tankers efficiently, fire managers must anticipate each day the likely patterns of fire occurrence, and must transfer aircraft to forward bases accordingly. Before the fire season starts, they must decide on appropriate aircraft to contract and where to base these air tankers. Their decisions depend upon several factors, including expectations about fire occurrence patterns throughout the season, transfer and use rules, and budget levels for the air tanker program.

This paper reports the development of a mixed integer linear program model to assist the manager of a wildfire suppression program in seasonal and daily assignment of air tankers. It describes the application of the model in District 1 of the California Division (now Department) of Forestry. The model is a more generalized form of a procedure given by Manne (1960).

MATHEMATICAL MODEL

Early in any given day during the fire season, the manager assesses the status of the air tanker fleet. The air tankers are assigned to air bases for that given day, as determined by several known factors, including

- Present location of each aircraft
- Type of fire-day
- Probability distribution of projected fire-day conditions
- Transfer costs, use costs, and productivity for each aircraft, airbase, and fire-day condition.

Aircraft assignment is made according to a transfer/use rule which maximizes expected output subject to such constraints as budget and aircraft availability.

Payment is based on the level of daily use, which includes the cost of transferring an air tanker between bases and the per diem cost of overnight stays away from its home base.

At the beginning of the fire season, air tankers are contracted and assigned to home bases. Air tanker assignments and the amount of funds allocated to the program imply specific daily transfer/use decisions. Both the seasonal and daily decisions should be so made that the total cost of operating the air tanker program for the season does not exceed budgeted funds, and expected output of the air tanker program remains as high as feasible for anticipated expenditures. A mixed integer linear program (MILP) model provides the framework for analysis and solution of the problem.

Variables

The model uses two different types of variables—integer and continuous. Variable values of interest are those assumed when the objective function attains its highest value over the feasible range as delimited by the set of constraints on air tanker activity. From these variable values are obtained the optimal decision rules for the specified model. (See the Glossary for definitions of all variables.)

A binary variable, D(I,JH), assigning air tanker I to airbase JH as its home base, is defined as equal to one if affirmative. In all other cases it is zero. The range of the index, I, is from 1 through IMAX. These variables represent the seasonal allocation decision. If D(I,JH) is zero for all air bases {JH} for any given air tanker I, it implies that air tanker I will not be used during the coming fire season. The set of air bases {JH} considered feasible home bases for air tanker I will generally depend on air tanker I, because rarely are no restrictions encountered on the assignment of aircraft to home bases.

A continuous variable, X(J1,J2,K2:I,JH), is defined over the closed interval [0,1]. It may be interpreted as the probability that air tanker I, which has home base JH, will be at J1 on the morning of some randomly selected day, that fire-day condition K2 is observed early in the day, and that the air tanker is then sent to airbase J2. It is possible, of course, that J2=J1. Constraints discussed later permit the probabilistic interpretation of this variable. The daily transfer/use decision rules are then easily derived from the optimum values of X(J1,J2,K2; I,JH):

$$X(J2 \mid J1,K2,I,JH) = \frac{X(J1,J2,K2,I,JH)}{\sum_{J2} X(J1,J2,K2,I,JH)} \qquad (1)$$

These values are the conditional probabilities of sending air tanker I, which has home base JH, to air base J2, given that the air tanker is currently at air base J1 (stationed there from the previous day), and that fire condition K2 has been observed. In almost all cases this value will be either zero or one. This situation is attributed to the model structure and greatly facilitates application of the derived decision rules.

Objective

The manager then selects those air tanker-home base combinations that, in conjunction with optimal expected daily decisions about air tanker usage, will be the most cost-effective. On any randomly selected day during the fire season the air tankers under contract are at specific air bases. Each air tanker I has an expected output, Q(I,J2,K2) which is sharply related to its assigned air base, J2, and the observed fire-day condition, K2. The objective, then, is to maximize expected output, Z, of all air tankers on any randomly selected day during the fire season:

$$Z = \sum_{I} \sum_{JH} \sum_{J1} \sum_{J2} \sum_{K2} X(J1,J2,K2;I,JH)Q(I,J2,K2) \qquad (2)$$

That is, the expected output for each air tanker-home base combination (I,JH) is obtained by summing the output function Q(I,J2,K2) over the probability space given by the frequency function X(J1,J2,K2;I,JH).

Constraints

The constraints define both the external limits on total system activity and the internally imposed restrictions on subsystem activity. For the basic mathematical model, the following constraints have been identified as the minimal necessary set.

An air tanker under contract can be assigned to only one home base. To enforce this restriction, a constraint is given for each air tanker I:

$$\sum_{JH} D(I,JH) \le 1 \qquad (3)$$

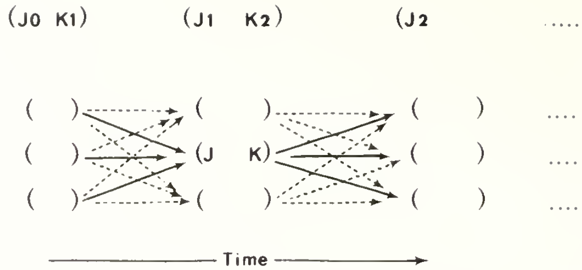
That is, the binary variable D(I,JH), when summed over the set of potential home bases {JH} for air tanker I, must be less than or equal to one.

It is assumed that the time series of fire-day conditions can be adequately described by a first-order Markov process. The probability, g(K2|K1), of observing fire-day condition K2 on any day depends only on the previous day's condition, K1. On any randomly selected day, designated as day 2 of a 2-day sequence, the state of the process for any specified air tanker-home base combination (I,JH) is given as (J1,K2). The index J1 designates the air base assignment prior to transfer. The index K2 is the fire-day condition observed on that same day. The system may be illustrated as follows:

(J1,K2)
(1,1)
(1,2)
(1,3)
(2,1)
(2,2)
(2,3)

In the above example, two air bases and three fire-day conditions give six possible states for the air tanker process. On the basis of the given state of the process, a decision (J2) is made to assign the air tanker to a particular location for that day.

Time is then brought into the diagram:



The arrows (both dotted and solid) represent the possible transitions from the states on one day to the states on the next. Attached to each arrow is a probability (to be calculated) of making any given transition. From this diagram, the steady state condition can be written. The probability of entering any arbitrary state, denoted as (J,K) and indicated by the converging solid lines, must equal the probability of leaving the same state, indicated by the solid diverging lines. Converging and diverging probabilities may be written as, respectively:

$$\sum_{K1} \left[g(K2=K|K1) \cdot \sum_{J0} X(J0,J1=J,K1;I,JH) \right]$$

and

$$\sum_{J2} X(J1=J,J2,K2=K;I,JH)$$

In order for steady state conditions to hold, the probability of entering a particular state must equal the probability of leaving. This condition must hold for every possible state; namely, the arbitrary state (J,K):

$$\sum_{J2} X(J1=J,J2,K2=K;I,JH) \qquad (4)$$

$$= \sum_{K1} \left[g(K2=K|K1) \cdot \sum_{J0} X(J0,J1=J,K1;I,JH) \right]$$

For each (I,JH) combination, an equation normalizing the probability space must also be given:

$$\sum_{J1} \sum_{J2} \sum_{K2} X(J1,J2,K2;I,JH) = D(I,JH) \qquad (5)$$

The binary variable D(I,JH) is either zero or one. If it is zero, the corresponding frequency function is zero throughout, the steady state conditions (eq. 4) are satisfied, and the contribution to the ATS output is zero. Non-negativity constraints on the continuous variables and a value of one for the binary variable in equation 5 permit the probabilistic interpretation which is given to the set of variables, X(J1,J2,K2;I,JH).

A budget, B, is allocated to air tanker use over the fire season. The expected number of days in the fire season, S, in conjunction with a guaranteed payment for each day that the air tanker is expected to be available, establishes a fixed cost, F(I,JH), for the season. An expected daily cost, C(I,JH,J1,J2,K2), is also associated with the air tanker-home base combination (I,JH) when the air tanker is sent from air base J1 to air base J2 and fire-day condition K2 prevails. It is assumed that total fire season costs will not exceed total budgeted expenditures:

$$S\left[\sum_{I}\ \sum_{JH}\sum_{J1}\sum_{J2}\sum_{K2} X(J1,J2,K2;I,JH)\ C\ (I,JH,J1,J2,K2)\right] \qquad (6)$$

$$+\sum_{I}\ \sum_{JH} D(I,JH)\ F\ (I,JH) \leq B$$

The summation of the cost function C(I,JH,J1,J2K2) over the probability space given by the frequency function X(J1,J2,K2;I,JH) for each air tanker-home base combination gives the expected ATS cost for any randomly selected day. Multiplying this term by the expected number of days in the season, S, and adding to it the applicable fixed seasonal costs, yields the expected expenditure for the season. This expected expenditure must be less than or equal to available budgeted funds, B.

In application, this constraint will not hold exactly because only expected values can be calculated at the beginning of the season. Since the actual air tanker system cost over the season will certainly differ from the expected cost, the problem arises of anticipating and adjusting for any wide deviation from the expected level of expenditure. The variance of expected cost could be calculated in order to give the manager some indication of potential problems. Another possibility is recomputing the results during the season by using an expenditures-adjusted current budget.

Integer and non-negativity constraints are also imposed:

$$D(I,JH) = \{0,1\} \qquad (7)$$

$$X(J1,J2,K2;I,JH) \geq 0 \qquad (8)$$

MODIFICATION AND EXTENSION

The basic model can be modified by adding constraints or extending its range of applicability through appropriate re-specification of model elements. Although it is impossible to list all possible constraints or to speculate on the outer limits of applicability, the following examples should give some insight to the range of possibilities.

The basic model can be modified substantially by defining additional constraints, such as those which restrict the allocation of funds or air tankers.

In some situations a minimum payment, B(I,JH), must be guaranteed for air tanker flight time during the season. Such a restriction may be stated in the following form:

$$S \sum_{J1}\sum_{J2}\sum_{K2} A(I,JH,J1,J2,K2)\ X(J1,J2,K2;I,JH) \geq B(I,JH) \cdot D(I,JH) \qquad (9)$$

in which A(I,JH,J1,J2,K2) is the payment for air tanker flight time under the given conditions.

The problem of air base set-up costs can be addressed. Assume that an amount W has been allocated to cover these expenditures. If airport JH is selected as a home base, then an expenditure F(JH) is incurred. Define the binary integer variable D(JH) such that:

$$D(JH) = \begin{cases} 1, \text{ if airport JH is used} \\ 0, \text{ otherwise} \end{cases}$$

The following constraints are added to the program:

$$\sum_{I} D(I,JH) \leq D(JH) \cdot IMAX, \quad \text{for all JH} \qquad (10)$$

$$D(JH) = \{0,1\}, \quad \text{for all JH} \qquad (11)$$

$$\sum_{JH} F(JH) \cdot D(JH) \leq W \qquad (12)$$

The allocation of an air tanker I to a particular air base J a proportion, r, of those days that fire-day condition index K is observed can be obtained by adding the constraint:

$$\frac{\sum_{J1} X(J1,J2 = J,K2 = K;I,JH)}{\sum_{J1}\ \sum_{J2} X(J1,J2,K2 = K;I,JH)} \geq r \qquad (13)$$

The expected number, $\overline{V}$, of air tankers working at base J, given fire-day condition K, can be controlled by adding a constraint of the following type:

$$\sum_{I}\sum_{JH}\left[\frac{\sum_{J1} X(J1,J2 = J,K2 = K;I,JH)}{\sum_{J1}\sum_{J2} X\ (J1,J2,K2 = K;I,JH)}\right] \leq (\geq)\ V^* \qquad (14)$$

or, after summing out terms,

$$\sum_{I}\sum_{JH}\left[\frac{X\ (J2 = J,K2 = K,I,JH)}{X\ (K2 = K,I,\ JH)}\right] \leq (\geq) V^* \qquad (15)$$

In order to put into linear form, substitute:

$$X\ (K2 = K,I,JH) = g(K2 = K) \qquad (16)$$

This result follows since the probability of observing fire-day conditions K does not depend on either I or JH and is equal to the steady state value which may be obtained from $g(K2 \mid K1)$. Significantly, variance of the number of air tankers allocated to air base J on fire-day condition K is low. $\overline{V}$ is the value of the left-hand side of equation 14 at the solution point. Where the constraint is active, then $\overline{V} = V^*$. On any day with fire condition index K the number, V, of air tankers working at base J is observed. V is not necessarily equal to $\bar{V}$, but:

$$\text{Var.}\{ V \} = \sum_{I} \sum_{JH} \left[X(J \mid K;I,JH) - X^2(J \mid K;I,JH) \right] \quad (17)$$

is low, since $X(J \mid K;I,JH)$ is in most cases either zero or one.

Integer variables permit a variety of possible constraints to be included (Dantzig 1960). For example, if it is desired to have at least one air tanker with air base JH as its home base, the following constraint should be added:

$$\sum_{I} D(I,JH) \geq 1 \quad (18)$$

The addition of such constraints usually reduces computer turnaround.

The scope of applicability can be extended by redefining the variable and constant elements of the basic model.

In developing the basic model, we assumed that a first-order Markov process adequately describes the flow of information on which the transfer/use decision is made. If, in fact, a higher order Markov process is more appropriate, such respecification is possible within the context of the basic MILP model.

Related to this respecification is the possibility of more than one transfer/use decision point during the day. In the current model the transfer/use decision is made once daily in the early morning hours. Futher information may normally arrive during the day and serve as the basis for a second transfer/use decision point in the afternoon. Adding this second decision point is possible within the basic model design.

The output values related to air tanker assignment and use at different air bases as specified in the objective function may be variously defined and estimated. These estimates may be relatively straightforward or the result of more sophisticated simulation techniques. The air tanker output may be defined only for the initial attack period on fires or, if secondary air tanker tasks are considered relatively important, for the entire period of uncontrolled burning.

The simulation techniques discussed above might include a fire behavior model, allowances for air tanker downtime, maneuverability of individual air tanker types, and any other factors which significantly affect output.

APPLICATION OF THE MODEL

The model was used to analyze the air tanker system of District 1, California Division (now Department) of Forestry (CDF) (*table 1*). This district, headquartered in Santa Rosa, includes all of northern coastal California. Three air bases serve as home bases for air tankers, from which initial attack sorties may be made on fires: (a) Rohnerville, in Humboldt County; (b) Ukiah, in Mendocino County; and (c) Sonoma County, at Santa Rosa. The model uses a fourth air base to represent release from standby. Zero cost and output are associated with assignment to this fourth air base.

Five air tankers are available for contract within the district: two F7F's and three TBM's. These aircraft have different costs and outputs associated with their use. One of the F7F's may be assigned to either Ukiah or Sonoma County. The other F7F may be assigned only to Rohnerville; the first TMB may be assigned only to Ukiah; the last two TBM's can be assigned only to the Sonoma County air base.

The expected period of air tanker use is 107 days, from July 1 through October 15, when the air tankers contracted for the season may be transferred between bases for use on initial attack fires.

Historically, these air tanker initial attack (ATIA) fires have been strongly correlated with the brush burning index classes for CDF fire danger rating areas 120 and 175. The daily brush burning index class for each of these two areas might then be considered as one possible basis for allocating air tankers.

Associated with each air tanker is a fixed cost for the season (*table 1*). When an air tanker is contracted, this fixed cost guarantees availability of the aircraft through the nominal length of the fire season.

A per diem cost of $20 is charged for every night an air tanker spends away from its home base. Air tankers are assumed to spend the night at the base to which they are assigned for the day. Returning the aircraft to its home base after a work day at another base is not considered, although it could be considered by adding two more dummy bases to the model. This cost is added to the transfer cost between bases. Costs and output were derived by using the data and procedures described by Greulich and O'Regan (1975).

Once an air tanker arrives at the air base where it will spend the next 24 hours, it becomes available for initial attack on any fire within the jurisdiction of that base. The number of ATIA fires and consequent cost and output associated with air tanker use may be predicted on the basis of the fire-day condition.

The fire-day condition is based on the brush burning index from CDF fire danger rating areas 120 and 175. The five burning index classes run from 1 (low) to 5 (extreme). The fire-day condition is based on combinations of the two burning index classes from areas 120 and 175. Of 25 possible combinations 18 were observed and subsequently used to constitute the fire-day condition index. These two fire danger rating areas were selected as the basis for the fire-day condition index

Table 1—*Fixed cost for availability of air tankers through expected fire season length*

Air tanker	(I)	Home base (JH)		Fixed cost (dollars)
F7F	(1)	Rohnerville	(1)	16,576
F7F	(2)	Ukiah or Sonoma County	(2) or (3)	16,576
TBM	(3)	Ukiah	(2)	11,396
TBM	(4)	Sonoma County	(3)	11,396
TBM	(5)	Sonoma County	(3)	11,396

Table 2—*Probabilities calculated from 9 years of five-season data for predicting tomorrow's fire-day (burning) condition indexes, given today's indexes, for assignment of air tankers*[1]

Today's fire-day condition (burning) indexes	Corresponding brush burning index Classes in CDF FDR areas[2]		Tomorrow's fire-day condition (burning) index																	
	120	175	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1	1	0.5000	0.4000					0.1000											
2	1	2	0.0843	0.3012	0.1807	0.0121			0.2048	0.1446	0.0361	0.0121		0.0241						
3	1	3	0.0370	0.1605	0.1729	0.0617			0.1358	0.2963	0.0864	0.0124		0.0370						
4	1	4		0.0238	0.2143	0.2857	0.0238		0.0714	0.1191	0.2143	0.0476								
5	1	5			0.1111	0.2222				0.2222	0.4445									
6	2	1							0.2000	0.4000				0.2000	0.2000					
7	2	2	0.0337	0.1461	0.0674	0.0112		0.0225	0.2809	0.2697	0.0674		0.0225	0.0562	0.0112		0.0112			
8	2	3	0.0115	0.0402	0.1092	0.0287	0.0057		0.1034	0.3046	0.1839	0.0230	0.0115	0.0805	0.0460	0.0345		0.0058	0.0115	
9	2	4	0.0086	0.0173	0.0948	0.0862	0.0172	0.0086	0.0345	0.2414	0.2328	0.1035		0.0517	0.0345	0.0603		0.0086		
10	2	5		0.0513	0.0769	0.1026	0.1282		0.0257	0.1282	0.2051	0.1795		0.0513	0.0256	0.0256				
11	3	2						0.1429	0.1428	0.2857			0.1429	0.1428			0.1429			
12	3	3		0.0755	0.0189				0.0566	0.2075	0.1321	0.0943	0.0377	0.2076	0.1321	0.0377				
13	3	4		0.0606		0.0606		0.0303	0.0606	0.1212	0.1819	0.0303		0.1212	0.1515	0.1212				0.0606
14	3	5		0.0370	0.0370					0.0370	0.2593	0.1852		0.0371	0.1482	0.2222			0.0370	
15	4	2												0.5000	0.5000					
16	4	3												0.5000		0.5000				
17	4	4							0.3333	0.3334		0.3333								
18	4	5												0.5000	0.5000					
	Associated steady state probabilities[3]		0.0400	0.1035	0.0999	0.0525	0.0113	0.0063	0.1131	0.2178	0.1451	0.0488	0.0088	0.0664	0.0414	0.0338	0.0025	0.0025	0.0038	0.0025

[1]Example of how values are applied: If today's fire-day condition is 8 (brush burning index classes 2 in Area 120, 3 in Area 175), probability that tomorrow's fire-day condition will be the same is .3046, or about one chance in three; probability that it will be worse in both areas is .0920 (sum of probabilities in columns 13, 14, 17, and 18 for line 8).

[2]CDF = California Division (now Department) of Forestry; FDR = Fire Danger Rating (indexes range from 1, or low, to 5, or extreme).

[3]Probability that any randomly selected day during fire season will have a given fire-day condition (for example, probability of observing brush burning index class 4 in Area 120 is .0113 (sum of columns 15-18 in this line).

These values also represent the expected proportions of the total number of days in the fire season that the designated fire-day condition will be observed (for the previous example, slightly more than 1 percent of the days during a typical fire season will be characterized by a brush burning index of 4 in Area 120).

because they correlate well with fire starts and because together they give adequate coverage of CDF District 1. Area 120 is contained almost entirely within Humboldt County, covering a central band about 12 miles wide extending from east of Eureka to the Mendocino County line. Area 175 covers the lower half of Lake County and the northeast half of Napa County in a band 25 miles wide extending from above Clear Lake to below Lake Berryessa.

Nine years of fire season data (1961-1969) were used to estimate the transition matrix elements for the first-order Markov process from which the steady state values may then be calculated (table 2). Differences between the steady state entries of the table and the values appearing in table 5 in an earlier report (Greulich and O'Regan 1975) are due to additional years incorporated into the data base.

RESULTS

An increase in budget level is matched by a corresponding increase in aircraft output (*figure 1*). The curve AA' is the convex envelope of cost-output points associated with the annual decision to contract all available air tankers (five) and to assign the second F7F to the Sonoma County air base as home base. The curve BB' is the convex cost-output envelope associated with the annual decision to contract all air tankers except the Ukiah-based TBM, with the second F7F assigned to the Sonoma County air base. The existence of fixed costs and integer decision variables give rise to the pronounced "lumpiness" of the cost-output frontier (solid line). Little variation is noted in the average cost over the range of output considered here (*table 3*). The marginal cost does, however, increase quite rapidly at the higher levels of output. Significantly, this increase is slow until a large percentage of maximum possible output has been achieved for any given set of air tanker home base configurations. Transfer activity now appears to be more economical than indicated in a previous study (Greulich and O'Regan 1975).

The optimal decision structure under an annual budget of $152,000 was examined in more detail. Of this annual budget, $67,340 was used to pay associated fixed availability costs of the air tankers. All five air tankers were contracted and the second F7F was stationed at Sonoma County. The balance of $84,660 was expended on transfer flight time ($1355) per diem costs ($4215), and flight time on fires ($79,090).

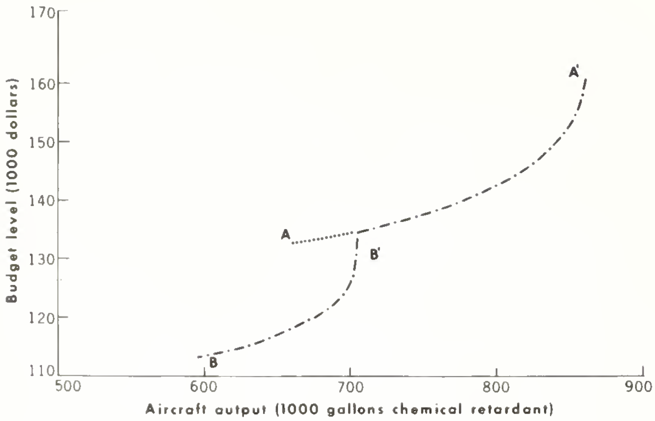


Figure 1—Cost-effective production frontier for California Division of Forestry District 1 air tankers and air bases used for initial attack.

Optimal transfer/use pattern (*table 4*) shows the air base to which each air tanker should be sent based on the fire day condition and its present air base location. The three TBM's spend every day at the Sonoma County air base regardless of the fire-day condition. The first F7F is at the Sonoma County air base under every fire day condition except for the first, when it is sent to Rohnerville. The second F7F is at Rohnerville 14 percent of the time when the first day condition is 1. For the balance of those days and for all other days of fire-day conditions other than 1, it is stationed at Sonoma County air base.

All of the air tankers, if possible, should have the Sonoma County air base as their home base. This result is a direct consequence of the particular cost-output structure used in the model. The procedure used to generate this data is open to review and modification (Greulich and O'Regan 1975). *Table 5* gives daily and seasonal costs and outputs, by airplane.

A fire season is essentially a series of days with random fire conditions. At the beginning of the season, a plan is devised that is optimal for an average season. For the season actually encountered, the plan will not necessarily meet budgetary and other constraints. Variances of expected payments could be computed to give some indication of the probabilities of failures to meet budgetary and other constraints. As an operational response to this essential randomness of the process, the model can be rerun at certain times, say halfway through and three-quarters of the way through the season. At each run, one would work with the remaining budget and the remaining season to devise new transfer use rules to come close to meeting budgetary and other constraints.

Table 3—*Cost-output relationships for nine different budget levels.*

Budget (dollars/year, 1000's)	Output (gal./year, 1000's)	Average cost per gal (dollars)	Marginal cost per gal (dollars)
161.37	857.391	0.188	3.288
152.00	846.411	.180	.649
147.00	825.510	.178	.187
142.00	788.836	.180	.101
137.00	739.108	.185	.101
130.00	703.711	.185	2.143
125.00	697.869	.179	.735
120.00	674.978	.178	.101
115.00	625.275	.184	.100

CONCLUSIONS

The results of this application of the model suggest that

- The basic model as described has the correct mathematical structure.
- The computer programs needed to generate the data structure, solve a large MILP, and interpret the solution can be written and executed.
- A first-order Markov process in at least one real-world situation seems to describe adequately the arrival of fire day condition information.

Dimensionality, though still a problem, is not insurmountable, if the analyst gives careful attention to problem specification, is prepared to use ancillary information, and is willing at times to sacrifice some detail.

The model allows a more general and realistic portrayal of the decision process within an air tanker program than has been heretofore possible and the important interrelationship between annual and daily decisions has been brought within its

Table 4—*Optimal decisions on assignment of air tankers, given a $152,000 budget*

Air tanker and seasonally assigned home base	Daily air base assignment, given fire-day condition index indicated
F7F—Rohnerville	In Sonoma County—under all fire-day conditions, except when index is one, in which case, air tanker transfered to Rohnerville.
F7F—Sonoma County	In Sonoma County—under all fire-day conditions, except when index is one. If index is one, decide whether to transfer air tanker to Rohnerville, and in such a way that it is expected to be sent there about 14 percent of the time, and kept in Sonoma County rest of the time. If index is one and air tanker is at Rohnerville, keep it there until index changes, at which time, transfer air tanker to Sonoma County.[1]
TBM—Ukiah	In Sonoma County—under all fire-day conditions (this air tanker had to use Ukiah as its home base; if that constraint lifted, Sonoma County would probably be selected as home base).
TBM, TBM—Sonoma County	In Sonoma County, for these two air tankers—under all fire-day conditions.

[1]Decision process is illustrated by use of a spin-wheel pointer that has 14 percent of the wheel circumference painted blue, and 86 percent painted red. If pointer stops on blue portion, send air tanker to Rohnerville; if it stops on red, tanker remains in Sonoma County.

Table 5—*Expected cost and output per day by air tanker under optimal seasonal configuration and daily transfer rules with $152,000 budget and 107-day season.*

Configuration		Expected cost per day[1]	Expected seasonal cost[1]	Expected output per day	Expected seasonal output
Air tanker	Home base				
		Dollars	*Dollars*	*Gallons*	*Gallons*
F7F	Rohnerville	190.63	20,397	1846.00	197,522
F7F	Sonoma County	156.77	16,775	1831.13	195,931
TBM	Ukiah	161.27	17,256	1411.08	150,986
TBM	Sonoma County	141.27	15,116	1411.08	150,986
TBM	Sonoma County	141.27	15,116	1411.08	150,986

[1]No fixed cost included.

structure. Daily transfer/use decisions are based on fire day condition information described as a Markov process. The system state includes not only fire day condition information but also the current location of air tankers.

Although the current model gives a better representation than was previously possible, it still has many limitations. Static modeling fails to recognize initial conditions or to allow possible changes in the decision rules during the season. Nonlinearity, which may be especially important in the daily output function, has not been recognized. Despite such limitations, the model possesses a good measure of realism and elegance in its structure and has much to offer the air tanker manager.

REFERENCES

Dantzig, George B. **On the significance of solving linear programming problems with some integer variables.** Econometrica 28(1):30-44; 1960 January.

Greulich, Francis E.; O'Regan, William G. **Allocation model for air tanker initial attack in firefighting.** Res. Note PSW-301. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1975. 8 p.

Manne, A.S. **Linear programming and sequential decisions.** Manage. Sci. 6(3):259-267; 1960 February.

GLOSSARY

A(I,JH,J1,J2,K2)	Expect payment for flight time during one day
B	Total annual budget for air tanker operations
B(I,JH)	Guaranteed annual minimum payment for flight time
C(I,JH,J1,J2,K2)	Expect payment for the air tanker through one day
D(JH)	Integer variable: 1 if used as a home base; 0 otherwise
D(I,JH)	Integer variable: 1 if the air tanker uses the base as home base; 0 otherwise
F(JH)	Home base set-up cost
F(I,JH)	Guaranteed, fixed, seasonal payment for air tanker availability
g(K2)	Probability that a randomly selected day has the indicated fire day condition
g(K2 | K1)	Conditional probability of the current fire day condition given the fire day condition of the previous day
I	Index for the air tankers in the system. I = 1 . . . IMAX
J	Index number for a particular air base in the system
J1	Air base at which an air tanker is stationed on the morning when a transfer/use decision is to be made
J2	Air base to which an air tanker is transferred following a transfer/use decision
JH	Home base number (JH always occurs with I as (I,JH). For example (1,3) indicates that aircraft 1 has base 3 as its home base)
K	Fire day condition for a particular day
K1	Fire day condition on the day preceding the transfer/use decision
K2	Fire day condition on the day of the transfer/use decision
Q(I,J2,K2)	Expected output of air tanker I transferred to J2 on a day of type K2
r	A fraction, less than one
S	Expected number of days in the fire season
V	Number of air tankers assigned to a particular air base on any given day
$\bar{V}$	Expected number of air tankers assigned to a particular base on any given day
V*	Limit on the number of air tankers assigned to a particular base on any given day
W	Total budget available to cover home base set-up costs
X(J1,J2,K2;I,JH)	Joint probability that air tanker I, which has home base JH, will be at air base J1 on same randomly selected day, that fire condition K2 is observed early the next day and air tanker I is sent to base J2
X(J2 | J1,K2;I,JH)	Conditional probability; transfer rules for the air tanker I
X(K2;I,JH)	Fire day condition probability; equivalent to g(K2)
Z	Expected total daily output of the air tanker system

Greulich, Francis E.; O'Regan, William G. **Optimum use of air tankers in initial attack: selection, basing, and transfer rules.** Res. Paper PSW-163. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 8 p.

Fire managers face two interrelated problems in deciding the most efficient use of air tankers: where best to base them, and how best to reallocate them each day in anticipation of fire occurrence. A computerized model based on a mixed integer linear program can help in assigning air tankers throughout the fire season. The model was tested using information from California Division (now Department) of Forestry District 1, which in 1967 maintained a fleet of five aircraft and three air bases. The results confirmed the soundness of the model's mathematical structure and demonstrated that a computer program can be written to interpret the solution to this resource allocation problem.

Retrieval Terms: air tanker model, initial attack, resource allocation

United States
Department of
Agriculture

Forest Service

**Pacific Southwest
Forest and Range
Experiment Station**

Research Paper
PSW-164

Stem Volume Losses in Grand Firs Topkilled by Western Spruce Budworm in Idaho

George T. Ferrell   Robert F. Scharpf

The Authors:

GEORGE T. FERRELL, a research entomologist, is studying the biology, ecology, and control of destructive forest insects, with headquarters in Berkeley, Calif. He earned three degrees at the University of California, Berkeley: a bachelor's in forestry (1959), a master's in zoology (1965), and a doctorate in entomology (1969). He joined the Station's research staff in 1969. **ROBERT F. SCHARPF**, a plant pathologist, is studying problems in forest diseases and their control, with headquarters in Berkeley, Calif. He earned a forestry degree (1954) at the University of Missouri, and a master's degree in forestry (1957) and a doctorate in plant pathology (1963) at the University of California, Berkeley. He joined the Forest Service in 1960, and has been with the Station's research staff since then.

Acknowledgment:

The study reported in this paper was originated by Max Ollieu, Forest Insect and Disease Management Staff, Intermountain Region, Forest Service, U.S. Department of Agriculture, Boise, Idaho.

Cover: The old topkill in this grand fir is visible as the central dead spike issuing from the forked stem.

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

December 1982

Stem Volume Losses in Grand Firs Topkilled by Western Spruce Budworm in Idaho

George T. Ferrell Robert F. Scharpf

CONTENTS

IN BRIEF . . .

Ferrell, George T.; Scharpf, Robert F. **Stem volume losses in grand firs topkilled by western spruce budworm in Idaho.** Res. Paper PSW-164. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 10 p.

Retrieval Terms: *Abies grandis*, *Choristoneura occidentalis*, *Echinodontium tinctorium*, topkilling, growth loss, decay, volume loss

Two stands, one cutover and one virgin, subjected to western spruce budworm (*Choristoneura occidentalis* Freeman) outbreaks in the years 1922-30, 1952-55, and 1969-78, were sampled in the Little Salmon River drainage of west-central Idaho. Forty mature grand firs (*Abies grandis* [Dougl. ex D. Don] Lindl.) were felled in August 1978, and their stems dissected and analyzed for growth reductions and defects associated with topkilling resulting from the outbreaks. Twenty firs, 14 inches (36 cm) or greater in diameter-at-breast-height (d.b.h.) were randomly selected from the residual overstory of a stand that had been sanitation-logged in the late 1960's; the same number of similarly selected firs was sampled in a nearby virgin stand.

The sample firs were rated for current defoliation, felled, and the stems examined for dead tops, remnants of dead tops, or for indicators of buried dead tops (crooks, forks). Dead tops, or deformities, and adjacent stem segments were dissected to determine the year when topkilled, the basal diameter of the dead top as an indication of the size of top killed, and the extent of any associated decay. Decay-causing fungi were identified in the field or by laboratory culture. Attacks by secondary insects (bark and boring beetles) were identified by their gallery patterns. Internode lengths were measured on the live regrown tops to analyze for height growth reductions. Radial growth was studied by measuring annual ring widths on cross-sections sawn from the lower, middle, and upper regions of the stem.

Growth index analyses were used to estimate reductions in height and radial growth resulting from the outbreak-caused topkilling. The growth indexes expressed annual increment as the percent growth predicted from long-term growth patterns in the trees. For each stand sampled, growth indexes of firs topkilled by each outbreak were compared with those of firs apparently not topkilled by that outbreak. Where percent growth reductions in the topkilled trees were found, they were converted to height or radial growth losses, using increments predicted by regression.

Volume losses were calculated for outbreak-caused topkilling that affected the stems to a minimum 4-inch (10-cm) diameter-inside-bark (d.i.b.). Volume losses resulting from growth reductions were calculated as the difference between existing stem volume and volume expected, if no growth reductions had occurred. Cylindrical volume deductions were made for stem deformities and associated decays. Volume losses were expressed in cubic feet, and as percentages of the stem volume.

Most volume loss was associated with tops killed by the 1922-30 outbreak. From 60 to 70 percent of the sample firs were topkilled by this outbreak and sizable tops, some exceeding 12 ft (3.6 m) in length and 6 inches (15 cm) in basal diameter, were killed. Extensive decay columns, some exceeding 50 ft (15.3 m) in length, were associated with these topkills. Height growth losses in firs topkilled by this outbreak were not measured. Volume losses from stem deformities and decays, although highly variable because of variations in the extent of decay, averaged 9.5 ft³ (0.3 m³) or 11.1 percent of stem volume in the sample firs topkilled by this outbreak in the cutover stand. Volume losses in the virgin stand averaged 26.3 ft³ (0.7 m³) or 20.5 percent per tree.

Less than 20 percent of the sample firs were topkilled by the 1952-55 outbreak and the basal diameters of the dead tops did not exceed 4 inches (10 cm). Volume losses in firs topkilled by this outbreak averaged 3.3 ft³ (0.1 m³) or 5.4 percent per tree in the cutover stand, and 0.5 ft³ (0.02 m³) or 0.3 percent in the virgin stand. Volume losses resulted primarily from reduced height growth. Almost no decays were associated with tops killed by this outbreak.

During the 1969-78 outbreak, 65 percent of the firs sampled in the cutover stand were topkilled, but none of the firs sampled in the virgin stand were topkilled. This difference was only partially attributable to differences in defoliation as rated in 1978, but may have resulted from differences in defoliation in earlier years of the outbreak when records were not available. No merchantable volume losses resulted from these topkills as they affected only the stem above the 4-inch (10-cm) diameter limit and no associated decays were found.

Radial growth was evidently not affected by the topkilling. Although radial growth of all sample firs decreased during the 1922-30 and 1969-78 outbreaks, no appreciable difference was found between the radial growth of firs topkilled and those not topkilled.

Galleries of bark beetles and flathead borers were found in some of the dead tops, but most of the older dead tops were missing or were too decomposed to allow the incidence of attack to be determined.

Stem decays, caused mainly by Indian paint fungus (*Echinodontium tinctorium* Ell. and Ev.), caused most of the volume losses associated with topkilling. Almost all the decay was associated with the larger tops killed by the 1922-30 outbreak. Little decay was found unless the top was killed more than 30 years ago and had a basal diameter exceeding 3 inches (8 cm).

Although based on relatively few trees, these results indicate that substantial volume losses can be expected in mature grand firs topkilled by the 1922-30 western spruce budworm outbreak in this region.

Extensive outbreaks of western spruce budworm (*Choristoneura occidentalis* Freeman) have repeatedly defoliated conifer forests of the American Northern Rocky Mountain and Intermountain Regions during the last six decades. The chronology and geographic extent of the outbreaks, as well as effects on host trees, have been reviewed (Johnson and Denton 1975). During these outbreaks, grand firs (*Abies grandis* [Dougl. ex D. Don] Lindl.), both a major component of these forests and an important host tree for this budworm, have often been extensively defoliated, resulting in radial growth reductions and considerable topkilling. Losses of height growth in grand firs topkilled by western spruce budworm outbreaks have been reported by Bousefield (1980) and Williams (1967) as the length of stem and years of growth involved in the diebacks. The dead tops frequently are replaced by upturned lateral branches. Little information is available, however, about potential height growth reduction resulting from the shorter internodes formed on these regrown tops. Also, potential reductions in radial growth in the living stem below the killed top, resulting from loss of the killed portion of the tree crown, have received little study. Furthermore, although studies of stem defect in grand firs in this region have indicated that topkills, of whatever cause, frequently result in stem deformities (spikes, crooks, forks) and are associated with stem decays (Aho 1977, Aho and others 1979, Maloy and Gross 1963), the extent of such defects resulting from budworm-caused topkilling has not been documented. Stem defects associated with these topkills need further assessment so that forest managers and pest management specialists can estimate losses and determine the possible benefits of preventing topkilling from future outbreaks.

This paper reports a study to assess growth reduction and stem defects in mature grand firs that were topkilled by one or more of several outbreaks of western spruce budworm in west-central Idaho during the last six decades. Stem volume losses associated with topkilling resulting from each outbreak are estimated and related to the size of the tops killed, the period of years elapsed since the outbreak, and the duration of the outbreaks and associated droughts. Both a cutover and a virgin stand were sampled to obtain an indication of the volume loss that might be expected in each.

METHODS

Tree Sampling

Mature grand firs were felled and their stems dissected and examined in two stands—one cutover, one virgin—located in the Boulder Creek drainage, tributary to the Little Salmon River, in west-central Idaho. Firs in both stands had been subjected to western spruce budworm outbreaks in the years 1922-30 (Johnson and Denton 1975), 1952-55 (Furniss 1957), and 1969-78 (Ollieu and others 1977). Many of the firs had spike tops and stem deformities (crooks, forks) indicating they had been topkilled by the budworm. The cutover stand had received a sanitation cut in the late 1960's, which removed the firs with the most serious stem deformities, including those resulting from topkilling during the two earlier budworm outbreaks. The virgin stand, located about 2 mi (3 km) from the cutover stand, was sampled to obtain a more complete representation of firs that had suffered extensive stem diebacks during these two outbreaks.

Twenty grand firs were felled in each stand by a sampling procedure that selected the first four overstory firs 14 inches (36 cm) or greater in diameter-at-breast-height (d.b.h.) on each of five, randomly located, one-chain-wide strips extending into each stand.

The study began in August 1978, after defoliation and tree growth for that year were essentially completed. With a method developed previously (Ferrell 1980), current defoliation of each test tree was estimated visually. Separate defoliation ratings were made for both the current year's, and older, foliage at three crown levels—lower, mid, and upper. On the basis of percent foliage consumed or destroyed, the ratings were 0 (none), 1 (<50 percent), 2 (50 to 90 percent), and 3 (>90 percent). Foliage ratings were weighted by factors of 1 (for current) and 4 (for older), on the basis of visual estimates of the contribution of new and old foliage to the crown biomass, and then averaged to obtain a defoliation rating for the entire crown. Ratings averaging <1.0 were considered light (<50 percent), 1.0 to 1.5 medium (50 to 70 percent), and >1.5 heavy (>70 percent) defoliation.

After rating for defoliation, each tree was felled and measured for *diameter-at-breast-height* to the nearest 0.1 inch (0.3 cm), *total stem length* to the nearest 0.1 ft (0.03 m), *tree age* (annual ring count on stump with 6 years arbitrarily added to reach stump height), and *height increments* (lengths of all externally visible internodes on the major living top, to the nearest 0.1 inch [0.3 cm]). *Radial increments* were sampled by sawing 1-inch-thick (2.5-cm) cross-sectional disks from each stem. Because radial growth reduction in grand firs defoliated by western spruce budworm was found to vary with height in the bole (Williams 1967), a disk was obtained from each of three bole levels defined as lower bole (at stump level), mid-bole (at the midpoint of the tree), and upper bole (approximately at the midpoint of the upper third of the bole). Three 1-inch-wide (2.5-cm) radial sections were sawn along equally separated radii from each disk. After cross-checking for traumatic, missing, or discontinuous annual rings, the widths, to the nearest 0.01 mm, of all annual increments present on the sections were measured. The three measurements of each annual ring were then averaged for analysis. *Disk diameter*, outside bark to the nearest 0.1 inch (0.3 cm), and *position*, distance from the tip of the tree to where the disk was cut to the nearest 0.1 ft (0.03 m), were also measured for volume calculations. Dead tops and stem deformities (crooks or forks) were dissected and these measurements taken: if present, the *dead top's basal diameter* at the lower limit of dieback, to the nearest 0.1 inch (0.3 cm), and whether it issued from the stem as a spike or stub, or was embedded in the stem; *stem diameter* (just below the deformity, to the nearest 0.1 inch [0.3 cm]); and *year when topkilling occurred*, determined by counting the number of annual rings formed around the dead top since topkilling (confirmed, in some of the recent topkills, by counting the number of internodes on the new top formed by an upturned branch). Any *beetle galleries* present were noted and the causal insects identified from their gallery patterns. The incidence and extent of all topkill-associated *decay* was determined by sectioning both within, and at 1-foot (0.3-m) intervals above and below the stem deformity until any decay present was no longer visible on the cut surfaces. The *total length of the decay column* to the nearest foot was then recorded. The *diameter of the decay column* was obtained as the average of diameters measured on the cut surfaces, to the nearest 0.1 inch (0.3 cm) and the presence or absence of "wetwood" was noted.[1] Decays that appeared to have originated as root or butt rots were noted but were not included in the results. *Causal fungi* were determined from field observations of decay characteristics. Decays of questionable origin were taken into the laboratory for further examination and identification.

Growth Analysis

Growth index analysis (Fritts 1966) was used to determine height and radial growth reductions attributable to the effects of topkilling caused by the outbreaks. The indexes eliminated growth patterns resulting from differences in tree size, age, and growing site, and isolated growth fluctuations caused by weather and outbreaks of defoliating insects. Growth index analysis previously had proven useful in isolating growth reductions caused by Modoc budworm (*C. retiniana* Walsingham = *viridis* Freeman) in northeastern California (Ferrell 1980), and a similar approach was used to analyze for tree growth reductions caused by western spruce budworm in Western Canada (Thomson and Van Sickle 1980).

The computer program INDXA (Fritts 1966) was used to calculate growth indexes for all annual increments measured. Either a straight line or a negative exponential curve was fit by least squares regression to each series of increment measurements representing annual growth in successive years (*fig. 1A*). Each year's index was obtained by dividing the increment measurement by the increment predicted by the regression function (*fig. 1B*). Separate regressions were calculated for the height increments, and for the radial increments at each bole level, in each tree. Index values of 1.0 (*fig. 1B*) represent the predicted annual growth for the tree in the absence of unusual factors, such as drought or outbreaks of defoliating insects. Indexes <1.0 indicate growth below that predicted from long-term patterns in the tree, and indexes >1.0 indicate annual growth above predicted levels.

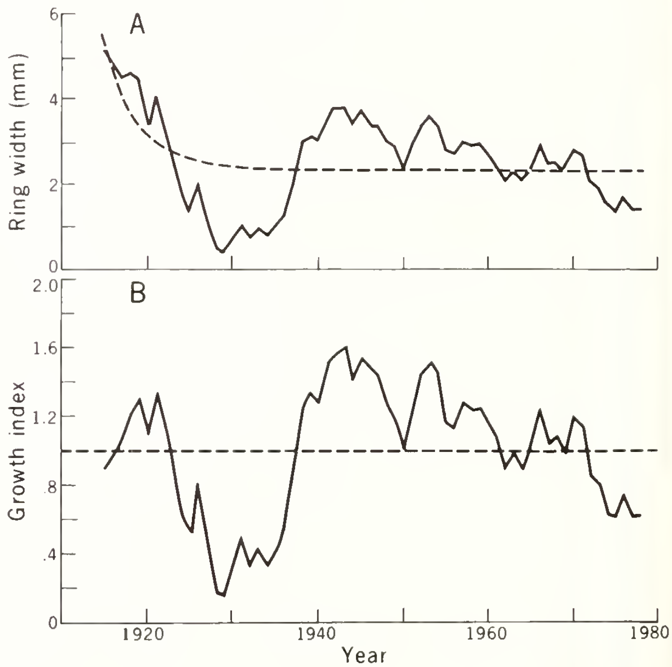


Figure 1—Annual growth indexes calculated for radial growth at the midbole level in a grand fir for the years 1915-78 by (*A*) fitting a negative exponential curve to the ring-width series to obtain predicted increments, and (*B*) dividing actual by predicted increments to obtain growth indexes. Horizontal line at an index value of 1.0 indicates predicted or expected growth.

[1] Wetwood is a condition in which the normally light-colored heartwood in firs turns darker, usually brownish, and is high in water content.

Outbreaks of conifer-feeding budworms usually have affected host trees for an unpredictable number of years after outbreaks have subsided (Johnson and Denton 1975, Kulman 1971). In this study, grand firs topkilled during or within the 3 years immediately after the outbreaks were attributed to the effects of the defoliation. Fir growth depressions that occurred during and persisted for several years after the outbreaks were attributed, at least partially, to defoliation, topkilling, or both.

Growth reduction was analyzed by comparing, in each stand, the mean annual growth indexes of firs that were topkilled by the outbreak with those of firs that were not. Mean growth indexes were plotted for years immediately before, during, and after each outbreak. Height growth and radial growth at each sampled bole level were compared separately. For periods when growth of topkilled firs was depressed below that of untopkilled firs, appreciable deficits—those that exceeded the pooled standard deviation for all trees and years compared—were attributed to the effects of topkilling caused by the outbreaks. This method was used because a tree's growth in any given year tends to be directly correlated with that in the next; therefore, the indexes did not represent the independent observations required by statistical tests. To facilitate interpretation, all growth indexes and their deficits were expressed as percentages of the predicted growth by multiplying them by 100. Growth deficits were then converted from percentages to feet of height, or inches of radius, by multiplying them by the periodic increment predicted by regression.

Volume Loss Calculations

Volume losses were calculated for topkills that affected the stems to a minimum 4-inch (10-cm) diameter top, the usual top diameter used in local cubic foot volume tables. As the diameters of the sample disks from the upper bole level averaged slightly more than 4 inches (10 cm), the merchantable stem was considered to consist of two logs bounded by upper, middle, and lower sample disks. Volume losses resulting from growth reductions were calculated as the difference between the existing stem volume, and the stem volume expected if no growth reductions had occurred, according to Smalian's formula. Volume losses because of topkill-caused stem deformities and associated decays were calculated according to local utilization standards. Because stem deformities were considered to result in the loss of 2 ft of log length, cylindrical volumes were calculated with the stem diameter measured 2 ft below the deformity. Cylindrical decay volumes were also calculated using the length and the average of the upper and lower diameters of the decay columns. The entire log was culled if the decay volume exceeded 67 percent of the volume of the log. Volume losses were expressed in cubic feet and as percent stem volume. No formal statistical tests were applied to log volumes and volume losses. The results are reported as averages and associated ranges or standard deviations.

RESULTS

Size and Age of Sample Firs

Grand firs sampled in the virgin stand were, on the average, both larger and older than those sampled in the cutover stand (*table 1*). This was probably the result of logging of the cutover stand in the late 1960's, which removed many of the larger and older firs. As this logging also removed the most defective trees, firs suffering the most severe topkilling from the budworm outbreaks in the 1920's and 1950's were probably also removed by the logging. Results from the cutover stand, therefore, represent only budworm-caused damage to the grand fir overstory that remained after the logging.

Incidence and Extent of Topkills

A total of 90 topkills was found, 45 in the 20 firs sampled in each stand. All but two of the 40 trees had been topkilled at least once, and the largest number of topkills found in any tree was eight. A topkill was visible as a dead top, or as crook or fork in the stem. Dead tops were either a spike or stub in 51 of the topkills (*fig. 2A, B*), but the dead top was completely embedded in the stem in 24 of the topkills. Dieback was extensive in most of the 75 topkills where a dead top was found. In more than half (37), basal diameter of the dead top exceeded 2 inches (5.1 cm) and five had basal diameters over 6 inches (15.2 cm). The length of some of the intact dead tops exceeded 12 ft (3.7 m). Small, usually embedded dead tops were found in an additional 15 topkills, indicating that top dieback was limited originally to only the terminal bud, or tip, of the tree.

On the basis of year of occurrence, 31 (69 percent) of the topkills in the cutover stand were attributed to the outbreaks. Only 20 (44 percent) of the topkills in the virgin stand, however, could be attributed to the outbreaks. In these old-growth firs, more topkills had occurred in years before there were any reliable records of budworm outbreaks. Topkilling increased in both stands in years near the end and immediately after the 1922-30 outbreak (*fig. 3*). For the period during and within 3 years after the 1922-30 outbreak, 29 topkills were found, 12 in the cutover stand, and 17 in the virgin stand (*table 2*). In the combined sample

Table 1—*Size and age of grand firs sampled in the cutover and virgin stands*

Size and age	Stand			
	Cutover		Virgin	
	Mean	Range	Mean	Range
Diameter-at-breast-height (d.b.h.) (inches)	18	(14 to 24)	25	(16 to 38)
Height (ft)	78	(40 to 101)	89	(35 to 129)
Age of stump (yrs)	123	(90 to 154)	192	(137 to 242)

Figure 2—Old topkills in grand firs evidenced by (*A*) dead spike protruding from a bole fork, and (*B*) dead stub issuing from bole crook.

of firs from both plots, 60 percent were topkilled at least once during this 11-year period. No such increase was associated with the 1952-55 outbreak, however, when only about 18 percent of the combined sample of firs were topkilled, and topkilling continued at the same low rate observed for periods between the outbreaks. Topkilling again increased during the 1969-78 outbreak, but only in the cutover stand where 65 percent of the sample firs were topkilled. During this period no topkills were found in the virgin stand. The difference in the incidence of topkilling in the stands during this outbreak was related only partly to differences in defoliation, as rated in 1978 (*table 3*). All 20 of the firs sampled in the cutover stand were rated as having either medium or heavy defoliation, and a total of 15 topkills was found in these firs. In contrast, although 16 of the firs sampled in the virgin stand also were rated as having medium or heavy defoliation, none of these firs was topkilled during this outbreak.

Thirty-four topkills could not be attributed to the outbreaks. For the remaining four topkills, the year of occurrence could not be determined because of advanced stem decay.

The most extensive budworm-caused topkills were from the 1922-30 outbreak in firs sampled in the virgin stand. Basal diameters of some of these dead tops exceeded 5 inches (12.5 cm) (*table 2*). The size of tops killed in this stand by the 1950-55 outbreak was much smaller, with no basal diameter larger than 0.9 inch (2.3 cm). In firs sampled in the cutover stand, the size of tops killed by each of the two earlier outbreaks was about the same, with basal diameters averaging slightly more than 2 inches (5 cm), but only small tops averaging 0.2 inch (0.5 cm) had been killed during the 1969-78 outbreak.

Incidence and Extent of Decay

A major portion of the stem decay found in the firs sampled in both stands was associated with outbreak-caused topkilling. Excluding decay resulting from root, or butt rots, about one-half of the trees sampled in each stand

Table 2—*Incidence and extent of topkills and associated decays associated with western spruce budworm outbreaks in grand firs sampled on the cutover and virgin stands*

Topkills and decay	Outbreaks					
	1922-30		1952-55		1969-78	
	Average	Range	Average	Range	Average	Range
Topkills						
Number						
Cutover	12		4		15	
Virgin	17		3		0	
Basal diameter (inches)[1]						
Cutover	2.2	1.0 to 3.5	2.1	0.0 to 4.1	0.2	0.0 to 0.7
Virgin	4.1	0.8 to 6.8	0.3	0.0 to 0.9	—[2]	—
Associated decays						
Number						
Cutover	6		1		0	
Virgin	13		0		—	—
Length (ft)						
Cutover	15	2 to 45	2	0	0	0
Virgin	16	2 to 55	0	0	—	—
Volume (ft^3)						
Cutover	3.2	0.1 to 10.1	0.1	0	0	0
Virgin	5.4	0.1 to 22.9	0	0	—	—

[1] Dead top at lower limit of dieback recorded as 0 where only terminal bud or small shoot had been killed.

[2] No data, as no topkills were found.

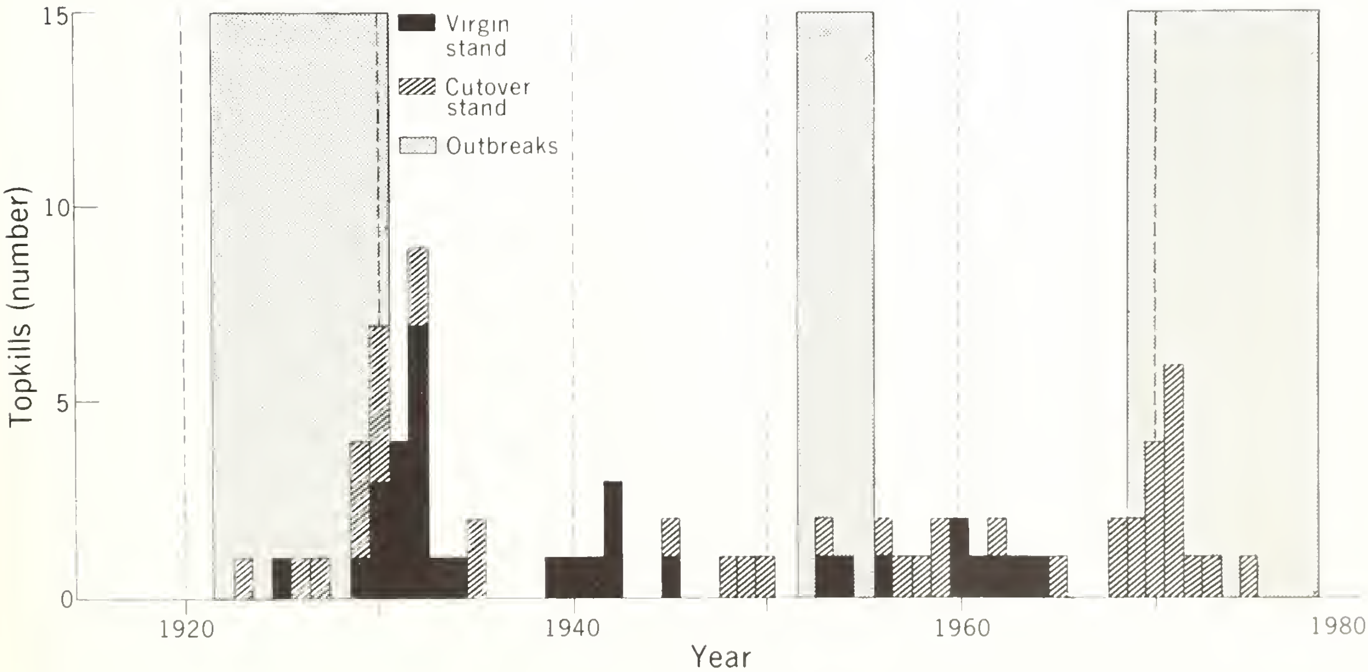


Figure 3—Incidence of topkills associated with outbreaks of western spruce budworm in sampled grand firs increased in the 1922-30 outbreak, showed no increase in the 1952-55 outbreak, and again increased in the 1969-78 outbreak, but only in the cutover stand.

Table 3—*Defoliation ratings and incidence of topkilling during the 1969-78 western spruce budworm outbreak in grand firs sampled in the cutover and virgin stands*

Defoliation rating[1]	Stand					
	Cutover			Virgin		
	Trees	Topkilled trees	Topkills	Trees	Topkilled trees	Topkills
Light	0	0	0	4	0	0
Medium	14	8	[2]9	14	0	0
Heavy	6	5	[2]6	2	0	0

[1] Percentage of crown defoliated, rated as light (<50), medium (50 to 70), or heavy (>70), August 1978.

[2] One was topkilled twice.

(10 in the cutover, 13 in the virgin) had at least some advanced stem decay, and in all but two of these trees, the decay appeared to have developed from topkills. Not all topkills, however, were associated with decay. Of the 45 topkills of whatever cause found in each stand, only 30 percent (12 in the cutover, 15 in the virgin) were associated with decay. Nearly all of the decays (19) developed in tops killed by the 1922-30 outbreak, and only one decay column was found in dead tops resulting from the more recent outbreaks (*table 2*).

Most of the decay associated with the 1922-30 topkills occurred in the old-growth firs in the virgin stand. Seventy-seven percent of these topkills in this stand had decay, compared with only 50 percent in the cutover stand (*table 2*). Decays were also more extensive in the virgin stand, and some of the decay columns exceeded 50 ft (15.3 m) in length and were 20 ft^3 (0.6 m^3) or more in volume. Consequently, the total volume of decay in the virgin stand (172 ft^3 or 4.8 m^3) greatly exceeded that in the cutover stand (37 ft^3 or 1.0 m^3).

The incidence and extent of decay caused by the outbreaks was directly related not only to the period of time elapsed since the outbreak but also to the size of the killed tops. Much larger tops were killed by the 1922-30 outbreak in the virgin stand, and these dead tops had a greater incidence and extent of associated decay (*table 2*). Neither the incidence nor the average extent of the associated decays was usually great, unless the topkill occurred more than 30 years ago and the basal diameter of the dead top exceeded 3 inches (7.6 cm) (*tables 4, 5*). In only one topkill did age appear to be more significant than basal diameter. In this situation, the top was killed more than 45 years ago and the basal diameter of the dead top was less than 1 inch (2.5 cm), but the volume of the associated decay was 22.9 ft^3 (0.6 m^3).

Most of the decay in tops was caused by the Indian paint fungus (*Echinodontium tinctorium* Ell. and Ev.). The fungus was associated with budworm-caused topkills in six of the sample firs, and with topkills of unknown cause in four firs.

Intact (spikes), broken-off (stubs), or embedded dead tops all had associated decay. Dead tops associated with decay had basal diameters averaging 4 inches (10.2 cm), and ranged from 2.5 inches (6.4 cm) to 6.5 inches (16.5 cm). The number of years that had elapsed since the fungus had become established was not precisely determined, but it was not associated with topkills occurring less than about 30 years ago.

Our finding that the Indian paint fungus occurs in association with dead tops in grand fir is more or less in agreement with the results of others (Aho 1977, Aho and others 1979). We could not determine, however, whether the dead tops served as entrance courts for the fungus, or whether the top dieback activated semidormant infections of the fungus already present in the tree, as proposed by Etheridge and others (1976).

Advanced decay from Indian paint fungus in grand fir can be readily detected by the presence of fruiting bodies (Maloy 1967, Aho 1977). In our study, 10 of the 12 trees with the fungus had fruiting bodies and their presence indicated extensive decay and cull. Three trees had one, two, or three fruiting bodies each and one tree had six. The presence and number of fruiting bodies produced by the fungus has been used in the past by foresters to estimate the amount of cull or loss from decay (Maloy 1967).

No fruiting bodies were found for any of the other fungi involved in decay of grand firs in this study.

The only other fungi we identified as decay organisms in dead tops were *Pholiota adiposa* Fries and *Hericium abietis* (Weir ex Hubert) K. Harrison. *Pholiota* was found in one tree and *Hericium* in two. Nine trees had some decay caused by fungi that were not identified. In almost all instances, the decays caused by these unidentified fungi were restricted to the embedded portions of dead tops.

Table 4—*Incidence and extent of associated decay in relation to age of topkills in the combined sample of grand firs in the cutover and virgin stands*

Topkills and decay	Years since topkill[1]			
	0 to 15	16 to 30	31 to 45	Over 45
Topkills				
Total number	20	15	11	29
With decay	0	2	4	17
Percent with decay	0.0	13.3	36.4	58.6
Decay volume (ft^3)				
Average	0.0	0.1	6.2	2.3
Range	0.0 to 0.0	0.0 to 1.0	0.0 to 66.0	0.0 to 22.9

[1] Includes all topkills examined, regardless of cause of topkill.

Table 5—*Incidence and extent of associated decay in relation to the basal diameter of dead tops in the combined sample of grand firs in the cutover and virgin stands*

Topkills and decay	Basal diameter of dead top (inches)				
	0.0 to 1.0	1.1 to 3.0	3.1 to 5.0	5.1 to 7.0	>7.1
Topkills[1]					
Total number	32	30	12	3	2
With decay	2	12	8	3	2
Percent with decay	6.3	40.0	66.7	100.0	100.0
Decay volume (ft^3)					
Average	0.8	0.9	2.2	4.8	58.2
Range	0.0 to 22.9	0.0 to 8.8	0.0 to 10.1	1.0 to 8.3	50.4 to 66.0

[1]Includes all topkills examined regardless of cause of topkill.

Galleries of bark beetles (*Scolytus ventralis* Lec.) and roundheaded borers (unidentified Cerambycidae) were found in some of the dead tops examined, including both those caused by the western spruce budworm outbreaks and those of unknown cause. Attacks by these beetles might have been found in more of the topkills if the dead tops had not been largely missing or badly decayed. As a consequence, we did not try to determine either the incidence of beetle attacks, or whether they were associated with the presence of decay as was found in grand fir tops killed by the Douglas-fir tussock moth, *Orgyia pseudotsugata* (McDunnough) (Aho and others 1979).

Wetwood, often confused with incipient decay, was almost always associated with dead tops in grand fir regardless of whether decay was present. Wetwood, however, apparently forms in response to wounding or injury in general, and is not, by itself, a reliable indicator of the presence of decay.

Growth Reductions From Topkilling

The only discernible growth loss attributable to topkilling was in the reduction of height growth of firs topkilled by the 1952-55 outbreak (*figs. 4, 5*). Height growth of firs topkilled in the cutover stand by this outbreak averaged 11.7 ft (3.6 m) or 72.6 percent of predicted increment (16.1 ft or 4.9 m) over the period 1948-59 (*table 6*). Height growth of firs that were not topkilled in this stand, however, averaged 17.4 ft (5.3 m) or 108.3 percent of predicted increment, for this same period. Compared with trees not topkilled, the topkilled firs grew an average of 35.7 percent less, amounting to 5.7 ft (1.7 m) less in height during this period. In the virgin stand, height growth deficits in firs topkilled by the 1952-55 outbreak occurred somewhat later, and were not as large as those in the cutover stand. Height growth of firs topkilled in the virgin stand was less than that predicted during the years 1955-67, averaging 8.6 ft (2.6 m), or 80.4 percent of predicted (10.7 ft or 3.3 m), for this period. Height growth of firs with no topkills, however, averaged 11.4 ft (3.5 m), or were 106.5 percent of predicted increment, for this period. In the virgin stand, height growth of the topkilled trees averaged 26.1 percent less than that predicted.

Table 6—*Height growth of grand firs topkilled, compared with those not topkilled, by the 1952-55 western spruce budworm outbreak in the cutover and virgin stands*

Stand	Trees	Height growth			
		Percent[1]		Feet	
		Mean	(S.D.)	Mean	(S.D.)
Cutover stand					
Trees not topkilled	15	108.3	(3.9)	17.4	(1.5)
Topkilled trees	4	72.6	(5.7)	11.7	(2.3)
Growth reductions		35.7	(1.8)	5.7	(0.8)
Virgin stand					
Trees not topkilled	16	106.5	(5.1)	11.4	(1.7)
Topkilled trees	3	80.4	(5.8)	8.6	(1.9)
Growth reductions		26.1	(0.7)	2.8	(0.2)

[1]Percent of predicted height growth.

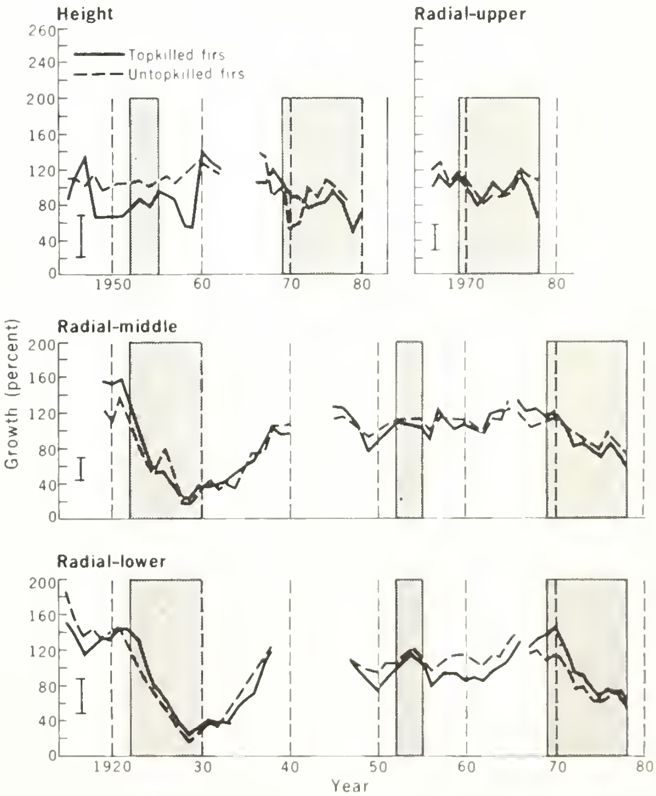


Figure 4—Except for reduced height growth in firs topkilled by the 1952-55 outbreak, height and radial growth of grand firs topkilled by western spruce budworm outbreaks in the cutover stand did not differ significantly from growth of untopkilled grand firs. Growth is expressed as percentages of increments predicted from long-term growth patterns in the trees.

Height growth reductions caused by topkilling by the 1922-30 outbreak were not studied because the internodes formed during this period were no longer visible on the exterior of the regrown tops at the time of sampling. During the 1969-78 outbreak, however, no appreciable difference was found between the height growth of topkilled and untopkilled firs in the cutover stand where a comparison could be made (*fig. 4*).

Height growth reductions found in topkilled firs resulted from the shorter internodes formed in the branches, which turned upward to replace the killed tops in all of the trees examined. For some of the tops killed by the 1952-55 outbreak in the cutover stand, the stem diebacks included internodes formed in the years 1948-51, before the outbreak began. The height growth reductions found for these years reflect the shorter internodes formed in the branches, which later became the new tops.

Radial growth of the firs was apparently not affected by outbreak-caused topkilling in either stand. When radial growth of firs during outbreak periods was expressed as percentages of predicted increments, trends were similar in both stands and at all bole levels sampled, and no appreciable differences between topkilled and untopkilled firs were found in any comparison made (*figs. 4, 5*).

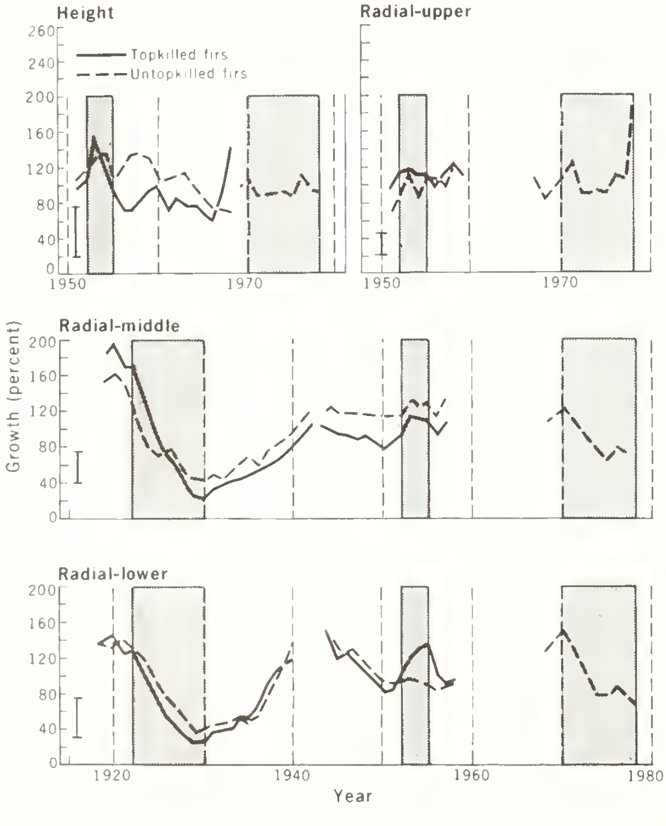


Figure 5—Height growth was reduced in firs topkilled by the 1952-55 outbreak in the virgin stand, but in other comparisons, height and radial growth of grand firs topkilled by western spruce budworm outbreaks was not significantly different from growth of untopkilled grand firs (no firs were topkilled in this stand by the 1969-78 outbreak).

Radial growth depressions did occur, however, during both the 1922-30 and 1969-78 outbreaks. Growth of firs in both stands fell below predicted levels within 2 to 3 years after the outbreaks began. During the earlier outbreak, fir radial growth fell to 20 to 40 percent of predicted increments and did not return to predicted levels until 7 to 12 years after the outbreak subsided. By 1978, during the most recent outbreak, radial growth declined to 60 to 80 percent of predicted increments at the mid- and lower-bole levels. Evidently, these radial growth depressions resulted from defoliation and subnormal precipitation, and not from topkilling. No pronounced depressions in radial growth were associated with the 1952-55 outbreak, in either stand at any bole level sampled.

Volume Losses From Topkilling

Most of the volume losses associated with budworm-caused topkilling occurred in firs topkilled by the 1922-30 outbreak. When volume losses due to height growth reduction, stem deformity, and decay were combined, firs topkilled by this outbreak in the cutover stand had volume losses averaging 9.5 ft^3 (0.3 m^3) or 11.1 percent of stem volume, with one tree losing 83.1 ft^3 (2.4 m^3) or 85.0 percent of stem volume (*table 7*). Virgin stand losses were greater, averaging 26.3 ft^3 (0.7 m^3) or 20.5 percent, and ranging up to 145.1 ft^3 (4.1 m^3) or 93.3 percent. In both stands, more than 90 percent of these volume losses resulted from decays, some so extensive that logs and entire trees were considered cull. Volume losses varied greatly among sample firs topkilled by this outbreak, mainly because of variations in the extent of the associated decays. Volume losses associated with topkilling by this outbreak would probably

Table 7—*Volume losses in merchantable stems of grand firs topkilled by western spruce budworm in the 1922-30 and 1952-55 outbreaks in the cutover and virgin stands*

Stand	Outbreaks 1922-30	Outbreaks 1952-55
Cutover stand		
Topkilled trees	11	4
Volume loss[1]		
Cubic feet		
Average	9.5	3.3
Range	0.0 to 83.1	0.4 to 6.6
Percent		
Average	11.1	5.4
Range	0.0 to 85.0	0.6 to 11.5
Virgin stand		
Topkilled trees	12	3
Volume loss[1]		
Cubic feet		
Average	26.3	0.5
Range	1.5 to 145.1	0.0 to 0.9
Percent		
Average	20.5	0.3
Range	0.6 to 93.3	0.0 to 0.6

[1]Combined volume loss due to height growth reduction, stem deformity, and decay, in cubic feet and as a percentage of the volume of the stem, to a minimum 4-inch diameter top.

have been even greater had we been able to measure height growth losses.

The few topkills caused by the 1952-55 outbreak resulted in smaller volume losses not exceeding 6.6 ft^3 (0.2 m^3) or 11.5 percent per tree, due primarily to height growth reductions and not decay. Volume losses from stem deformities caused by the topkills were minor, never exceeding 5 percent of stem volume for the 1922-30 outbreak, or 1 percent for the 1952-55 outbreak. No volume losses resulted from tops killed by the 1969-78 outbreak. These occurred in the upper region of the stem less than 4 inches in diameter and did not result in stem defects below this region.

DISCUSSION AND CONCLUSIONS

A high incidence of topkilling, attributed to three western spruce budworm outbreaks during the last six decades, was found in the mature grand firs sampled. More than 75 percent of these firs were topkilled at least once, and some several times as a result of one or more of the outbreaks. Some of the dead tops were large, resulting in serious stem deformities, some height growth loss and, eventually, substantial volumes of associated decay. Incidence and size of the tops killed, as well as the effect of topkilling on fir stems, varied among the outbreaks and between the stands studied.

Most tree damage and volume losses resulted from the 1922-30 outbreak—60 to 70 percent of the firs sampled had topkills. Some of the tops killed were large with basal diameters exceeding 6 inches (15 cm). Because these large tops were killed 50 to 60 years ago, the stem deformities and decays associated with them affected merchantable portions of the stem, resulting in combined volume losses that were highly variable, but exceeded 80 percent of stem volume in some trees. Volume losses recorded for this outbreak might have been even larger if we had measured height growth reduction.

Topkills resulting from the 1952-55 outbreak were found in less than 20 percent of the sampled firs. Because the basal diameter of the dead tops never exceeded about 4 inches (10 cm) and the tops were killed only about 25 years ago, combined volume losses (due mainly to height growth reductions) never exceeded about 12 percent of the volume of the stem.

In the cutover stand, volume losses found for topkilling resulting from the 1922-30 and 1952-55 outbreaks might have been greater if this stand had not been subjected to a sanitation cut in the late 1960's.

During the 1969-78 outbreak, incidence of topkilling was highly variable between the two stands. Sixty-five percent of the firs sampled in the cutover stand were topkilled, but none of the firs sampled in the virgin stand were topkilled. This difference in the incidence of topkilling was only partially attributable to differences in defoliation observed on the two plots in 1978, but may have resulted from differences in defoliation in earlier years of the outbreak, for which records were not available. As the basal diameters of the killed tops never exceeded 0.7 inch (1.4 cm) and the tops were killed within the last 9 years, these topkills had not resulted in volume loss in the merchantable stems.

The frequency and size of tops killed appeared to be related to the duration of the outbreaks and the duration and intensity of any associated droughts. The earliest outbreak, 1922-30, was accompained by severe and protracted drought. Weather records from nearby McCall, Idaho (obtained from annual summaries of Idaho weather published by the U.S. Weather Bureau) indicated that precipitation was 12 percent below normal for the years 1917 to 1922, and 27 percent below normal for the years 1928 to 1937. The relatively short 1952-55 outbreak, however, was not accompanied by drought, and precipitation was considerably below normal (21 percent) only in 1952. Also, this outbreak was terminated by insecticide spray projects in 1955 and 1956. Severe drought did not occur during the 1969-78 outbreak although precipitation was somewhat below normal for 1969 (13 percent), 1971-72 (6 percent), and 1976-78 (9 percent).

Radial growth was evidently not affected by the topkilling during any of the outbreaks, perhaps because not enough of the crowns were killed. But the radial growth depressions found in all sampled firs, topkilled or not, during the 1922-30 and 1969-78 outbreaks were doubtless caused by the interaction of the defoliation and subnormal precipitation during these periods.

The largest source of volume loss associated with the budworm-caused topkilling was stem decay, caused mostly by the Indian paint fungus. Almost all of this decay was associated with tops killed by the earliest (1922-30) outbreak, which was undoubtedly related to the large size of some of the tops killed by this outbreak and also to the years elapsed since the topkilling during which decay could develop. Among all topkills examined, associated decays were neither frequent nor extensive, unless the topkill occurred more than 30 years ago and the basal diameter of the dead top exceeded 3 inches (7.6 cm). Somewhat different results were found in grand firs topkilled by Douglas-fir tussock moth in eastern Oregon where the incidence and extent of decay was associated with the size, but not the age, of the topkill; the oldest topkills studied, however, occurred only 28 years ago (Aho and others 1979). In contrast, it was concluded that nearly all balsam fir (*Abies balsamea* [L.] Mill.) tops killed by spruce budworm *C. fumiferana* (Clemens) in New Brunswick, with basal diameters over 0.5 inch (1.3 cm), would eventually develop decay (Stillwell 1956).

Our results indicate that grand firs suffering severe topkill by western spruce budworm can, after 30 to 60 years, suffer substantial volume losses from decay. In managing stands for the future, grand firs with large tops killed by western spruce budworm outbreaks should be harvested within 30 years to avoid losses from extensive decay. Trees with tops killed that are less than 3 inches (7.6 cm) in basal diameter will suffer some height growth reduction but likely will not experience volume loss from decay. For some time, however, forest managers can expect substantial volumes of decay in some mature grand firs topkilled by the 1922-30 western spruce budworm outbreak in west-central Idaho.

REFERENCES

Aho, Paul E. **Decay of grand fir.** Res. Paper PNW-229. Portland, OR: Pacific Northwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1977. 18 p.

Aho, Paul E.; Wickman, Boyd E.; Roe, Lee. **Decay in tops killed by Douglas-fir tussock moth in the Blue Mountains.** Res. Paper PNW-250. Portland, OR: Pacific Northwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1979. 22 p.

Bousefield, Wayne E. **The effects of height growth loss on stands damaged by the western spruce budworm.** Forest Insect and Disease Management. Rep. 80-11. Missoula, MT: Northern Region, Forest Service, U.S. Department of Agriculture; 1980. 3 p.

Etheridge, D. E.; Craig, H. M.; Farris, S. H. **Factors influencing infection and initiation of decay by the Indian paint fungus (*Echinodontium tinctorium*) in western hemlock.** Can. J. Forest Res. 6:299-318; 1976 September.

Ferrell, George T. **Growth of white firs defoliated by Modoc budworm in northeastern California.** Res. Paper PSW-154. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1980. 9 p.

Fritts, H. C. **Growth-rings of trees: their correlation with climate.** Science 154:973-979; 1966 November.

Furniss, M. M. **Entomological aspects of the 1955 southern Idaho spruce budworm control project.** Misc. Publ. 10. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1957. 22 p.

Johnson, Phillip C.; Denton, Robert E. **Outbreaks of the western spruce budworm in the American Northern Rocky Mountain area from 1922 through 1971.** Gen. Tech. Rep. INT-20. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1975. 144 p.

Kulman, H. M. **Effects of insect defoliation on growth and mortality of trees.** In: Smith, Ray F.; Mittler, Thomas E., eds. Annual review of entomology, Vol. 16. Palo Alto, CA: Annual Reviews, Inc.; 1971: 289-324.

Maloy, Otis C. **A review of *Echinodontium tinctorium* Ell. and Ev., the Indian paint fungus.** Bull. 686. Pullman, WA: Washington Agriculture Experiment Station, Washington State Univ.; 1967. 21 p.

Maloy, Otis C.; Gross, H. C. **Decay in young grand fir.** J. For. 61:850-853; 1963 November.

Ollieu, M.; Livingston, L; Bousefield, W. **Impact of defoliation by spruce budworm.** Boise and Payette National Forests and intermingled Federal, State, and private lands. 1977. Unpublished report supplied to authors by Max Ollieu.

Stillwell, M. A. **Pathological aspects of spruce budworm attack.** Forest Sci. 2:174-180; 1956 September.

Thomson, A. J.; Van Sickle, G. A. **Estimation of tree growth losses caused by pest activity.** Can. J. Forest Res. 10:176-182; 1980 June.

Williams, Carroll B., Jr. **Spruce budworm damage symptoms related to radial growth of grand fir, Douglas fir, and Engelmann spruce.** Forest Sci. 13:274-85; 1967 September.

Ferrell, George T.; Scharpf, Robert F. **Stem volume losses in grand firs topkilled by western spruce budworm in Idaho.** Res. Paper PSW-164. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 10 p.

Mature grand firs (*Abies grandis* [Dougl. ex D. Don] Lindl.) were sampled in two stands, one cutover and one virgin, in the Little Salmon River drainage in west-central Idaho, to estimate stem volume losses associated with topkilling. Damage to the stands resulted from three outbreaks of western spruce budworm (*Choristoneura occidentalis* Freeman) in 1922-30, 1952-55, and 1969-78. Stems of the firs were dissected and examined for reductions in height and radial growth, stem deformities, and decay associated with topkills. Merchantable volume losses (to a minimum 4-inch diameter top) were calculated for each outbreak. Greatest volume loss was associated with tops killed by the 1922-30 outbreak. Loss varied widely among the trees and stands sampled. In the cutover stand, which received a sanitation cutting in the late 1960's, firs topkilled by the 1922-30 outbreak averaged losses of 9.5 ft^3 (0.3 m^3), amounting to 11.1 percent of merchantable stem volume. In the virgin stand, losses averaged 26.3 ft^3 (0.7 m^3) or 20.5 percent of stem volume. Topkill-associated decays, caused mainly by Indian paint fungus (*Echinodontium tinctorium* Ell. and Ev.), were responsible for most of this loss. Smaller volume losses were recorded in firs topkilled by the 1952-55 outbreak. Losses per tree averaged 3.3 ft^3 (0.1 m^3) or 5.4 percent in the cutover stand, and 0.5 ft^3 (0.02 m^3) or 0.3 percent in the virgin stand. These losses resulted mainly from height growth reductions rather than decay. No merchantable volume losses were recorded for the 1969-78 outbreak.

Retrieval Terms: Abies grandis, Choristoneura occidentalis, Echinodontium tinctorium, topkilling, growth loss, decay, volume loss

Research Paper PSW-165
is available on microfiche
located on third level in
cabinets behind the information
desk.

United States Department of Agriculture

Forest Service

Pacific Southwest Forest and Range Experiment Station

Research Paper PSW-166

Ranking Independent Timber Investments by Alternative Investment Criteria

Thomas J. Mills   Gary E. Dixon

Authors:

THOMAS J. MILLS, a forest economist, is in charge of the Station's unit studying fire management planning and economics, with headquarters at the Forest Fire Laboratory, Riverside, Calif. He earned degrees at Michigan State University (B.S. in forestry, 1968; and M.S., 1969, and Ph.D., 1972, in forest economics). **GARY E. DIXON**, formerly a forester at the Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo., is now a computer programmer/analyst with the Timber Management Staff, Forest Service, U.S. Department of Agriculture, stationed in Fort Collins. He is a graduate of Colorado State University (B.S. degree in forest science, 1973; M.S. degree in biometrics, 1974; and doctorate in biometrics, 1977).

Mills, Thomas J.; Dixon, Gary E. **Ranking independent timber investments by alternative investment criteria.** Res. Paper PSW-166. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 8 p.

A sample of 231 independent timber investments were ranked by internal rate of return, present net worth per acre, and the benefit/cost ratio—the last two discounted by 3, 6.4, 7.5, and 10 percent—to determine if the different criteria had a practical influence on timber investment ranking. The samples in this study were drawn from a group of timber investments partially financed by Forestry Incentives Program cost-share funds. The investment rankings were quite similar among the three criteria. Under constrained investment budgets, the benefit/cost criteria produced the investment selection with the greatest cumulative present net worth. Under less severe budget constraints, all three criteria produced investment selections with essentially the same cumulative present net worth.

Retrieval Terms: internal rate of return, present net worth, benefit/cost ratio, marginal investments, perpetual rotations, multiple rates of return

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

December 1982

Ranking Independent Timber Investments by Alternative Investment Criteria

Thomas J. Mills   Gary E. Dixon

CONTENTS

IN BRIEF . . .

Mills, Thomas J.; Dixon, Gary E. **Ranking independent timber investments by alternative investment criteria.** Res. Paper PSW-166. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 8 p.

Retrieval Terms: internal rate of return, present net worth, benefit/cost ratio, marginal investments, perpetual rotations, multiple rates of return

Commonly applied criteria for ranking investments can lead to the same investment selections. The investment scale, reinvestment rate, and investment period should be comparable among competing investments. In analyzing timber investments, these comparability adjustments are often not made.

In this study, three investment criteria were applied to a set of 231 independent timber investments to determine how significant the theoretical considerations are in empirical analyses of independent timber investments. The sample investments were drawn from a group of timber investments partially financed by the Forestry Incentives Program cost share funds in 1974. The three criteria tested were internal rate of return (IROR), present net worth (PNW) per acre, and benefit/cost ratio (B/C)—the last two discounted at 3, 6.4, 7.5, and 10 percent.

When the sample of 231 investments were ranked by these three criteria, individual investments were often only displaced by a few rank positions between the several criteria. When the investment budget was severely constrained, the B/C criterion consistently selected investments with the highest cumulative PNW, but the B/C criterion advantage quickly dissipated as the budget constraint was relaxed. An error in the selection of the discount rate to use in the PNW calculation led to greater differences in investment ranking by PNW per acre than were found in comparisons of the IROR ranking with the PNW per acre ranking. Multiple IROR's, a source of ambiguity, occurred so infrequently as to be of little importance.

These empirical results suggest that certain practical aspects of the timber investment analysis situation, such as the certainty of the input data, must be considered along with the theoretical factors when an investment criterion is chosen.

The two most commonly compared criteria for rating the desirability of alternative investments are present net worth (PNW) and internal rate of return (IROR). Each criterion is described in a number of forms in the literature. The benefit/cost ratio (B/C) formulation of the PNW criteria is a common example. The economics literature contains works by Fisher (1930), Lutz and Lutz (1951), Boulding (1955), McKean (1958), Solomon (1959), Hirshleifer (1958, 1970), Mishan (1976), and Bierman and Smidt (1980). Examples in the forestry literature include works by Gaffney (1960) and Bentley and Teeguarden (1965).

A theoretical discussion about the relative merits of the investment criteria has practical relevance since different criteria can lead to dissimilar investment rankings and, therefore, investment selection. As is typical in long-standing debates, much of the difference in rankings lie in the assumptions underlying each criterion.

This paper applies three commonly used criteria to a sample of 231 independent timber investments to determine if they had any practical influence on investment ranking. It also discusses some practical aspects of their use in timber investment analysis.

CRITERIA ASSUMPTIONS AND AMBIGUITIES

This study had four objectives. One was to determine the frequency and severity of ranking differences among independent timber investments. The investments were ranked by three criteria: PNW per acre, IROR, and B/C. PNW per acre was used rather than total PNW for the investment because it partially standardizes for the investment scale, and is also more commonly used in timber investment guides.

Another objective was to determine how much the investment ranking differences are influenced by the discount rate, since the discount rate is seldom known with certainty. This objective also addresses how much ranking differences are influenced by investment diversity and how much the impact of ranking differences is affected by the size of a fixed investment budget.

The third objective was to determine how often multiple IROR's exist for the same investment. The fourth objective was to determine how much the inclusion of perpetual rotations in the analysis, rather than just first rotation results, affects the estimated financial return. Perpetual rotations standardize the investment period among competing investments, but perpetual rotation data are often less accurate than first rotation data, and the extra data collection adds cost to the analysis.

Assumptions

The ranking criteria commonly found in the literature are based on certain assumptions. Assumptions which relate to access to factor markets have been examined by Bentley and Teeguarden (1965). The IROR rule assumes there is no access to the capital market—the total pool of investment capital is fixed. The selection of investments which maximizes the IROR responds correctly to that assumed situation by maximizing the return or "rent" on the limited capital. Similarly, the general PNW criterion assumes that the management factor is fixed so selection based on the PNW criterion maximizes the return to management. The Faustmann or soil-rent PNW formulation maximizes the return to land.

Other important assumptions concern the scale of investment and the return on reinvested intermediate returns. Investment selection based upon PNW and IROR estimates implicitly assumes either that all investments are of the same scale or that they are infinitely divisible and expandable. The PNW criterion assumes that all intermediate net returns prior to the investment maturity date can be reinvested at the rate of discount. The IROR criterion assumes that they can earn the same return as the parent investment from which the net intermediate returns originated.

If the choice among the criteria is based on theoretical considerations only, the analyst's choice should rest on which assumptions are valid in the particular situation being analyzed. If the assumptions for the investment situation meet the conditions underlying criterion A, then criterion A will yield the correct investment selection for that situation.

McKean's (1958) advocacy of the IROR criterion, for example, may very well have arisen from his focus on public investments where the fixed capital assumption is valid in the short run. Annual budgets are generally fixed in public agencies by the annual appropriation process. It can hardly be argued, however, that an annually fixed budget is the same as an absolutely fixed pool of investment capital. Public investments which are not funded this year can be funded from next year's budget and a 1-year delay is trivial when the maturity period for public timber investments typically exceeds 50 years. The fixed capital assumption may be valid for public agencies in underdeveloped countries, but it is difficult to support in the United States

(Gregory 1972), as is apparent from the magnitude of government borrowing in this country.

Ambiguities

In addition to analyzing the validity of underlying assumptions, the analyst should also study the criteria for possible ambiguities. The possibility of multiple IROR's for a single investment, for example, has been cited as an ambiguity of the IROR criterion (Hirshliefer 1970, Mishan 1976). In applying Descartes' rule of signs, there are as many potential IROR's as there are sign reversals in the time stream of net benefits.

We believe that the multiple IROR's are a signal of the ambiguity of the investment itself rather than of the IROR criterion. The multiple IROR's display the ambiguity underlying a particular investment, whereas the same ambiguity remains hidden in the PNW calculation. The estimated PNW yields equally ambiguous results when the discount rate is varied.

Using Gansner and Larsen's (1969) example investment, which could correspond to an increment in timber management intensity, a net benefit time stream of:

year 0	= −$ 25.00
year 10	= + 112.25
year 20	= − 169.96
year 30	= + 80.78

produces IROR's of 2, 4, and 6 percent. A PNW which is positive at discount rates of 0 to 2 percent, negative at rates of 2 to 4 percent, positive at rates of 4 to 6 percent, and negative at rates above 6 percent is no less ambiguous than the multiple IROR's. If the correct discount rate were known with certainty, the PNW variability for this example investment would not create ambiguity because there is a single PNW for a single discount rate. Perfect information is a harsh assumption, however, as is evident from the long-standing debate over the appropriate discount rate for public sector investments. The continuing debate over discount rates for long-term forestry investments also shows that the question is not likely to be answered with finality in the near future (Row and others 1981).

The multiple IROR can be solved by (a) compounding all positive intermediate net benefits to the end of the investment period, using the "lending" rate or alternative rate of return, and (b) all negative intermediate net benefits to the beginning of the period, using the "borrowing" rate (Marty 1970). The IROR calculated from this simple time stream of one positive and one negative net benefit, which is called a composite internal rate of return by Marty, always yields a single IROR. Use of the composite IROR avoids the problem of the more commonly applied form of IROR, which assumes that intermediate net benefits from different investments earn different rates of return when they are in turn reinvested. The composite IROR calculation forces inclusion of an explicit reinvestment rate, thus permitting its standardization among competing investments. An explicit reinvestment rate can lead to substantially different IROR estimates if the reinvestment rate is much different from the IROR (Schallau and Wirth 1980).

The IROR criterion can be ambiguous when net disinvestment actions are being evaluated. The IROR is infinite when there are no negative net benefits in the investment time stream, as in alternative commercial thinning regimes. The IROR may also be very high for low-cost precommercial thinnings which increase yields substantially.

It is generally conceded that all three commonly employed investment criteria used in this study bisect the ranking of investments at the same alternative rate of return or discount rate threshold *if* the competing investments are independent and *if* the investment budget is not fixed. The same subset of investments is accepted and the same subset is rejected by all three criteria. Investments are independent if the undertaking of one does not materially affect the net benefit time stream of another or exclude another investment from consideration altogether. Although not completely independent, timber investments can generally be treated as such as long as they are treatments of separate pieces of land. Alternative investment or treatment designs on the same piece of land are not independent investments.

Unfortunately, as they are conventionally applied, the three selection criteria may rank investments differently. The three criteria need not, therefore, produce the same selection of investment cases when the investments are mutually exclusive or when the pool of investment capital is fixed at a less than optimum level.

These theoretically possible ranking differences disappear if the investments are all "normalized" (Mishan 1976). The three conditions of normalization are standardization of (1) the reinvestment return on intermediate positive net benefits, (2) the scale of the investment, and (3) the investment maturity period. One way to standardize the reinvestment rate in the IROR criterion has already been explained—calculation of Marty's (1970) composite IROR. One way to standardize for the time horizon among timber-growing investments is to follow the first rotation investment with successive rotations into perpetuity. Standardization for scale is more cumbersome, but the same end can be achieved by identifying, from among the set of all possible investment combinations, the investment subset that maximizes the value of the selected investment criterion (Mishan 1976).

All of these normalization steps are seldom used in practice, especially the standardization of investment scale. Most timber investment guides use unnormalized PNW per acre (Beuter and Handy 1974) or IROR (Manthy 1970). If we fail to take the normalization steps and choose a criterion on the basis of theoretical considerations alone, then the selection among criteria must be based upon the soundness of the respective assumptions for the particular investment decision being evaluated. We feel that the assumptions underlying the PNW criteria are generally more sound for public sector timber investment situations than are the IROR assumptions, but the failure to adjust for scale differences may cause serious errors.

What if all the criteria produce the same investment selections? If the investment selections are the same in a particular evaluation, or substantially so, then the theoretical distinctions are not very relevant in practical applications. It is our thesis that if the ranking results are similar, the selection of an investment criterion should be swayed by practical considerations, such as the relative sensitivity of the criteria to data variability.

METHODS AND RESULTS

The timber investments analyzed in this study were drawn from the 1433 sample investments evaluated by Mills and Cain (1978) from the 1974 Forestry Incentives Program. The investments are independent and structured in a marginal analysis format. Each criterion estimates the financial return on the increment of management activity applied to the timber stand rather than the entire management activity. The first rotation was followed by a second rotation and the second was repeated into perpetuity. All costs and prices were expressed in real dollars. The initial investment cost includes both the private and public cost share, which in combination equal the direct cost.

A single time stream of net benefits was constructed for each investment. The IROR, PNW per acre, and B/C were calculated from each time stream, the latter two criteria at 3, 6.4, 7.5, and 10 percent discount rates. No normalization of investment scale nor reinvestment rate was made, but the perpetual rotations normalize for the investment period.

The 3 percent rate was an arbitrarily low rate which coincidentally is close to the 4 percent rate proposed for land management planning analysis on Forest Service lands (U.S. Dep. Agric., Forest Serv. 1980; Row and others 1981). The 6.4 percent was the Water Resource Council rate at the time the calculations were made (U.S. Dep. Agric., Soil Conserv. Serv. 1973), 7.5 percent was similar to the long-term borrowing rate of government bonds, and 10 percent was the rate that the Office of Management and Budget (U.S. Office of Manage. and Budget 1972) estimated was the real rate of return on investments in the private sector.

Different subsets of the total 1433 investments were evaluated to fulfill each of the four study objectives. Because of the similarities among some of the 1433 cases, a subset of the 231 investments was selected to determine the frequency and impact of ranking differences (objective 1). The 231-investment subset contained examples of most of the major silvicultural practices commonly encountered throughout the country. Investment cases in southern pine, northern pine, other northern conifer, central hardwoods, northern hardwoods, and western conifer species groups were represented. The silvicultural practices represented included planting on bare land, site preparation and planting, understory release, precommercial thinning, intermediate treatments, pruning, and pruning and intermediate treatments together. The mean financial returns on the sample cases were higher than has generally been estimated for timber investments. The mean IROR of the 231 cases was 16.7 percent, the mean PNW per acre at the 7.5 percent discount rate (at 7.5 pct) was $311, and the mean B/C (at 7.5 pct) was 7.8.

These 231 investments were subdivided into six similar groups to determine if investment diversity influenced the ranking results (objective 2). The entire 1433 investments were searched for multiple IROR's (objective 3). A subset of 90 investments was evaluated to determine the impact of removing second rotation data (objective 4).

The rankings of 231 investments were compared two ways. The first comparison was made by measuring the percentage difference in investment rank. The percentage rank difference is a convenient descriptive device for identifying ranking patterns even though rank differences themselves do not measure the cost of any investment selection errors. The rankings were then compared by measuring the total PNW of the program of investments that would be selected from the different rankings to fulfill each of several fixed investment budgets. The difference in the total PNW of the selected investment programs provides an estimate of the financial return foregone if the wrong investment criterion is selected.

The use of the PNW of the total program of investments as a yardstick for comparison implicitly assumes that total PNW is the best investment criterion. Total PNW was used because we judged its underlying assumptions to be more commonly valid in public sector timber investment situations than those underlying IROR. The total IROR or B/C could also have been used as a common measurement for comparison.

Influence on Rank Position

The first method for quantifying the rank position differences—the percentage rank difference—is the absolute percentage difference in rank position of an individual investment when ranked by one financial return criterion as opposed to another. It was calculated as follows:

$$\text{percentage rank difference} = \left| \frac{R_i - R_j}{n} \right| (100 \text{ percent})$$

in which

R_i = rank position by criterion i

R_j = rank position by criterion j

n = number of investments in the rank (231 cases)

For example, if case A is in rank position 93 in the IROR rank and in position 115 in the PNW per acre (at 7.5 pct) rank, the percentage rank difference is 9.6. Case A is ranked 9.6 percent higher on the investment list developed from IROR than the one developed from PNW per acre (at 7.5 pct).

The percentage rank differences for individual cases were then grouped into percentage rank difference classes. For example, if 35 cases had percentage rank differences between 0 and 5 percent, they were grouped. The number of cases in the class was then expressed as a percentage of the total number in the list. In the example, 15 percent of the cases (35/231) have rank differences of 0 to 5 percent. The mean percentage rank differences for all the cases were calculated for all of the 36 paired comparisons possible from the financial return criteria tested here: IROR, PNW per acre, and B/C at 3, 6.4, 7.5, and 10 percent discount rates.

Several ranking patterns were apparent. First, roughly half (42 to 53 pct) of the investments had ranking differences of 5 percent or less when IROR, PNW per acre (at 7.5 pct) and B/C (at 7.5 pct) were compared (*table 1*). Less than one-quarter of the investment cases (10 to 23 pct) had rank differences of more than 20 percent. The mean difference varied from 8 to 13 percent for these three comparisons.

Second, the IROR ranking of investments was more different from the PNW per acre (at 7.5 pct) and the B/C (at 7.5 pct) rankings than the latter two were from each other. The closeness of the IROR rank to the PNW per acre and B/C ranks increased dramatically, however, as the discount rate was increased. For example, the mean percentage rank difference decreased from 21 percent when IROR was compared to PNW per acre (at 3 pct) to 10 percent when IROR was compared to PNW per acre (at 10 pct). PNW per acre and B/C rankings were constructed with higher discount rates to determine if this convergence with the IROR rank continued, but most of the convergence had occurred by the 10 percent discount rate.

Third, the investment rankings constructed from the same investment criterion calculated at different discount rates sometimes differed more than the ranks constructed by different criteria. For example, when the PNW per acre rank at 3 percent was compared to the PNW per acre at 10 percent, only 24 percent of the cases had percentage rank differences of 5 percent or less. The IROR and PNW per acre (at 10 pct) rankings show more agreement than that; 50 percent of the cases had ranking differences of 5 percent or less. This discount rate effect is unimportant if the correct discount rate is known with certainty, but that is an heroic, and generally invalid, assumption in the public sector.

Impact under Constrained Budgets

The IROR criterion should be used if the total pool of investment capital is fixed. The B/C criterion is probably more appropriate in constrained budget conditions than PNW unadjusted for investment scale differences because B/C more closely corresponds to maximizing the added PNW per dollar of constrained budget. In actual practice, all three criteria have been used in fixed budget situations in the past.

Budget levels from $20,000 to $140,000 were tested in $20,000 increments. Only the first-year investment cost was considered constrained by the budget. The total PNW of each investment was calculated by multiplying the acreage of the investment case by the PNW per acre. The total PNW of the investments selected to fulfill each fixed budget level is the sum of the total PNW for each investment case. This total PNW of the program of investments is termed the "program PNW." The program PNW was always calculated using the same discount rate that was used to construct the PNW per acre and B/C ranks. We prorated investment cases at the budget margin by using average costs per acre, so that the budget level was met exactly.

To facilitate comparison, the program PNW that ranked highest among the criteria being compared at that budget level was specified as 100 percent. The PNW of the investment program selected from other financial return criteria was then recorded as a percentage of that highest program PNW. For example, if the program PNW's at a $40,000 budget level were $36,000, $43,000, and $54,000 for IROR, PNW per acre (at 7.5 pct), and B/C (at 7.5 pct), respectively, the B/C criterion was shown at 100 percent. The program PNW for IROR was 67 percent and for PNW per acre was 80 percent of the maximum. The fall down in program PNW is a direct measure of the cost of selecting an incorrect investment criterion.

At low budget levels, the B/C criterion consistently produced the largest program PNW of the three financial return criteria tested at all four discount rates. The PNW per acre consistently provided the next highest program PNW and the IROR provided the lowest program PNW. The B/C selection was probably superior to that of PNW per acre because the B/C ratio more closely approximates added PNW per dollar of constrained budget than does PNW per acre. The B/C criterion is also more neutral to investment scale than unnormalized PNW per acre. A direct criterion of PNW per dollar of constrained budget would probably have performed better than B/C (Lorie and Savage 1959).

The program PNW shortfall resulting from application of the PNW per acre and IROR criteria declined as the budget constraint was relaxed. For example, the IROR's program PNW at the first budget level was 26 percent below the maximum program set by the B/C (at 7.5 pct), but the IROR's program PNW was only 5 percent below at the third budget level (*table 2*). The program PNW from the IROR criterion was at least 90 percent as large as the maximum program PNW by the third budget level for all discount rates except 3 percent. The program PNW for the PNW per acre criterion was at least 95 percent of the maximum by the third budget level for all discount rates.

Table 1—*Differences in rank position of 231 forestry investment cases in paired-rank comparisons using criteria of internal rate of return (IROR), percent net worth (PNW) per acre, and benefit/cost (B/C) ratio.*

Criteria (and discount rate) compared	Difference (pct) in rank position							Mean difference
	0-5	6-10	11-20	21-30	31-40	41-50	51+	
	Percent of Cases							*Percent*
IROR and . . .								
PNW per acre (3)	19	17	22	13	11	8	10	21
PNW per acre (6.4)	37	17	18	10	10	5	3	15
PNW per acre (7.5)	42	18	17	11	5	6	2	13
PNW per acre (10)	50	17	18	6	5	4		10
B/C (3)	25	12	23	16	8	9	7	20
B/C (6.4)	42	13	20	13	7	4		12
B/C (7.5)	47	16	14	16	4	3		11
B/C (10)	54	20	18	7	1	1		7
PNW per acre (3) and . . .								
PNW per acre (6.4)	34	27	25	7	3	3		10
PNW per acre (7.5)	30	23	30	8	5	2	1	12
PNW per acre (10)	24	16	29	18	6	4	3	16
B/C (3)	50	25	19	3	2	1		7
B/C (6.4)	27	19	28	15	6	4	1	14
B/C (7.5)	23	17	28	18	7	5	2	16
B/C (10)	19	17	26	18	10	4	6	19
PNW per acre (6.4) and . . .								
PNW per acre (7.5)	86	11	3					3
PNW per acre (10)	47	28	19	5				7
B/C (3)	37	17	27	9	6	2	1	12
B/C (6.4)	50	24	16	8	2			8
B/C (7.5)	50	21	8	7	1	2		8
B/C (10)	39	23	20	11	4	2	1	11
PNW per acre (7.5) and . . .								
PNW per acre (10)	64	25	9	1				5
B/C (3)	34	18	28	9	7	2	2	13
B/C (6.4)	52	20	19	6	2			8
B/C (7.5)	53	20	17	6	2	1		8
B/C (10)	45	28	15	6	4	2		9
PNW per acre (10) and . . .								
B/C (3)	28	19	24	16	6	4	3	15
B/C (6.4)	45	21	23	9	1	1		9
B/C (7.5)	52	22	18	8				8
B/C (10)	57	23	11	6	3			7
B/C (3) and . . .								
B/C (6.4)	34	19	28	12	5	1	1	12
B/C (7.5)	31	17	27	14	7	1	1	14
B/C (10)	25	17	24	16	12	3	3	17
B/C (6.4) and . . .								
B/C (7.5)	84	15	2					3
B/C (10)	47	26	22	5				7
B/C (7.5) and . . .								
B/C (10)	66	22	11					5

Table 2—*Percent of the largest program present net worth*[1] *achieved when investments are selected from 231 investments ranked by internal rate of return (IROR), present net worth (PNW) per acre, and benefit/cost (B/C)*

Constrained budget level (thousand dollars)	IROR	PNW per acre[2]	B/C[2]
		Percent	
20	74.4	89.1	100.0
40	83.2	92.7	100.0
60	94.5	95.7	100.0
80	98.2	97.9	100.0
100	100.0	99.5	100.0
120	100.0	100.0	100.0
140	100.0	100.0	100.0

[1]Program PNW is defined as the accumulated PNW of the entire program of investments that are selected from the various rankings to fulfill each of the fixed investment budgets.
[2]Discount rate of 7.5 percent.

The program PNW's for the various criteria converged rapidly because individual investments were often displaced by only a few rank positions from one criterion to another. This displacement was demonstrated by the percentage rank difference measurements. If the constrained budget were large enough to finance the top 75 investments, it made little difference if an investment's rank was 25 or 45.

The program PNW from the IROR rank was much further behind the B/C criterion maximum at low discount rates than at high ones. The IROR's program PNW at the first budget level was 38 percent of the maximum set by B/C (at 3 pct). The shortfall gradually declined as the discount rate increased. At the 10 percent discount rate, the IROR's program PNW was 87 percent of the maximum at the first budget level. This difference was probably related to the convergence of the discount rate and the mean IROR for the investment sample.

The 231 sample investments represent a diversity typical in the development and evaluation of national-scope timber investment programs. The six subsets of silviculturally similar investments were constructed to determine whether investment diversity affects ranking differences. These silviculturally similar groups are more typical of the timber investment diversity faced by a small landowner.

The constrained budget results from the subsets of similar investments were consistent with the results from the more diverse set of 231 investments in two respects (*table 3*). The B/C criterion almost invariably yielded the greatest program PNW, and the program PNW's from the different criteria converged as the amount of the fixed budget increased. Although the budget levels are not directly comparable, it appears that the program PNW's converged faster for the more similar investment subsets than they did for the full sample.

Contrary to the results from the 231-investment set, however, the IROR's program PNW was consistently greater than that of the PNW per acre criterion. The shortfall of the IROR's program PNW below the maximum established by the B/C criterion was negligible in all situations except the first budget level in two subsets. There is no readily apparent reason for this relative change.

Table 3—*Percent of the largest program present net worth (PNW)*[1] *achieved when investments are selected from alternative rankings of six similar investment groups, by budget level and investment criteria applied*

Investment group[1]	Budget level (thousand dollars)	Internal rate of return	PNW per acre[2]	Benefit/cost[2]
		Percent		
Planting of southern pine (41)	2.5	81.9	62.3	100.0
	5.0	99.9	77.3	100.0
	7.5	100.0	83.5	97.6
	10.0	100.0	92.8	100.0
	12.5	99.6	96.5	100.0
	15.0	99.9	95.8	100.0
	17.5	100.0	93.5	100.0
	20.0	99.9	98.3	100.0
Planting of northern conifers (20)	2.5	100.0	100.0	100.0
	5.0	100.0	100.0	100.0
	5.0	100.0	100.0	100.0
	7.5	100.0	100.0	100.0
Planting of western conifers (13)	2.5	100.0	79.3	100.0
	5.0	100.0	99.8	100.0
	7.5	100.0	99.8	100.0
Understory release of southern pine (14)	2.5	89.9	100.0	100.0
	5.0	100.0	99.6	99.2
	7.5	100.0	100.0	100.0
Intermediate treatment in oak-hickory and cove hardwood (15)	2.5	98.3	92.6	100.0
	5.0	98.7	99.8	100.0
	7.5	100.0	100.0	100.0
	10.0	100.0	100.0	100.0
Intermediate treatment in northern hardwoods (23)	2.5	94.2	86.4	100.0
	5.0	98.2	94.6	100.0
	7.5	98.8	95.4	100.0
	10.0	100.0	100.0	100.0

[1]Values in parentheses show number of investments.
[2]Discount rate of 7.5 percent.

Frequency of Multiple Internal Rates of Return

Silvicultural practices analyzed as marginal investments usually contain more than one sign reversal in their time stream of net benefits. The time stream of net benefits often starts then with a treatment (negative net benefit), followed by a harvest of the treated stand (positive net benefit), and followed in turn by the foregone harvest of the timber stand that would have occurred if the stand had not been treated (negative net benefit). A time stream with two sign reversals has the potential for two unique IROR's.

All 1433 investments originally sampled from the 1974 Forestry Incentives Program were searched for multiple IROR's. Only two had more than one IROR. One was a Douglas-fir planting investment with IROR's of 2.7 and 12.9 percent. The other was a ponderosa pine pruning investment which had 3.7 and 7.8 percent IROR's.

Effect of Perpetual Rotations

All timber investments analyzed to this point included a second timber rotation which was repeated into perpetuity. Ninety investments were drawn from the original 1433 investments to test the impact of removing the second and perpetual rotations. These 90 were then combined into 5 subsets of similar investments (*table 4*). The length of time between the treatment and the end of the first rotation was 40 to 50 years for most of the sample cases. The mean IROR, PNW per acre (at 7.5 pct), and B/C (at 7.5 pct) were calculated for the investments in each subset, both with and without the second and perpetual rotations.

The impact on IROR of removing the perpetual rotations was very low. The greatest IROR reduction was 0.13 percentage points of interest or a 0.01 percent decline. The mean B/C ratio was affected more, but the mean change was still small. The greatest impact was on the PNW per acre criterion. The average PNW per acre reduction was $11/acre or 11.45 percent.

Perfect knowledge is usually assumed in theoretical discussions of the several investment criteria, yet it never exists in reality (Hirshleifer 1958). This is especially relevant in forestry investments with their very long maturity periods. The relative effect of input data uncertainty on the performance of the several investment criteria should be considered.

This relatively lower sensitivity of IROR to the analysis simplification of removing the perpetual rotations is similar to the results derived by Mills and others (1976) in their analysis of financial return sensitivity to the possibility of data errors. They estimated the percentage change in input data required to yield an IROR which was 1 percent of interest higher or lower than the IROR using the base data. A comparable threshold for the effect of input data changes on estimated PNW was then calculated to deter-

Table 4—*Estimated mean financial return with and without the second and perpetual timber rotation for five groups of similar investments, by investment criteria applied*

Investment group[1]	Average first rotation	Internal rate of return	Present net worth per acre[2]	Benefit/cost[2] ratio
	Years	*Pct*	*Dollars*	
Site preparation and plant southern pine, Alabama (20):	44.2	-		
With perpetual rotations		11.37	155.25	3.88
With first rotation only		11.33	139.69	3.78
Intermediate treatment of southern pine and oak-pine, Louisiana (19):	44.4			
With perpetual rotations		13.16	150.47	5.82
With first rotation only		13.15	131.80	5.69
Plant northern conifers, Michigan (25):	116.8			-
With perpetual rotations	-	8.19	6.72	1.58
With first rotation only	-	8.19	6.66	1.57
Intermediate treatment of oak-hickory, Pennsylvania (5):	50.6			
With perpetual rotations	-	15.75	187.09	5.10
With first rotation only	-	15.75	181.94	5.01
Intermediate treatment of northern hardwoods, Michigan (21):	48.0	-		
With perpetual rotations	-	12.67	50.81	2.97
With first rotation only	-	12.54	35.20	2.47

[1]Values in parentheses show number of investments.
[2]Discount rate of 7.5 percent.

mine if the estimated IROR was more or less sensitive than estimated PNW to input data changes.

Their results showed that the estimated IROR was far less sensitive to input data changes than was the estimated PNW for investments which had an IROR that approached the discount rate. Those investments are the very ones in which the decisionmaker wants the most confidence, because they are near the acceptance-rejection threshold. The lower sensitivity of the IROR criterion to input data uncertainty translates directly into reduced data collection costs because data standards can be less stringent. The costs of data collection are just as important as the costs of errant investment selections.

DISCUSSION AND CONCLUSIONS

Three previous studies evaluated how much the ranking of independent timber investments differed among the three major investment criteria and all three reached the same conclusion. Ranking differences did occur, but with very low frequencies.

Webster (1968) analyzed 23 independent timber investments in Pennsylvania. The investment cases were structured as marginal investments. That is, the treatment which represented the investment was an increment of management intensity added to some base level management. The 23 cases were about equally split between conifer plantings and intermediate treatments in cove hardwoods, oak-hickory, and northern hardwoods. The study included the IROR, PNW, and B/C criteria, the last two at 3 and 6 percent discount rates. Webster found some difference in ranking, but the relative displacement on the rank was usually only a few positions.

Haley (1969) analyzed 12 Douglas-fir investments in British Columbia using a marginal analysis format. Eight of the investments were reforestation and four were precommercial thinning. The two investment sets were ranked separately by IROR, PNW, and B/C; the last two at 3, 4, 5 and 6 percent discount rates. The rankings differed, but only slightly, and Haley concluded that the differences were not large enough to be of practical importance.

Goforth and Mills (1975) ranked 21 independent timber investments by IROR, PNW per acre, and B/C, the last two discounted at 5 percent. The marginal investments included reforestation, understory release, and precommercial thinning. Species included Douglas-fir, fir-spruce, lodgepole pine, ponderosa pine, and the major southern pines. There were only minor differences in the investment rankings.

These studies reached similar conclusions but each evaluated a small set of investments, many of the investments were similar, and a range of discount rates was not always studied. Their empirical results may not hold for a larger set of more diverse timber investments, such as might be encountered by a large private landowner or in the development of a national-scope public timber investment program. This study was undertaken to overcome those limitations.

Important theoretical distinctions underlie the several investment criteria. And the analyst must understand these distinctions before choosing a criterion for a particular analysis. If the theoretically possible difficulties which plague the criteria occur infrequently, however, practical considerations should have a major effect on the criterion choice.

In this study, the theoretically possible ambiguity of multiple IROR's was not a problem. They were only found in two of the 1443 investments analyzed. When the subset of 231 independent investments were ranked by IROR, PNW per acre, and B/C, ranking differences did occur, but the displacement of an investment was usually only a few rank positions.

Given a fixed investment budget, the B/C criterion consistently produced the selection of investments which had the highest cumulative PNW. The advantage of the B/C criterion quickly disappeared, however, when the magnitude of the fixed budget was increased. The performance of the several investment criteria was similar at higher budget levels. Given large investment budgets, the consequences of ranking differences between the criteria were minimal, particularly if the investments were similar silviculturally.

In contrast to the general similarities in investment rankings displayed by the criteria, a differential sensitivity to input data errors or uncertainties was evident. The results from the PNW per acre criterion were much more affected by the removal of the second and perpetual rotations than was the IROR results. Changes in the discount rate, which are comparable to errors in the discount rate specification, also materially affected the PNW per acre investment ranking. The appropriate discount rate for public investments has been, and probably will be, a continuing point of debate. An error in the selection of the proper discount rate for the PNW per acre criterion may have more of an impact on investment ranking than the use of another investment criterion altogether.

Only independent timber investments were evaluated in this study. The differences that result from application of the different investment criteria would be more significant for mutually exclusive investments. A difference in rank position of a few places is quite unimportant if the investments are independent but a lower ranking would lead to the discarding of an investment from a group of mutually exclusive investments.

It is apparent from the literature that the several criteria produce investment ranking differences, that multiple IROR's do occur, and that the removal of perpetual rotations does affect financial return estimates. In this study, empirical results suggest that the practical importance of these theoretical problems for a sample of 231 independent timber investments was small.

REFERENCES

Bentley, William R.; Teeguarden, Dennis E. **Financial maturity: a theoretical review.** Forest Sci. 11(1):76–87; 1965 January.

Beuter, John H.; Handy, Jeffrey K. **Economic guidelines to reforestation for different ownerships; a case study for the coast range of western Oregon.** Res. Paper 23. Corvallis, OR. School of For., Oregon State Univ., 1974. 69 p.

Bierman, H., Jr., Smidt, S. **The capital budgeting decision: economic analysis of investment projects.** New York: MacMillan Co.; 1980. 544 p.

Boulding, Kenneth E. **Economic analysis.** 3d ed. New York: Harper and Brothers; 1955. 905 p.

Fisher, Irving. **The theory of interest.** New York: MacMillan Co.; 1930. 566 p.

Gaffney, M. Mason. **Concepts of financial maturity of timber and other assets.** A. E. Inf. Series 62. Raleigh, NC: North Carolina State Univ.; 1960. 105 p.

Gansner, David A., Larsen, David N. **Pitfalls of using internal rate of return to rank investments in forestry.** Res. Note NE-106. Broomhall, PA: Northeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture; 1969. 5 p.

Goforth, Marcus H., Mills, Thomas J. **A financial return program for forestry investments; including sensitivity results to data errors.** Agric. Handb. 488. Washington, DC: U.S. Department of Agriculture; 1975. 18 p.

Gregory, G. Robinson. **Forest resource economics.** New York: Ronald Press Co., 1972. 548 p.

Haley, David. **A comparison of alternative criteria for the evaluation of investment projects in forestry.** Vancouver, BC: Univ. British Columbia. 1969. 93 p.

Hirshleifer, J. **On the theory of optimal investment decisions.** J. Polit. Econ. 66(4):329–352; 1958 April.

Hirshleifer, J. **Investment, interest, and capital.** Englewood Cliffs: Prentice-Hall, Inc.; 1970. 320 p.

Lorie, James H.; Savage, Leonard J. **Three problems in rationing capital.** In: Solomon, Ezra, ed. The management of corporate capital. Glencoe: Free Press; 1959: 56–66.

Lutz, Frederick; Lutz, Vera. **The theory of investment of the firm.** Princeton: Princeton Univ. Press; 1951. 253 p.

Manthy, Robert S. **An investment guide for cooperative forest management in Pennsylvania.** Res. Paper NE-159. Broomhall, PA: Northeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture; 1970. 59 p.

Marty, Robert. **The composite internal rate of return.** Forest Sci. 16(3): 276–279; 1970 September.

McKean, Roland N. **Efficiency in government through systems analysis.** New York: John Wiley; 1958. 336 p.

Mills, Thomas J.; Cain, Daria. **Timber yield and financial return performance of the 1974 Forestry Incentives Program.** Res. Paper RM-204. Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1978. 56 p.

Mills, Thomas J.; Goforth, Marcus H.; Hart, Thomas P. **Sensitivity of estimated financial returns on timber investments to data errors.** Res. Paper WO-31. Washington, DC: Forest Service, U.S. Department of Agriculture; 1976. 31 p.

Mishan, Edward J. **Cost-benefit analysis.** New York: Praeger Publishers; 1976. 454 p.

Row, Clark; Kaiser, H. Fred; Sessions, John. **Discount rate for long-tern Forest Service investments.** J. For. 79(6):367–369, 376; 1981 June.

Schallau, C. H.; Wirth, M. E. **Reinvestment rate and the analysis of forestry enterprises.** J. For. 78(12):740–742; 1980 December.

Solomon, Ezra, ed. **The management of corporate capital.** Glencoe: Free Press; 1959. 327 p.

U.S. Department of Agriculture, Forest Service. **Forest Service Manual 1970** (draft). Washington, DC; 1980.

U.S. Department of Agriculture, Soil Conservation Service. **Watersheds Memorandum—92** (rev. 6). Washington, DC; 1973. 3 p.

U.S. Office of Management and Budget. **Circular A-94.** Washington, DC; 1972. 4 p.

Webster, Henry H. **Profit criteria and timber management.** J. For. 63(4): 260–266; 1968 April.

United States Department of Agriculture

Forest Service

Pacific Southwest Forest and Range Experiment Station

Research Paper PSW-167

Land Management Planning: a method of evaluating alternatives

Andres Weintraub **Richard Adams** **Linda Yellin**

The Authors:

ANDRES WEINTRAUB is professor of industrial engineering, Universidad de Chile, Santiago, and an assistant research engineer, University of California, Berkeley. This publication reports a study done in cooperation with The University of California. **RICHARD ADAMS**, formerly District Ranger, Mammoth Ranger District, Inyo National Forest, in northern California, is now District Ranger, Lowman Ranger District, Boise National Forest, in Idaho. **LINDA YELLIN**, at the time of this study, was an operations research analyst at the Operations Research Center, University of California, Berkeley.

Acknowledgments:

We thank the following persons for their helpful comments in their review of this paper: Melvin J. Bobier, Daniel I. Navon, Giuseppe Rensi, and Gideon Schwarzbart.

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

December 1982

Land Management Planning: a method of evaluating alternatives

Andres Weintraub Richard Adams Linda Yellin

CONTENTS

Whether they are in public or private agencies, land management planners must carefully evaluate the effects of the alternatives being considered. Forest Service, U.S. Department of Agriculture planners deal with a variety of activities ranging from National Forest Management Plans, such as environmental studies, to designs of specific projects, such as recreation complexes. They need a way of reaching decisions in a rational, efficient approach—one in which all aspects of significance, such as environmental, economic, cultural, and social conditions, are considered.

Implicit in such work is a need to develop an evaluation procedure (Brown 1976; U.S. Dep. Agric., Forest Serv. 1976). Some investigators have proposed specific methodologies to carry out this process, illustrated by case studies (U.S. Dep. Agric., Forest Serv. 1975).

This paper describes a heuristic procedure for selecting land management plans from among mutually exclusive alternatives and its application to a case study of the Truckee-Little Truckee Rivers Planning Unit, Tahoe National Forest, in northern California.

LAND MANAGEMENT PLANNING PROCEDURE

The planning procedure described in this report is detailed in an earlier report (Weintraub 1978). Consisting of 15 steps, the process is structured in the sense that it covers sequentially all necessary planning steps. It does, however, permit changes to accommodate a particular case.

To investigate the soundness of the procedure, we tested it on an actual problem. For this purpose, we used an environmental impact study completed in 1975 (U.S. Dep. Agric., Forest Serv. 1975, 1976). Our intent was to replicate that earlier study by using the proposed method. As it turned out, all aspects that had been covered in the environmental impact study could be repeated—and in the more structured form with the proposed method. Furthermore, several additional notions of interest and improvement could be introduced with its use.

The results obtained in this application are not important in most cases by themselves, but just to serve as an illustration of how to apply the method. The usefulness of the method can be deduced by the structure it provides for following the steps needed in developing the environmental impact statement, and by suggesting additional aspects of interest not covered in the original study.

The 15 steps forming the proposed method are:

1. Define the boundaries of the problem—area of study and types of alternatives.
2. Identify decision-influencing elements, criteria, or goals.
3. Identify major forms of activities and areas where they can be carried out.
4. Define basic alternatives to be considered.
5. Define the major types of impacts or effects of each alternative in relation to the goals established.
6. Screen the alternatives.
7. Determine for the alternatives passing the screening their impacts in a disaggregated and quantified form in relation to established goals.
8. Reduce the number of impacts to be considered by discarding and aggregating those according to the established goals.
9. Check the legal, institutional, environmental, political, and economic acceptability of each alternative.
10. Generate new alternatives that are significantly different from those already proposed, and return to Step 6.
11. Determine if new areas of concern or types of impact need to be defined; if yes, return to step 6, and check alternatives.
12. Present the summarized results in adequate visual format.
13. Evaluate alternatives presented in Step 12.
14. Generate new alternative views—those marginally different from the ones selected in Step 13.
15. Select the preferred alternative.

TRUCKEE-LITTLE TRUCKEE CASE STUDY

Following is a description of how the procedure was applied in a case study of a Truckee-Little Truckee Rivers Planning Unit environmental impact statement.

Problem Definition

The area under study is the Truckee-Little Truckee Rivers Planning Unit. A land-use plan is to be developed with consideration of physical and socioeconomic impacts to the region. The alternatives to be evaluated correspond to varying production levels of timber, range, goods and services within the planning unit (U.S. Dep. Agric., Forest Serv. 1975, 1976).

Criteria or Goals

For this study, four broad types of goals were identified: physical, (or the preservation of environmental quality), economic, social, and institutional.

1. Physical goals:
   a. Maintain visual quality (scenic beauty)
   b. Maintain water quality, runoff
   c. Protect wildlife, wilderness
   d. Protect fish habitat
   e. Protect endangered species
   f. Maintain air quality within standards
   g. Protect cultural, historical, archaeological sites
   h. Maintain noise levels within standards
   i. Maintain soil quality (avoid erosion)
   j. Beware of hazards created (avalanche, landslide, fire)
   k. Have a good pattern of use of natural resources
   l. Dispose of solid and liquid wastes
   m. Use water within available allocations
2. Economic goals:
   a. Increase value of outputs and services at national level
   b. Enhance opportunities for economic development in region, especially in rural communities
   c. Have economically and environmentally consistent timber production in the long and short run
   d. Increase range capacity through improved management and controlled development
3. Social goals:
   a. Ensure equal opportunity for all people to use National Forests
   b. Provide for a variety of recreation opportunities in the present and the future
   c. Enhance social well being:
      - Promote a good distribution of income
      - Have acceptable patterns and distribution of employment
      - Do not harm social structures of communities
      - Have acceptable distribution of negative impacts of plan
      - Avoid overcrowding of community services and facilities; e.g., road congestion, housing, police, schools
4. Institutional goals:
   a. Maintain (or improve) National Forest landownership pattern that efficiently advances public programs
   b. Plan development with recognition of other governmental (local, State and Federal) plans

Major Activities

Six major activities for the area were identified. Most of the planning unit provides for recreation. In the summer recreation is developed along the Truckee River from Tahoe City to Truckee in the complex containing Boca, Prosser and Stampede Reservoirs in Dog Valley, along the Little Truckee River and Sagahen Creek and the Roadside Rest on Interstate Highway 80 at Donner Summit. In the winter, most of the major winter recreation activities are found in this planning unit. Ski resorts are located at Alpine Meadows, Boreal Ridge, Powder Bowl, Sugar Bowl and Blythe Arena. Possible development in Mt. Lola-Independence Lake region is being considered. Visitors to recreation areas often spill over to neighboring communities.

Timber and range production is found throughout the unit. Range production is or could be developed in the 13 grazing allotments of Boca, Sagahen, Kyburz, Summit, Webber Lake, Truckee River, Anderson Peak, Ever, Payen, Perazzo, Bickford, Independence, Smithneck, and Big Meadows. Timbering takes place throughout National Forest lands.

Fishery and wildlife resources exist in abundance. Fish are stocked in most of the major lakes in the unit, as well as the Truckee River, Little Truckee River, and Donner Creek. A pure strain of the Lahotan cutthroat trout is native to Independence Lake.

The major water resources consist of the Truckee River Basin. The Little Truckee River and Prosser Creek contribute to the Stampede, Boca and Prosser Reservoirs. Other lakes in the unit include Donner, Independence and Webber Lakes.

The planning unit has no area classified as a wilderness. Possible wilderness areas include the Castle Peak area, the Pacific Crest Trail, and the Granite Chief inventoried roadless areas.

Basic Alternatives

In the study, four basic alternatives were identified. In text and tables, each alternative is designated by the letter in parentheses:

- Continue current management direction into the future *(A)*
- Emphasize those natural and cultural amenities that affect the quality of human life *(B)*
- Emphasize production of goods and services *(C)*
- Emphasize timber production *(D)*

Impacts from Alternatives

The impact or effect that an alternative may have in relation to the goals established must be defined. Following is a list of physical, economic and social, and administrative effects resulting from the alternative chosen (shown in parentheses).

Physical Impacts

1. Scenic beauty deteriorates (C, D)
2. Water quality deteriorates (C, D)
3. Wilderness decreases (C, D)
4. Wildlife habitat deteriorates (C, D)
5. Fish habitat deteriorates (C, D)

6. Number of endangered species increases (C, D)
7. Air quality deteriorates (C, D)
8. Cultural, archaeological sites are lost (C, D)
9. Noise pollution increases (C, D)
10. Erosion increases (C, D)
11. Hazards increase (fires) (B, C)
12. Domestic water use increases; water availability decreases (B, C)
13. Sewage and solid waste disposal availabilities decrease (B, C)
14. Pattern of natural resources meets needs of people (B)

Economic and Social Impacts

1. Recreation services increase (B, C)
2. Stimulus for manufacturing, agriculture industry is provided (C, D)
3. Timber production increased (D)
4. Range production increased (C, D)
5. Scarce resources (energy) are used (B, C)
6. Utility usage increase (electricity, phones) (B, C)
7. Increase in private investment (C, D)
8. Enhance national economic development (C, D)
9. Taxes are provided for the counties (C, D)
10. Unemployment is reduced (C, D)
11. Pressure on community services increases (B, C)
12. Traffic congestion increases (B, C)
13. Housing problems, congestion increase (B, C)
14. Social structure of community deteriorates (C)

Administrative Impacts

1. Conflicts arising from landownership pattern and problems for public programs (A, C)
2. Conflicts with other agencies' plans increase (D)

Screening Process

To screen the alternatives, we use an index. Ratings of activities are assigned on the basis of general information available and judgment of the decisionmaker.

- − 3 (most negative—indicates detrimental activities)
- 0 (indifference)
- + 3 (most positive—indicates beneficial activities)

An alternative can be eliminated from further analysis for several reasons. Its performance may be low overall (*table 1*), could have negative socioeconomic impact on communities, or unacceptable harm to the environment. An alternative could be dominated by other alternatives. And lastly, legal considerations could render an alternative unacceptable—it does not meet local, State or Federal regulations, for example.

On the basis of the criteria, alternative C (production of goods and services emphasized) fails screening because of the unacceptable socioeconomic impacts: Excess use of scarce resources and utilities, unacceptable urban and traffic congestion, unacceptable impact on social structure, and excessive use of water. It also failed because of legal-administrative

Table 1—*Ratings of impacts, by alternatives*

Impacts	Alternatives[1] A	B	C	D
Physical:				
1. Visual quality	−1	0	−2	− ½
2. Water quality	0	+1½	−1	+1½
3. Wilderness	−1½	0	−2	−1½
4. Wildlife	−2	0	−2	0
5. Fish habitat	−1	0	−1	0
6. Endangered species	−1	0	−1	−2
7. Air quality	−2	−1	−2	−1
8. Cultural, etc. sites	0	+1	− ½	−1
9. Noise	−1½	−1	−2	−1
10. Erosion	0	−2	−1	−2
11. Hazards (mainly fires)	−2	0	−1	0
12. Water quality availability	−2	−1	−3	−1
13. Use of natural resources	−1	−2	−1	−2
Socioeconomic:				
1. Recreation services	+1	+ ½	+2	+ ½
2. Industrial stimulus (local economic development)	+2	0	+3	+ ½
3. Timber production	0	− ½	0	+2
4. Range production	+ ½	+2	+2	+2
5. Use of scarce resources	−1	0	−3	−1
6. Use of utility usage	−1	0	−3	0
7. Private investment	+1½	0	+3	+1
8. National economic development	+1	0	+2	+ ½
9. Provision of taxes (local revenue base)	+1	0	+3	0
10. Employment	+1	+ ½	+2	+ ½
11. Pressure on community services	−2	− ½	−2½	− ½
12. Traffic congestion	−2	−1	−3	−1½
13. Housing requirements	−1	− ½	−2	− ½
14. Stress on social structure	−1	0	−3	0
15. Ensure equal opportunity for all	0	0	−1	0
Institutional				
1. Landownership advances public programs	−2	− ½	−2	−1
2. Conflicts with other government levels	−1	−2	−2	−2
3. Irreversible and irretrievable commitment of resources	−2	− ½	−2½	−1

[1]Alternatives:
A = current management direction continued
B = amenities affecting quality of life emphasized
C = goods and services emphasized
D = timber production emphasized

Rating index:
−3 = most negative (detrimental activity)
0 = indifference
+3 = most positive (beneficial activity)

Table 2—*Analysis of how alternatives satisfy screening criteria*

Screening criteria	Alternatives[1] A	B	C	D
Overall low performance	no	no	yes-[2]	no
Unacceptable socioeconomic impact	no-[3]	no	yes	no
Unacceptable harm to environment	yes-	no	yes-	no
Dominated alternative	no	no	no	no
Legal problems	no	no	yes-	no
	pass	pass	fail	pass

[1]Alternatives

A = current management direction continued

B = amenities affecting quality of life emphasized

C = goods and services emphasized

D = timber production emphasized

[2]Yes- = closer to yes

[3]No- = closer to no

considerations—poor landownership pattern, conflicts with other agencies, and high irreversible and irretrievable commitment of resources. Alternative C has an overall low rating—except for stimulus to recreation activities and related industry (*table 2*).

Disaggregate Evaluation

The impacts of the alternatives to be evaluated are determined in a disaggregated and as quantified as possible form. Under "Type of information" a 1 indicates that the information is relatively hard, a 2 indicates problems in quantifying the information, while 3 and 4 indicate soft and uncertain information respectively (*table 3*). We define as soft, information with insufficient data, and uncertain information reflects significant lack of certainty on future events.

The evaluation process leading to ratings can be guided through an intermediate stage evaluation. One form of doing this is to determine differences among alternatives by impacts in percentages. For example, in the average number of direct jobs, if alternative P is 100 percent, then A would be 109 percent, B 57 percent, and D would be 62 percent.

A more elaborate approach would be to try to standardize the ratings, by assigning numbers to results in the impacts (for example, increase of 10 percent in jobs). While this process is more structured, it also is more complex, requiring a tailoring for each particular planning situation.

In studies carried out up to the present, whenever ratings have been assigned they have been based on intuitive judgment.

Aggregation of Impacts

This process led to the aggregated impacts listed below (*table 4*). Since no physical quantity can be assigned to these impacts, ratings were given values going from −10 (most negative) to +10 (most positive). For example, the decisionmaker derived one rating for visual quality by using the five numerical impacts given for visual quality (acreage of preservation, retention, partial retention, modification and maximum modification), knowledge of the location of these acreages, and his judgment. The type of information used (hard, qualitative, soft, uncertain) provides a range of possible deviations from the expected value of the rating.

The aggregated impacts were assigned values or ratings for each alternative (*table 4*). For example, all through the elimination and aggregation process, air quality, noise, and hazards were not considered individually, as in all cases, these impacts were well within nondisturbing limits. They were included in an overall environmental rating for each alternative. Wildlife, fisheries, wilderness and endangered species where aggregated were given the relative similarities of impacts, and that none of these impacts had dramatic weight.

Acceptability of Alternatives

All alternatives are within legal bounds. Alternative A has drawbacks in environmental and social impacts, and positive impacts in recreation and overall production of goods and services. Alternative B has positive environmental impacts, but has drawbacks in recreation and production of other goods and services. And alternative D has positive impacts in production of timber and range, but is weaker than either alternative A or B in other aspects. At this stage, the consideration of public response would be especially important.

Additional Alternatives

Additional alternatives can be generated within the present scheme, but lack of data does not allow us to carry out thoroughly this step. The additional alternatives were proposed in the Truckee-Little Truckee Rivers study—and are designated P and E.

The step for generating new alternatives are these: For each alternative already considered, describe the main actions involved and location of them. Maps are provided, describing the location of all actions taken under different alternatives. Steps 2, 3, and 4 are presented sequentially for each alternative. For each action in any alternative, evaluate the main positive and negative impacts on defined goals, and check what changes could decrease major negative impacts or increase major positive impacts. Determine corresponding action to bring about these changes.

Table 3—*Quantifying disaggregated impacts, by alternatives*

Impacts		Alternatives[1] P	A	B	D	Type of information[2]
Physical:						
Visual quality:						
Preservation	acre	0	0	0	0	1,2
Retention	acre	87,965	87,565	92,355	92,355	1,2
Partial retention	acre	63,830	64,200	59,600	59,600	1,2
Modification	acre	4,716	9,730	4,700	4,700	1,2
Maximum modification	acre	444	460	300	300	1,2
Water quality:						
Increased sedimentation	cu ft/yr	−2,900	−900	−5,600	−3,900	1
Increased water yield by year 2000	acre-ft/yr	1,000	0	0	1,000	1
Wilderness:						
Unroaded areas where development allowed	acre	820	3,283	0	3,173	1,2
Wildlife:						
Wildlife improvement projects by year 2000	acre	1,480	500	1,000	200	1,2
Increased hunting by year 2000	visitor-day/yr	45,000	45,000	45,000	45,000	4
Increased annual vehicle trips (thousands) per year by year 2000	no.	6,000	1,237	50	559	4
Average per acre change in habitat	[3]	0	−2	0	1	2
Fish habitat	[4]	2	2	2	2	2
Endangered species	[4]	1	3	1	2	2
Air quality	[4]	4	3	4	2	2,3
Archaeological, cultural sites	[4]	3	3	4	1	2
Noise	[3]	3	3	4	1	2,3
Erosion	[4]	4	3	4	1	2
Hazards	[4]	16	20	15	14	2,4
Fire frequency	[5]	16	20	15	14	2,4
Domestic water use	[6]	47	52	39	37	3,4
Socioeconomic:						
Recreation services by year 2000	[7]					
Overnight camping (249,000)	visitor-day/yr	1,679,500	2,890,000	1,679,500	1,260,000	4
Dispersed recreation (400,000)	visitor-day/yr	600,000	1,720,000	545,000	450,000	4
Downhill skiing (184,000)	visitor-day/yr	570,000	650,000	276,000	276,000	4
Cross country skiing (23,000)	visitor-day/yr	90,000	100,000	90,000	56,000	4
Snowmobiling (32,000)	visitor-day/yr	51,000	56,000	51,000	55,000	4
Off-road vehicle use (33,000)	visitor-day/yr	31,000	40,000	29,000	31,000	4
Hunting (80,000)	visitor-day/yr	125,000	125,000	125,000	125,000	4
Day-use activities (146,000)	visitor-day/yr	300,000	496,000	365,000	464,000	4
Water-related activities (161,000)	visitor-day/yr	379,000	379,000	379,000	379,000	4
Hunting (open)	acre	154,955	153,955	155,055	155,355	4
Hunting (closed)	acre	2,000	3,000	1,900	1,600	4
Overnight camping permitted outside developed sites	acre	111,467	110,742	117,457	148,855	4
Overnight camping prohibited outside developed sites	acre	45,488	46,213	39,498	8,100	4
Off-road vehicle use on-the-ground:						
Nonuse	acre	11,708	11,708	12,348	9,790	4
Limited use	acre	97,040	97,040	144,607	86,375	4
Dispersed open use	acre	48,063	48,063	0	60,790	4
Concentrated open use	acre	144	144	0	0	
Over snow vehicle:						
Nonuse	acre	24,968	0	21,068	18,525	4
Open	acre	131,987	156,955	135,887	138,430	
Cross country skiing:						
Permitted	acre	148,220	156,955	148,220	148,220	4
Prohibited	acre	8,735	0	8,735	8,735	4
Recreation experience levels:						
Primitive	acre	0	0	0	0	
Level 1	acre	14,400	12,960	14,400	10,500	4
Level 2	acre	19,405	75,015	85,455	83,305	4
Level 3	acre	56,500	59,500	54,700	61,000	4

Table 3—*Quantifying disaggregated impacts, by alternatives (continued)*

Impacts	Alternatives[1] P	A	B	D	Type of information[2]
Level 4 . . . acre	6,640	9,465	2,390	2,150	
Level 5 . . . acre	10	15	10	10	4
Timber resources by year 2000:					
Increased timber outputs . . . MMBF	1.1	0	0	2.7	3,4
Increase in intensive management . . . acre	29,100	14,100	14,700	40,800	3,4
Range resources by year 2000					
Increase . . . animal-unit month	2,960	400	2,400	2,720	3,4
Type conversion . . . acre	3,700	500	2,610	3,200	3,4
Net present worth @ 7 pct interest . . . million dollars	166	200	194	208	3,4
Increase in Federal 25 pct receipts to counties . . . dollars/year	269,237	327,500	189,500	220,680	4
Increase in gross value of goods and services . . . million dollars	10.1	17.2	2.5	2.3	3,4
Increase in annual value of costs of production . . . million dollars	8.3	12.5	0.1	0.2	3,4
Mineral resources:					
Withdrawn from mineral entry . . . acre	5,177	5,177	5,177	5,177	2
Proposed mineral withdrawal . . . acre	1,995	1,385	1,995	1,995	2
Weeks Law status . . . acre	71,360	71,360	71,360	71,360	2
Open for mineral entry . . . acre	78,423	79,033	78,423	78,423	2
Employment:					
Average annual number of direct jobs[8] . . . no.	1,050	1,050	600	650	3,4
Traffic congestion by year 2000					
Increased yearly vehicle trips (thousands) . . . no.	500	1,237	50	559	4
Increase in average daily traffic on Highway I-80 west of Highway 89-S	3,000	6,190	750	2,800	4
Population by year 2000:					
Increase in permanent population	0	0	0	0	4
Average daily number of transients in affected area:					
Summer . . . no.	66,000	128,000	62,000	56,000	3,4
Winter . . . no.	77,000	88,000	37,000	37,000	3,4
Housing availability[9]					

Alternative A

2. Evaluate impacts.
    - Main positive impacts: More than triples current value of goods and services produced, enhances opportunities for private economic development of rural communities, provides wide variety of recreation opportunities.
    - Main negative impacts: Limits future options, has environmental drawbacks, creates pressures on social structure in nearby communities and local services, creates institutional conflicts derived from increased development.
3. Reduce number of recreation visitors. This will reduce both environmental problems to the National Forest area, and social problems in nearby communities.
4. Reduce availability of overnight camping and dispersed recreation.

Alternative B

2. Evaluate impacts.
    - Main positive impacts: Low harm to environment, low pressure in community social structure and services, leaves many options open to future, high regard for amenity values.
    - Main negative impacts: Low production of goods and services, low rural economic growth and tax receipts for counties, limited recreation opportunities.
3. Increased level of recreation, goods and services.
4. Increased facilities for camping, skiing, dispersed recreation.

Alternative C

2. Evaluate impacts.
    - Main positive impacts: Provides very good skiing facili-

Table 3—*Quantifying disaggregated impacts, by alternatives (continued)*

Impacts		Alternatives[1] P	A	B	D	Type of information[2]
Institutional:						
Conflicts with other plans[4]						
Nevada County General Plan		2	1	3	3	2
Sierra County General Plan		2	1	3	2	2
Placer County General Plan		1	1	2	1	2
Martis Valley General Plan		1	2	2	2	2
Bear Creek General Plan		0	0	0	1	2
Washoe County General Plan		1	1	1	1	2
Tahoe Basin Management Unit		1	1	1	1	2
Irreversible and irretrievable commitments of resources						
Additional roads developed						
Recreation sites	acre	7,164	8,804	3,310	2,890	1,4
Developed roadless or undeveloped areas	acre	820	3,283	0	3,173	1,4
Mining	acre	200	200	200	200	1,4
Special use permits	acre	500	500	500	500	4
Total	acre	9,134	12,787	4,010	6,753	

[1]Alternatives:
A = Current management direction continued
B = Amenities affecting quality of life emphasized
D = Timber production emphasized
P = Proposed plan of management, reduction of winter recreation areas with respect to alternative E (combination of alternative C [winter sports], B and D [logging areas])

[2]Type of information
1 = Relatively hard
2 = Problems in quantifying information
3 = Soft, informal
4 = Uncertain information

[3]Scale of 1 to 5; 3 = present habitat
[4]Scale of 1 to 5; 1 = lowest, 5 = highest
[5]Average number of human-caused fires per year (present condition = 12)
[6]Acre-feet per year (present condition = 8)
[7]Present condition shown in parentheses
[8]Present condition: 400
[9]Varies inversely in proportion to general level of economic activity, indicated by jobs.

ties, good overnight camping, high economic impact and tax receipts resulting from recreation activities.
- Main negative impacts: Environmental damage, pressure on social structure and services of communities, future options closed, institutional conflicts due to development.

3. Reduce visitors (skiers mainly) to area, reduce conflict caused by developments.
4. Reduce areas assigned to skiing developments.

Alternative D

2. Evaluate impacts.
   - Main positive impacts: Higher yield of timber.
   - Main negative impacts: Some problems in environment due to excessive logging, low overall economic impact, low recreation services provided.
3. Reduce logging, augment recreation (skiing) possibilities.
4. Reduce areas assigned to logging, define additional facilities for recreation (skiing).

New Alternatives

In the next step, an attempt is made to generate new alternatives. It is clear that in this case, combinations should consider the efficiency of the activities in defining trade-offs, i.e., if an alternative (X) emphasizing timber production is to be combined with one (Y) with intensive ski facilities, a new alternative generated should consider those areas which in alternative X have the most efficient timber yield for logging and use the areas most adequate for skiing from alternative Y for ski developments. This process of finding new alternatives can be

Table 4—*Values or ratings of aggregated impacts by alternative*[1]

Impacts	Alternatives A	B	D
Physical:			
Wilderness, wildlife, fish, endangered species	−4(±1)	0(±1)	−3(±½)
Water quality availability	0(−1, +½)	4(−1½, +1)	5(±1)
Visual quality	−5(−1, +1½)	−1(±½)	−1(±½)
General environment	−4(−2, +1)	−2(±1)	−2(±1)
Economic:			
Timber	0(±½)	0(−1, +½)	6(±½)
Range	0(±½)	4(±½)	5(±½)
Goods and services produced in area	5(±1)	1(±½)	1(±½)
Tax receipts	4(±1)	1(±½)	2(±½)
Social:			
Recreation	5(±½)	2(±½)	2(±½)
Employment	4(±½)	2(±½)	2(±½)
Traffic, housing, social pressure	−4(−2, +1)	−1(±1)	−1½(±1)
Institutional:			
Conflicts (with other agencies and others)	−3	−2	−2
Irreversible, irretrievable commitment of resources	−5	−2	−3

[1]Alternatives:
A = current management direction continued
B = amenities affecting quality of life emphasized
D = timber production emphasized
Range of values (−10 to +10) shown in parentheses

carried out through detailed observation of the actions defined, the location of them, and the expected results of these actions. This process can lead to alternative E (U.S. Dep. Agric., Forest Serv. 1976). This alternative basically takes best suited areas for winter recreation sports from alternative C, other areas to be managed as in alternative B for amenity values and others for logging as in alternative D. This alternative leads to the aggregated impacts listed in *table 5*.

Another alternative that can be generated through this process, which includes public participation, is the Proposed Plan of Management, which is alternative P. Its main characteristic is a large reduction in areas assigned to winter recreation from alternative E. The areas eliminated are adjacent to lands which may be declared protected wilderness areas and as such would suffer from the heavy use of the ski areas. In this case, uncertainty plays a role in the decision of which lands to eliminate.

Presentation of Results

Several alternative formats are proposed to reflect both expected values of aggregated impacts and their range of deviation. Some of these have been suggested in previous works (Goeller, 1973). These formats are given for the comparison of alternatives A, E, P:

- Value of expected aggregated impacts and range (±) (*table 5*).
- Low, expected, and high values of the aggregated impacts (*table 6*).
- Expected value of the aggregated impacts, indicating with lines the range (*table 7*).
- Graphical description of the impacts (*table 8*).

Another possibility which is an extension of the format of *table 6* is to give, in addition to the expected value and degree of uncertainty, a cause for uncertainty and its direction. Consider the example of the recreation impact. Let **1** indicate a case whose soft information was used, let **2** indicate uncertainty about growth of demand for winter recreation, which could be quite larger than expected, leading to a value of the recreation impact of alternative E of up to 9. This recreation impact would then be presented as follows:

<table>
<tr><td>Impact
Recreation</td><td colspan="3">Alternative</td></tr>
<tr><td></td><td>A</td><td>E</td><td>P</td></tr>
<tr><td></td><td>|5|
1</td><td>|7||2
1</td><td>|3|
1</td></tr>
</table>

The **2** on the right hand side of the recreation impact of alternative E indicates that the demand for recreation facilities

Table 5—*Aggregated impacts of three alternatives*

Impacts	Alternatives[1] A	E	P
Physical:			
Wilderness, wildlife, fish, endangered species	5(±1)	−5(±1)	0(±1)
Water quality availability	0(−1, +½)	0(±½)	3(±1)
Visual quality	−5(−1, +½)	−6(−1, +½)	−4(−1, +½)
General environment	−4(−2, +1)	−4(±1)	−2(±1)
Economic:			
Timber	0(±½)	2(±½)	2(±½)
Range	0(±½)	4(±½)	1(±½)
Goods and services produced in area	5(±1)	7(±1)	4(±1)
Tax receipts	4(±1)	6(±1)	3(±½)
Social:			
Recreation	5(±1)	7(−1, +2)	3(±½)
Employment	4(±½)	6(±1)	4(±1)
Traffic, housing, social pressure	−4(−2, +1)	−7(−2, +1)	−2(±1)
Institutional:			
Conflicts (with other agencies and others)	−1	−4	−2
Irreversible, irretrievable commitment of resources	−5	−7	−2

[1]Alternatives:
A = Current management direction continued
E = Combination of alternatives C (winter sports), B and D (logging areas)
P = Proposed plan of management; reduction of winter recreation areas with respect to E
Range of values (−10 to +10) shown in parentheses

could be quite larger than the expected value (bold numbers). The range of variation is shown by length of lines at each side of a value.

In many instances the process of working with multiple objectives goes further, trying to find in some form the relative importance of each objective and thus be able to assign to each alternative a single value, a monetary one, we hope (Keeney and Raiffa 1976). One usual form of doing this is through the generation of weight to describe the importance of goals.

This approach simplifies the selection of the preferred alternative, as all impacts can be reduced to a single weight average value. In some cases, users have defined weights to consider the relative importance of each impact. This approach, however, presents serious methodological problems, given the usual complexity of utility functions. These functions are difficult to express explicitly and present nonlinear characteristics. Thus, the weights associated with the impacts depend often in part on the level of the impacts. For example the importance given to air pollution will depend on whether the level of pollution is critical, how many people are subject to this pollution, etc. This makes the definition of weights *a priori* difficult to implement.

A more rigorous approach is to define relative importance of impacts interactively with the decisionmaker along the process. This requires, however, considerably more effort, and may not be even possible in many cases. To extract preferences, which are essentially subjective from decisionmakers is no simple task. It is a time-consuming process, and inconsistencies as well as errors may distort the results. For this reason, we preferred not to implement this stage in handling multiple objectives.

Stability of Solutions

The three alternatives considered are quite stable in their expected values. Alternative E presents some larger deviations in terms of predicting the level of recreation used and its impact on neighboring communities.

While there is lack of solid information in several aspects, these are not essential for the decisionmaking (e.g., noise level, as none of the possible values is critical).

Alternative P was selected as most attractive.

Generation of New Alternatives

There is not enough information to carry out the generation of new alternatives marginally different to alternative P.

Table 6—*Aggregated impacts of alternatives A, E, P*

Impacts	Alternatives[1] A	E	P
Physical:			
Wilderness, wildlife, fish, endangered species	(−6, **−5**, −4)	(−6, **−5**, −4)	(−1, **0**, +1)
Water quality availability	(−1, **0**, +½)	(−½, **0**, +½)	(2, **3**, 4)
Visual quality	(−6, **−5**, −4½)	(−7, **−6**, −5½)	(−5, **−4**, −3½)
General environment	(−6, **−4**, −3)	(−5, **−4**, −3)	(−3, **−2**, −1)
Economic:			
Timber	(−½, **0**, +½)	(2½, **2**, 1½)	(2½, **2**, 1½)
Range	(−½, **0**, +½)	(3½, **4**, 4½)	(−1½, **−1**, −½)
Goods and services produced in area	(4, **5**, 6)	(6, **7**, 8)	(3, **4**, 5)
Tax receipts	(3, **4**, 5)	(5, **6**, 7)	(2½, **3**, 3½)
Social:			
Recreation	(4, **5**, 6)	(6, **7**, 9)	(2½, **3**, 3½)
Employment	(3½, **4**, 4½)	(5, **6**, 7)	(3, **4**, 5)
Traffic, housing, social pressure	(−6, **−4**, −3)	(−9, **−7**, −6)	(−3, **−2**, −1)
Institutional:			
Conflicts (with other agencies and others)	−1	−4	−2
Irreversible, irretrievable commitment of resources	−5	−7	−2

[1]Alternatives:
A = Current management direction continued
E = Combination of alternatives C (winter sports), B and D (logging areas)
P = Proposed plan of management; reduction of winter recreation areas with respect to E
Bold numbers indicate expected values, other numbers are estimated range

Preferred Alternative

Alternative P is chosen.

DISCUSSION AND CONCLUSIONS

The method described herein allows the analyst to structure the decision process in an orderly way, so that alternatives, impacts, and evaluations are properly handled. Although the idea of presenting a systematic procedure is not new, the present work has novel aspects that are particularly relevant to the decisionmaking process and can help in providing a structured analysis format:

- A procedure for generating additional alternatives, which appears to be promising based on information already evaluated, through the modification (mitigating actions) and combination of alternatives already defined.
- An analysis on how to handle the problem of multiple objectives, including the use of visual aids for presentation of results in tables and scoreboards which show information to the decisionmaker and to the public in a clear, stable way.
- Indications on how to incorporate into the evaluation situations with uncertainty and lack of information.
- A hierarchical structuring of the problem, in which alternatives are first analyzed in a more general form, including a screening process where the obviously noncompetitive alternatives are disregarded. The impacts caused by the alternatives are then disaggregated, in order to derive physical measurements. The number of impacts are reduced to a few through an elimination and aggregation process, consistent with the defined goals.

The proposed method is flexible and applicable to a broad range of planning problems in land management. The decision process will differ according to the problem at hand. Land management plans involve more activities than individual single projects, and consequently, a richer variety of possibilities exists in combining the elements forming a plan.

Clearly different procedures could be employed in a planning process. The presented scheme attempts to provide a coherent and simple-to-use process, following a rational line

Table 7—*Expected values of aggregated impacts of alternatives A, E, P*

Impacts	Alternatives[1] A	E	P
Physical:			
Wilderness, wildlife, fish, endangered species	|−5|	|−5|	|0|
Water quality availability	|0|	|0|	|3|
Visual quality	|−5|	|−6|	|−4|
General environment	||−4|	|−4|	|−2|
Economic:			
Timber	|0|	|2|	|2|
Range	|0|	|4|	|−1|
Goods and services produced in area	|5|	|7|	|4|
Tax receipts	|4|	|6|	|3|
Social:			
Recreation	|5|	|7||	|3|
Employment	|4|	|6|	|4|
Traffic, housing, social pressure	||−4|	||−7|	|−2|
Institutional:			
Conflicts (with other agencies and others)	−1	−4	−2
Irreversible, irretrievable commitment of resources	−5	−7	−2

[1]Alternatives:
A = Current management direction continued
E = Combination of alternatives C (winter sports), B and D (logging areas)
P = Proposed plan of management; reduction of winter recreation areas with respect to E
Range of variation indicated by length of lines at each side of value

Table 8—*Aggregated impacts of alternatives A, E, P*[1]

Physical impacts	Range of values −10	−9	−8	−7	−6	−5	−4	−3	−2	−1	0	1	2	3	4	5	6	7	8	9	10
Wilderness																					
Wildlife, etc.					— **A** —						··· **P** ···										
					--- **E** ---																
Water quality-availability											— **A** —				--- **P** ---						
											--- **E** ---										
Visual quality																					
General environment																					
Timber																					
.																					
.																					

[1]Alternatives:
A = Current management direction continued
E = Combination of alternatives C (winter sports), B and D (logging areas)
P = Proposed plan of management; reduction of winter recreation areas with respect to E
Bold letters indicate expected values

of reasoning in planning procedures. Once basic alternatives are defined, a disaggregation process allows exploration of the full range of consequences of each alternative. The aggregation process is essential to reduce the impacts to a manageable format which allows for comparison among the alternatives by a decisionmaker.

REFERENCES

Brown, T.C. **An alternative analysis for multiple use management: a case study.** Res. Paper RM-176. Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1976. 16 p.

Goeller, Bruce; and others. **San Diego Clean Air Project, R1362-SD.** Rand Corporation 1973. 178 p.

Kenney, R. I.; Raiffa, H. **Decisions with multiple objectives: preferences and value trade-offs.** New York: John Wiley; 1976. 493 p.

U.S. Department of Agriculture, Forest Service. **Decision analysis: Mount Shasta.** Redding, CA: Shasta-Trinity National Forest. 1975a; 43 p.

U.S. Department of Agriculture, Forest Service. **Truckee-Little Truckee Rivers Planning Unit alternatives.** Nevada City, CA: Tahoe National Forest. 1975b; 158 p.

U.S. Department of Agriculture, Forest Service. **Truckee-Little Truckee Rivers Planning Unit Environmental Statement.** Nevada City, CA: Tahoe National Forest. 1976; 463 p.

U.S. Department of Agriculture, Forest Service. **North Fork American River study: management alternatives for inclusion in the National Wild and Scenic Rivers System.** Nevada City, CA: Tahoe National Forest. 1978; 269 p.

Weintraub, A. **A methodology for decisionmaking in project evaluation in land management planning.** Gen. Tech. Rep. PSW-32. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1978: 109-117.

Weintraub, Andres; Adams, Richard; Yellin, Linda. **Land management planning: a method of evaluating alternatives.** Res. Paper PSW-167. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 12 p.

A method is described for developing and evaluating alternatives in land management planning. A structured set of 15 steps provides a framework for such an evaluation, when multiple objectives and uncertainty must be considered in the planning process. The method is consistent with other processes used in organizational evaluation, and allows for the interaction of decisionmakers, specialists, analysts, and the general public. The method incorporates several novel aspects that help in structuring the decision process. Application of the method is illustrated by replicating the development of an environmental study in the Truckee-Little Truckee Rivers Planning Unit, Tahoe National Forest, California.

Retrieval Terms: land management planning, evaluation of alternatives, multiple objectives, uncertainty, structured format

United States
Department of
Agriculture

Forest Service

**Pacific Southwest
Forest and Range
Experiment Station**

Research Paper
PSW-168

Log Bioassay of Residual Effectiveness of Insecticides Against Bark Beetles

Richard H. Smith

The Author:

RICHARD H. SMITH is a research entomologist with the Station's research unit that is studying improved technology for integrated management of western forest insects, with headquarters in Berkeley, California. He holds B.S. (1942) and M.S. (1947) degrees from New York State University, College of Forestry, and a Ph. D. degree (1961) from the University of California, Berkeley. He has been with the Station since 1955.

Cover: An insectary unit at the Forest Service's Institute of Forest Genetics, near Placerville, California, served as the field laboratory for testing nine insecticides on bark beetles.

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

December 1982

Log Bioassay of Residual Effectiveness of Insecticides Against Bark Beetles

Richard H. Smith

CONTENTS

IN BRIEF . . .

Smith, Richard H. **Log bioassay of residual effectiveness of insecticides against bark beetles.** Res. Paper PSW-168. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 8 p.

Retrieval Terms: Western pine beetle, mountain pine beetle, Jeffrey pine beetle, lindane, Sevin, Reldan, Dursban, Sumithion, Imidan, malathion, permethrin, decamethrin

Protecting individual pines from bark beetle attack can be a viable option when beetles are active in the immediate area. Only lindane and Sevin are now permitted for this use in California. This paper reports on the results of a log bioassay procedure, with ponderosa and Jeffrey pine, in testing other insecticides for use as protective sprays for western, mountain, and Jeffrey pine beetles. Insecticides used and found to be effective in addition to lindane and Sevin were Dursban, Reldan, Sumithion, and two pyrethroids, permethrin and decamethrin. Imidan and malathion were not effective. Testing was carried out during a 5-year period.

Trees 10 to 13 inches (25 to 33 cm) in diameter growing in well-stocked stands at 2700-ft (825-m) elevation near Placerville, California, were sprayed with varying concentrations of the insecticides ranging from 0.002 percent to 0.25 percent for the pyrethroids and 0.2 percent to 2 percent for the others. A dosage of 1 gal (3.8 l) per 40 ft^2 (3.6 m^2) of bark was used in all but one test for which 1 gal (3.8 l) per 80 ft^2 (7.2 m^2) was used. Included in the testing were these variables: pH of water for Sevin only, temperature of water for Dursban only, postspray exposure to sun and water for lindane only, beetle source and attack density, and spray additives (molasses or latex).

From 2 to 13 months postspray, trees were felled and cut into 15- to 18-inch (37- to 45-cm) logs. The ends were paraffined to retain moisture and to prevent beetle attack on cut surfaces. Logs from the untreated portion of the trees served as checks. Single-log and group-log tests were used; results were comparable with both procedures. For single-log testing, the logs were individually caged and a specified number of beetles collected from naturally infested brood material was added. For group-log testing, logs for each treatment in a test were stacked in a unit of a walk-in insectary. Naturally infested brood material from which beetles would soon emerge was added to the insectary unit. This arrangement was replicated in 2 to 4 units.

About 2 weeks after beetles began to attack, the bark of all logs was shaved off down to the xylem and the length of egg galleries measured. Gallery length per square foot on the logs of each treatment was compared with that of the untreated check logs. Effectiveness of treatment was based on the reduction in length of egg gallery expressed as a percent.

To make optimal use of trees and insecticides and to examine the greatest number of treatments, there was no conventional replication. But during the 5-year period there was considerable approximate repetition of test conditions.

All chemicals were quite effective for 2 to 13 months, except for malathion and Imidan, which were relatively ineffective, depending largely on concentration and application rate. Based on equivalent amounts of lindane the ranking of effectiveness is as follows: for western pine beetle on ponderosa pine: decamethrin > permethrin > lindane > Reldan > Dursban ≅ Sumithion > Sevin; for mountain pine beetle on ponderosa pine: decamethrin > permethrin > lindane > Dursban ≅ Reldan > Sevin > Sumithion; for Jeffrey pine beetle on Jeffrey pine: decamethrin > permethrin > lindane > Sevin.

Water at pH 8 greatly reduced the effectiveness of Sevin. The addition of molasses greatly increased the effectiveness of lindane. Effectiveness was inversely related to beetle attack density. There was very little effect attributable to bark moisture and exposure, water temperature, and beetle source. The addition of latex to the water of sprays did not increase effectiveness. The most promising avenues for future work are the use of pyrethroids and the addition of molasses to potentiate lindane.

Insecticides[1] are commonly used to control infestations of bark beetles, chiefly the western pine beetle (*Dendroctonus brevicomis* LeConte) and the mountain pine beetle (*D. ponderosae* Hopkins). As a protective measure, residual insecticides can be applied to the trunks of uninfested trees. In California, only two compounds—lindane and Sevin—are registered by the U.S. Environmental Protection Agency for this purpose. And the continued use of lindane is currently being investigated by that Agency.

Other insecticides have shown promise in preventing attacks by bark beetles in field and laboratory tests. Dursban and Sevin performed well in field tests (Smith and others 1977). Sumithion and Imidan had excellent ratings in laboratory bioassays (Hastings and Jones 1976, Robertson and Gillette 1978, Robertson and Kimball 1978). Topical application studies in the laboratory (Lyon 1971) showed pyrethrins to be toxic to western pine beetle; however, the lack of persistence of pyrethrins ruled against field tests. Newly developed pyrethroids were shown to be equally or more toxic to western pine beetle than the pyrethrins (Robertson and Gillette 1978, Robertson and Kimball 1978). Earlier, a similar conclusion was reached for southern pine beetle (*D. frontalis* Zimmerman). Pyrethroids, in general, have been found to combine persistence with the toxicity of the natural pyrethrins without an appreciable shift in environmental hazards (Elliott and others 1978).

To assess their residual toxicity, I studied nine insecticides—lindane, Sevin, Dursban, Reldan, Sumithion, Imidan, malathion, and the pyrethroids, permethrin and decamethrin—for their effectiveness in preventing attack of western pine beetle and mountain pine beetle on ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.). I also did preliminary studies with some of these insecticides to assess the residual toxicity to Jeffrey pine beetle (*D. jeffreyi* Hopkins) on Jeffrey pine (*P. jeffreyi* Grev. & Balf.).

The experiments were carried out during a 5-year period (1976-1980) at the Forest Service's Institute of Forest Genetics, near Placerville, in northern California. Single-log and group-log bioassays were done for western and mountain pine beetle; only group-log testing was done for Jeffrey pine beetle. Also, compared in the tests were the effects of pH, water temperature, low insecticide concentration, bark moisture and exposure, beetle source and attack density, and spray additives on the residual effectiveness of the sprays.

This paper reports the results of log bioassays that compared the residual effectiveness of nine insecticides. Effectiveness of treatment was based on the percent reduction in length of egg gallery when compared with untreated checks. The information obtained in these tests can be useful in direct application and in deciding the approach that further field tests might take.

[1]This publication does not contain recommendations for the pesticide uses reported, nor does it imply that they have been registered by the appropriate government agencies.

METHODS

Treatment Application

All trees were 40 to 50 years old and growing at 2700-ft (825-m) elevation in well-stocked stands. Diameter-at-breast height (d.b.h.) ranged from 8 to 30 inches (20 to 76 cm); however, only those trees with d.b.h. between 10 and 13 inches (25 to 33 cm) were included in the study. None of the trees was growing under open conditions. Limbs of all trees were removed to a height of 25 ft (7.6 m) before spray application.

Insecticides were sprayed at various concentrations: Sevin, Reldan, Dursban, Sumithion, and Imidan—from 0.5 to 2 percent; lindane—from 0.2 to 2 percent; permethrin—from 0.01 to 0.25 percent; decamethrin—from 0.002 to 0.1 percent; and malathion—at 1 percent.

All insecticides were aqueous emulsions except Sevin, which was a suspension made from Sevimol concentrate. All were applied to dry bark at dosages of approximately 1 gal (3.8 l) per 40 ft^2 (3.6 m^2) or 80 ft^2 (7.2 m^2) of bark surface. All sprays were prepared within 2 h of use and were applied with a 3-gal (11.4 l) hand-pressured garden tank sprayer. Trees were sprayed to a height of 25 ft (7.6 m). Spraying was done from early spring to midsummer in early morning when there was little or no breeze and air temperatures ranged from 60° to 75°F (16° to 24°C). Water temperatures were from 55° to 60°F (13° to 16°C).

Specific conditions were established for some of the tests. The pH of the water for the preparations of Sevin was adjusted to 6 or 8 by the use of buffers. The Dursban sprays were prepared with water of different temperatures. In one test the trunks of trees sprayed with 0.5 percent and 1 percent lindane were selected so that one-half of the trees had trunks exposed to direct sunlight and the other one-half had trunks not exposed to direct sunlight. Also, the trees with exposed trunks were sprayed with water to simulate rain during the first, second, and third weeks after the insecticide was applied. Latex and molasses were added to lindane and the pyrethroids in two tests. One of the preparations of Sevin, Sevimol, was formulated by the manufacturer as a suspension, containing molasses as a major constituent. Sevimol was not altered in any way at the experimental level except for dilution. Three different source preparations of Sevin were compared. The effect of a three-fold increase in the attack density of western and mountain pine beetles was tested. Two widely separated sources of western pine beetle were compared.

Brood material for all three beetles was obtained from Eldorado County in northern California. But for the test comparing geographic sources of western pine beetle, a second brood source of beetles was Shasta County, 200 miles (322 km) to the north. The source for western pine beetle was bark from infested ponderosa pine (*Pinus ponderosa* Dougl. ex Laws); for mountain pine beetle, logs of infested sugar (*P. lambertiana* Dougl.) or lodgepole pine (*P. contorta* Dougl. ex Loud.); and for Jeffrey pine beetle, logs from infested Jeffrey pine (*P. jeffreyi* Grev. & Balf.).

All sprayed trees were exposed to the prevailing weather conditions at the Forest Service's Institute of Forest Genetics near Placerville for the varying residual periods tested. In general, the first 6 months after treatment air temperatures ranged from 60° to 90°F (16° to 32°C) with very little rainfall. During the next 6 months, the temperatures were much lower, generally ranging from 20° to 70°F (−7° to 21°C) with rainfall of about 40 inches (102 cm).

Log Bioassay

At designated periods treated trees were felled and the sprayed portion sectioned into several 15- to 18-inch (38- to 46-cm) logs. Similar sections were cut from the unsprayed portions of the trees to serve as untreated checks. Earlier work (Smith and others 1977) showed that, essentially, no difference exists in the rate of success of beetle attack on cut logs taken from various heights along the trunk of ponderosa pines of the size range included in the test. The ends of each log were given two coats of hot paraffin. The first coat was hot enough to penetrate the bark and wood tissues. The second coat was hot enough to flow easily and deposit a surface layer of paraffin. The paraffin treatment retained phloem and xylem moisture and also prevented attack through the cut surfaces.

The prepared logs, with the appropriately aged insecticide deposits, were exposed to beetles either by caging the logs singly or in groups. For single-log testing, the log was placed on short blocks to raise it off the floor of the cylindrical cage. Beetles, reared from natural brood material, were added to the cage at a rate of about 100 per ft^2 (1100/m^2) of bark surface for a given log for western pine beetle and about 30 per ft^2 (330/m^2) for mountain pine beetle. Jeffrey pine beetle was not used in single-log testing.

Group-log testing was done in units of a screened walk-in insectary at the Institute. The units were about 6-ft (1.8-m) cubes. From 8 to 12 test logs were arranged in stacks of 3 or 4 along the side of the unit with the greatest light intensity. The logs were stacked end-to-end and separated from each other by double nailed cleats to ensure beetle attack through the treated bark surface and not through the cut, paraffined surfaces. Treated and untreated logs were located randomly within the stacks of an insectary unit containing at least one log of each treatment in the particular test. Usually, three insectary units were used for each bioassay test with each beetle. In a few instances either two or four units were used, depending on the supply of brood material and the size of the test. For group-log testing, brood material from which beetles were about to emerge was placed along the dark side of the insectary unit. As beetles emerged, therefore, they flew toward the light side and the test logs. When caged, beetles readily enter freshly cut logs. The attack density, however, could only be crudely estimated with the group-log procedure. Because each treatment was represented in each insectary unit, all treatments were assumed to be exposed to an equivalent beetle attack density. In general, sufficient brood material was placed in each unit to ensure that the tests were exposed to adequate attack density. It is estimated that the numbers of beetles were as high or higher than those used in single-log testing.

Examination and Analysis

From 2 to 3 weeks after beetles began their attack, depending on temperature, all logs were examined. The bark of each log was shaved off to expose the adult galleries at the phloem-xylem interface. Total length of successful galleries, those with evidence of oviposition, was measured and converted to inches per square foot of phloem surface. Average gallery length per square foot of each treatment was compared with the untreated checks. The difference between treated and untreated logs in inches of gallery per square foot was converted to the percent reduction resulting from treatment.

Egg gallery construction was selected over other performance measures because it was the result of the full establishment phase— boring, mating, gallery construction, and oviposition.

To make optimal use of trees and insecticides and to look at the greatest number of treatment variables, there was no conventional replication. That is, all the trees with a given treatment were not cut and tested at the same time. Instead, the trees were usually cut and tested at different residual periods. At least three logs were cut from each treated tree to serve as a type of replication to test the procedure. Additionally, usually two different species of bark beetle were tested against the logs from each tree. Also, during the course of 5 years many test conditions, or approximate test conditions, were repeated. Therefore, the data seem suitable for discussion and tentative conclusions.

RESULTS

Western and Mountain Pine Beetles on Ponderosa Pine

Pyrethroids

In the 1978 tests, both permethrin and decamethrin were effective at such low concentrations that it was decided to

Table 1—*Reduction in length of egg galleries of western and mountain pine beetles in ponderosa pine logs, by months after insecticide application, 1978 and 1979*[1]

Insecticide (pct) and additive[2]	Western pine beetle			Mountain pine beetle			Western pine beetle	Mountain pine beetle
	Months after application in . . .							
	1978			1978			1979	1979
	6	9	12	6	9	12	5	6
	Percent[3]							
Lindane:								
0.5	100	97	—	85	54	—	—	—
0.5 + Mol	100	100	—	93	94	—	—	—
1.0	100	100	100	100	92	100	100	100
1.0 + Mol	100	100	100	95	100	99	—	—
2.0	[4]—	—	100	—	—	100	—	—
2.0 + Mol	—	—	100	—	—	100	[5]100	[5]100
Permethrin:								
0.01	—	42	—	—	18	—	—	—
0.01 + Ltx	—	0	—	—	5	—	—	—
0.10	96	64	—	94	58	—	74	95
0.10 + Mol	—	—	—	—	—	—	98	95
0.10 + Ltx	92	27	—	53	45	—	—	—
0.25	—	—	—	—	—	—	97	100
Decamethrin:								
0.01	—	—	[7]84	—	—	[7]68	—	—
0.01 + Ltx	—	—	[7]35	—	—	[7]2	—	—
0.05	—	—	—	—	—	—	100	100
0.05 + Mol	—	—	—	—	—	—	100	100
0.10	[6]100	—	—	[6]100	—	—	100	100
0.10 + Ltx	—	—	[7]100	—	—	[7]100	—	—
Untreated	(22)	(33)	(25)	(17)	(18)	(16)	(22)	(11)

[1]Tested by group-log method: logs of different treatments stacked togther in same unit.
[2]Mol = 2 pct molasses; Ltx = 2 pct latex.
[3]Average for three logs. Values in parentheses are centimeters of gallery per 100 cm^2, representing 0 pct reduction.
[4]— = Not tested.
[5]16 months.
[6]4 months.
[7]10 months.

repeat some of the tests in 1979 (*table 1*). In 1978, 0.1 percent permethrin was nearly as effective as 0.5 percent lindane against both western and mountain pine beetle for 6 months, which can be considered a full season of beetle activity. At 9 months, however, the effectiveness of 0.1 percent permethrin was decreasing; the addition of latex decreased effectiveness against both species of beetle. Permethrin at 0.01 percent was ineffective at 9 months; unfortunately, a 6-month test was not conducted. Latex again decreased effectiveness. Decamethrin at 0.1 percent was fully effective for 4 to 6 months. With the addition of latex it was fully effective for 10 months. However, the data do not permit separation of the effect of decamethrin from latex. But, since latex had no positive effect in other tests, one might conclude that the 0.10 percent decamethrin alone would have been fully effective for the 10-month period. Decamethrin at 0.01 percent was surprisingly effective, though not fully so, at 10 months, and likely would have been fully effective at 6 months, but a 6-month test was not done. Latex again decreased effectiveness.

In one 1979 test, permethrin at 0.25 percent was nearly fully effective against both beetle species for 5 to 6 months; 0.10 percent was slightly less effective; the effect of molasses was inconclusive (*table 1*). Both 0.10 percent and 0.05 percent decamethrin were fully effective in the first 1979 test against both beetle species for 5 to 6 months; molasses did not decrease effectiveness. In the second 1979 test, very low concentrations—permethrin at 0.01 and decamethrin at 0.002 percent—were not fully effective for a 2½ month period (*table 2*).

The pyrethroids—permethrin and decamethrin—at comparatively low concentrations were effective against western and mountain pine beetle for prolonged periods of time. Results indicate that decamethrin might be at least five times as effective as permethrin which, in turn, is at least two times more effective than lindane. Both western and mountain pine beetle are somewhat equally affected by both insecticides, although western pine beetle seems to be slightly more susceptible. Neither molasses nor latex appeared to increase the effectiveness of either pyrethroid.

Table 2—*Reduction in length of egg galleries of western pine beetle in ponderosa pine logs, by months after insecticide application and by dosage, 1979*[1]

Insecticide (pct) and additive[2]	Months after application and dosage (gal/ft² bark)			
	2½		5	
	40	80	40	80
	Percent[3]			
Lindane:				
0.2	72	25	46	34
0.2 + Mol	97	99	85	87
Permethrin:				
0.01	21	0	27	0
0.01 + Mol	0	0	29	0
Decamethrin:				
0.002	60	27	40	6
0.002 + Mol	38	30	31	0
Untreated	(30)		(27)	

[1]Tested by group-log method; logs of different treatments stacked together in same unit.

[2]Mol = 2 pct molasses.

[3]Average for three logs. Values in parentheses are centimeters of gallery per 100 cm^2 phloem surface, representing 0 pct reduction.

Lindane

Lindane performed well over the whole testing period (*tables 1-10*). Two percent lindane was fully effective against both beetles for 12 months (*table 1*). At 0.5 percent, lindane was fully effective against western pine beetle for 6 months, but not quite fully effective against mountain pine beetle. At 1 percent it was usually nearly fully effective for more than 9 months and often for 12 months.

Molasses apparently potentiates lindane. The addition of 2 percent molasses to 0.2 percent lindane nearly doubled the effectiveness of the lindane (*table 2*). From previous results it would seem that 0.2 percent lindane with 2 percent molasses is equivalent to 0.5 percent lindane without molasses. It also appears that the addition of molasses reduces the amount of spray required. Lindane without molasses was less effective at the lower dosage of 80 ft^2 (7.2 m^2), but lindane with molasses was equally effective at both dosages (*table 2*). Molasses, therefore, can lower both the concentration of lindane and the amount of spray needed for effective treatment.

Table 3—*Reduction in length of egg galleries of western and mountain pine beetles by residual sprays of insecticides on ponderosa pine, with postspray bark conditions for lindane, 1977*[1]

Insecticide and concentration (pct)	Postspray condition	Western pine beetle		Mountain pine beetle	
		Months after application			
		4	5	4	5
		Percent[2]			
Lindane:					
0.5	Shade and dry	97	[3]—	76	—
0.5	Sun and wet	98	—	80	—
1.0	Shade and dry	—	98	—	87
1.0	Sun and wet	—	98	—	85
Dursban:					
1.0	–	—	100	—	97
Sevin:					
2.0	–	—	91	—	87
Untreated		(29)	(16)	(32)	(22)

[1]Tested by group-log method: logs of different treatments stacked together in same unit.

[2]Average for three logs. Values in parentheses are centimeters of gallery per 100 cm^2 phloem surface, representing 0 pct reduction.

[3]— = Not tested.

Sevin, Dursban, Sumithion, and Reldan

All four insecticides were effective, depending on the concentration and residual period. At 0.5 percent, all were generally reasonably effective for about 2 months (*tables 3-9*). For longer periods effectiveness was uncertain, though decreasing. At 1 percent all were quite effective for 4 to 6 months and sometimes longer, even at times for nearly 10 months. At 2 percent all were usually fully effective for 10 months or longer. There was no sharp difference in effectiveness against the two beetle species, though Sevin seemed slightly more effective against mountain pine beetle and Reldan slightly more effective against western pine beetle.

Imidan and Malathion

Imidan was ineffective at 4 months at all three concentrations (0.5, 1, and 2 percent) and was not tested further (*table 5*). Malathion at 1 percent was fairly ineffective at 4 months on western pine beetle, and even more ineffective at 5 months on mountain pine beetle (*table 6*). It was not tested further.

Other Variables Tested

Water pH—pH greater than 7 markedly reduced the effectiveness of Sevin, even for as short a period as 2 h between mixing and spraying. The other insecticides were not tested for this factor (*table 6*).

Rate of application—Reducing the rate of application from 40 to 80 ft^2 per gal (3.6 m^2 to 7.2 m^2/l), noticeably reduced effectiveness (*table 2*).

Beetle source and attack density—Lindane and Sevin were equally effective against beetles from Shasta or Eldorado Counties (*table 8*). In general, there was an inverse association between effectiveness and density of the beetle population (*tables 4, 8*). This association appears to be much stronger for mountain pine beetle than for western pine beetle, and appears to be independent of the insecticide (*table 4*).

Source of Sevin—There was a difference in the effectiveness of Sevin attributable to the source material. However, the testing was limited (*table 8*).

Water temperature—Low water temperature did not alter the effectiveness of Dursban (*table 7*).

Bark moisture and exposure—At both 4- and 5-month residual periods, there was essentially no difference attributable to postspray bark moisture or exposure. The results were the same against both western and mountain pine beetle by 0.5 percent and 1 percent lindane either on bark exposed to sunlight and postspray moisture or on bark in shade and without postspray moisture (*table 3*).

Table 4—*Reduction in length of egg galleries of western and mountain pine beetles by residual sprays of insecticides on ponderosa pine, with different attack densities, 1976*[1]

Insecticide and concentration (pct)	Western pine beetle				Mountain pine beetle			
	Months after application and attack density[2]							
	3		6½		3		6½	
	Light	Medium	Light	Heavy	Light	Medium	Light	Heavy
	Percent[3]							
Lindane:								
0.5	98	98	72	58	83	43	60	50
1.0	99	99	100	98	100	81	94	82
Dursban:								
1.0	86	79	100	87	100	47	64	53
2.0	93	89	100	100	100	76	88	78
Sevin:								
2.0	92	82	[4]—	91	—	—	71	31
Untreated	(8)	(17)	(8)	(39)	(2)	(19)	(26)	(39)

[1]Tested by group-log method: logs of different treatments stacked together in same unit.
[2]Light, medium, and heavy are generalized population levels of attacking beetles; medium is about twice the density of light and heavy is about three times the density of light.
[3]Average of three logs. Values in parentheses are centimeters of gallery per 100 cm² phloem surface, representing 0 pct reduction.
[4]— = Not tested.

Table 5—*Reduction in length of egg galleries of western and mountain pine beetles in ponderosa pine logs by months after insecticide application, 1978*[1]

Insecticide and concentration (pct)	Western pine beetle			Mountain pine beetle		
	Months after application					
	4	7	10	4	7	10
	Percent[2]					
Sevin:						
0.5	0	[3]—	—	[4]+	—	—
1.0	53	—	—	+	—	—
2.0	74	63	36	+	68	86
Dursban:						
0.5	40	—	—	+	—	—
1.0	85	—	—	+	—	—
2.0	98	99	97	+	97	85
Sumithion:						
0.5	21	—	—	+	—	—
1.0	88	—	—	+	—	—
2.0	92	99	90	+	82	68
Imidan:						
0.5	4	—	—	*	—	—
1.0	10	—	—	*	—	—
2.0	35	—	—	*	—	—
Lindane:						
1.0	—	100	100	+	98	92
Untreated checks	(17)	(22)	(33)	[3](*)	(17)	(18)

[1]Tested by group-log method: logs of different treatments stacked together in same unit.
[2]Average of three logs. Values in parentheses are centimeters of gallery per 100 cm² phloem surface, representing 0 pct reduction.
[3]— = not tested.
[4]Because of few beetles, only one untreated check log was attacked; * = attacked, + = unattacked.

Table 6—*Reduction in length of egg galleries of western and mountain pine beetles in ponderosa pine logs, by months after insecticide application and pH of formulations, 1976*[1]

Insecticide and concentration (pct)	pH	Western pine beetle		Mountain pine beetle	
		Months after application			
		4	13	5	13
		Percent[2]			
Sevin:					
0.5	6	80	[3]—	78	—
0.5	8	35	—	67	—
1.0	6	97	49	80	65
1.0	8	56	—	74	—
Lindane:					
0.5	[4]–	100	91	92	86
1.0	–	—	99	—	91
Reldan:					
0.5	–	96	—	61	—
1.0	–	100	97	81	63
2.0	–	—	100	—	79
Dursban:					
1.0	–	96	95	88	83
Malathion:					
1.0	–	62	—	45	—
Untreated		(22)	(24)	(15)	(30)

[1]Tested by single-log method: each log of each treatment in a separate cage.
[2]Average for three logs. Values in parentheses are centimeters of gallery per 100 cm² phloem surface, representing 0 pct reduction.
[3]— = Not tested.
[4]– = pH not altered.

Table 7—*Reduction in length of egg galleries of western and mountain pine beetles in ponderosa pine logs, by months after insecticide application and water temperature of formulation, 1976*[1]

Insecticide and concentration (pct)	Water temperature (°C)	Western pine beetle	Mountain pine beetle	
		Months after application		
		3	3	5
		Percent[2]		
Sevin:				
0.5	15	53	72	56
Lindane:				
0.5	15	99	95	70
Dursban:				
0.5	15	98	94	77
0.5	3	97	97	79
0.5	[3]3	100	100	82
Untreated		(17)	(18)	(26)

[1]Tested by single-log method: each log of each treatment in a separate cage.
[2]Average for three logs. Values in parentheses are centimeters of gallery per 100 cm² phloem surface, representing 0 pct reduction.
[3]For 4 h before application.

Table 8—*Reduction in length of egg galleries of western pine beetle in ponderosa pine logs, by months after insecticide application and source of beetles, 1977*[1]

Insecticide and concentration (pct)	Months after application			
	2	5	2	2
	Eldorado County			Shasta County
	Percent[2]			
Lindane:				
0.5	91	[3]—	87	98
1.0	100	94	100	100
2.0	—	100	—	—
Sevin:[4]				
0.5	89	19	89	86
1.0	100	—	100	100
Sevin:[5]				
1.0	98	93	100	93
Sevin:[6]				
1.0	98	0	100	95
Untreated	(31)	(18)	(42)	(20)

[1]Tested by single-log method: each log of each treatment in a separate cage.
[2]Average for three logs. Values in parentheses are centimeters of gallery per 100 cm² of phloem surface, representing 0 pct reduction.
[3]— = not tested.
[4]From Sevimol, a suspension concentrate in molasses.
[5,6]From two different water emulsion concentrates.

Table 9—*Reduction in length of egg galleries of western and mountain pine beetles in ponderosa pine logs, by months after insecticide application, 1977*[1]

Insecticide and concentration (pct)	Western pine beetle			Mountain pine beetle		
	Months after application					
	2	5	13	2	5	13
	Percent[2]					
Lindane:						
0.5	100	94	90	94	73	80
1.0	[3]—	—	98	—	—	82
Dursban:						
0.5	98	33	—	95	78	—
1.0	—	—	95	—	—	90
Sevin:						
0.5	48	12	—	69	36	—
1.0	—	—	65	—	—	47
Reldan:						
1.0	—	—	98	—	—	63
2.0	—	—	100	—	—	75
Untreated	(29)	(39)	(20)	(18)	(19)	(30)

[1]Tested by group-log method: logs from different treatments stacked together in same unit.
[2]Average for three logs. Values in parentheses are centimeters of gallery per 100 cm² phloem surface, representing 0 pct reduction.
[3]— = not tested.

Table 10—*Reduction in length of egg galleries of Jeffrey pine beetle in Jeffrey pine logs, by months after insecticide application, 1981*[1]

Insecticide and concentration (pct)	Months after application	
	3	5½
	Percent[2]	
Lindane:		
0.5	99	30
1.0	100	100
Decamethrin:		
0.01	95	89
0.05	100	83
Permethrin:		
0.05	22	0
0.1	46	20
Sevin:		
2.0	93	92
Untreated	(3)	(5)

[1]Tested by group-log method: logs of different treatments stacked together in same unit.

[2]Average of three logs. Values in parentheses are centimeters of gallery per 100 cm^2 phloem surface, representing 0 pct reduction.

Jeffrey Pine Beetle on Jeffrey Pine

Results of tests with Jeffrey pine beetle (*table 10*) show that lindane at 1 percent was fully effective at 3 and 5½ months, but at 0.5 percent was fully effective only at 3 months and ineffective at 5½ months. Sevin at 2 percent was nearly fully effective for 3 and 5½ months. Decamethrin at both 0.05 percent and 0.01 percent was about as effective as the 1 percent lindane and 2.0 percent Sevin for 3 months; at 5½ months effectiveness had dropped off a bit, but was still above 85 percent reduction. Permethrin at 0.1 percent was only partially effective at either 3 or 5½ months; but based on equivalent amounts, it appears to be more effective than lindane.

DISCUSSION

Of the insecticides tested, only malathion and Imidan were ineffective. All others—lindane, Sevin, Dursban, Reldan, Sumithion, permethrin, and decamethrin—were effective and could be considered for field application. The choice of insecticides and concentrations depends on other characteristics of the chemicals, environmental considerations, and on the length of protection desired.

Differences among the insecticides tested appear to be fairly consistent over time, concentration and, in some instances, formulation source. Four variables that appear to be of little significance are water temperature, postspray precipitation, exposure of bark, and source of beetle. Extremes of these variables could have some effect, but preliminary evidence points to other variables as being more significant.

Water pH was particularly significant in the tests with Sevin. Under most conditions in the West, pH is likely to be acidic and, therefore, favorable to insecticide stability. If Sevin is used, however, water pH should be adjusted to be lower than 7.

Application rate of 1 gal per 40 ft^2 (3.8 l/3.6 m^2) is considerably more effective than 1 gal per 80 ft^2 (3.8 l/7.2 m^2). Thus the current recommendation of 40 ft^2 should be maintained.

Beetle density could be a significant variable and, perhaps, could explain some differences between tests. Beetles do not appear to attack a log randomly because dead ones are usually found in clusters around treated logs. The behavior suggests, rather, the possibility that the spot where one beetle attempts to enter is more attractive than other spots. Successive attempts by a queue of beetles to enter the bark at a localized spot could eventually result in success in penetrating the bark, if beetle density were high enough. A large attacking population would also have a better chance of successfully penetrating the bark because of the simple increase in probability of longer queues and of finding a weak spot in the treatment.

Although no test was designed to compare single-log with group-log assay, the general results of somewhat similar tests indicate no noticeable difference. Each method has its advantages, however. Single-log testing permits regulation of attack density and compels the beetles to attack a specific log. But it requires greater handling of beetles and more time to conduct the study. Group-log testing provides more natural conditions because the beetles are not handled and there are choices for attack. Much less time is required to conduct the study. This method, however, does not permit control of attack density and does not ensure that each log is brought under the same attack pressure.

In previous work (Smith and others 1977), the effective residual periods were surprisingly long when the general ephemeral nature of some of the insecticides, such as Sevin and Dursban and, particularly, the two pyrethroids, is considered. Again, this points to an interaction between pine bark and the insecticide. Spraying pine bark might be likened to changing the place of storage of the insecticide, that is, from container to bark. Pine bark appears to trap and hold these molecules and prevent their rapid breakdown. This is a favorable environmental condition because tree bark is a relatively inert portion of the forest ecosystem. When insecticides are applied to pine bark, therefore, they remain effective for 6 to 12 months with minimum hazard to the environment. If care is taken in spraying trees, most, possibly 80 percent, of the spray will be on or beneath the surface of the bark. The small amount of drift can either be tolerated, or if necessary, caught in devices around the tree. Drift is greatly increased, however, when powered equipment is used. Where applicable, these results agree fairly well with results of extensive and intensive testing of southern pine beetle on loblolly pine (Hastings and Coster 1981).

Future studies should continue testing the pyrethroids—permethrin and decamethrin—and potentiating lindane by addition of molasses. Both offer possibilities of significant increases in tree protection through the use of lower dosage and safer insecticides.

REFERENCES

Elliott, M.; Janes, R. F.; Potter, C. **The future of pyrethroids in insect control.** Ann. Rev. Entomol. 23:443-69; 1978.

Hastings, Felton L.; Jones, Alice S. **Contact toxicity of 29 insecticides to southern pine beetle.** Res. Note SE-245. Asheville, NC: Southeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture; 1976. 6 p.

Hastings, Felton L.; Coster, Jack. **Field and laboratory evaluation of insecticides for southern pine beetle.** Gen. Tech. Rep. SE-21, Asheville, NC: Southeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture; 1981. 40 p.

Lyon, Robert L. **Contact toxicity of 17 insecticides applied topically to adult bark beetles.** Res. Note PSW-249. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1971. 3 p.

Robertson, Jacqueline L.; Gillette, Nancy L. **Contact toxicity of insecticides to western pine beetle, 1977.** Insecticide and Acaricide Tests 3:147; 1978.

Robertson, Jacqueline L.; Kimball, Richard A. **Feeding toxicity of insecticides to western pine beetle, 1977.** Insecticide and Acaricide Tests 3:148; 1978.

Smith, R. H.; Trostle, G. C.; McCambridge, W. F. **Protective spray tests on three species of bark beetles in the western United States.** J. Econ. Entomol. 70(1):119-125; 1977 February.

Smith, Richard H. **Log bioassay of residual effectiveness of insecticides against bark beetles.** Res. Paper PSW-168. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 8 p.

Residual effectiveness of nine insecticides applied to bark was tested against western, mountain, and Jeffrey pine beetles. Ponderosa and Jeffrey pine trees were treated and logs cut from them 2 to 13 months later, and bioassayed with the three beetles. The insecticides were sprayed at the rate of 1 gal (3.8 l) per 40- or 80-ft^2 (3.6 or 7.2 m^2) bark surface at varying concentrations. Effectiveness of treatment was based on reduction in length of egg galleries 2 to 3 weeks after initiating bioassay. All chemicals were quite effective for 2 to 13 months, except for malathion and Imidan which were relatively ineffective, depending largely on concentration and application rate. On the basis of equivalent amounts of lindane, the ranking of effectiveness of insecticides tested was as follows: (a) on western pine beetle: decamethrin > permethrin > lindane > Reldan > Dursban ≅ Sumithion > Sevin; (b) on mountain pine beetle: decamethrin > permethrin > lindane > Dursban ≅ Reldan > Sevin > Sumithion; (c) on Jeffrey pine beetle: decamethrin > permethrin > lindane > Sevin. The residual effectiveness of lindane was about doubled by adding 2 percent molasses, and high pH of water reduced effectiveness of Sevin. Other application parameters had little effect.

Retrieval Terms: Western pine beetle, mountain pine beetle, Jeffrey pine beetle, lindane, Sevin, Reldan, Dursban, Sumithion, Imidan, malathion, permethrin, decamethrin

United States
Department of
Agriculture

Forest Service

**Pacific Southwest
Forest and Range
Experiment Station**

Research Paper
PSW-169

Growth of 11 Introduced Tree Species on Selected Forest Sites in Hawaii

Michael G. Buck Roger H. Imoto

The Authors

are resource survey foresters for the Division of Forestry and Wildlife, Hawaii Department of Land and Natural Resources, Honolulu, Hawaii. **MICHAEL G. BUCK** holds a bachelor's degree (1976) in resource management from the State University of New York College of Environmental Science and Forestry, Syracuse. He has been with the Division since 1977. **ROGER H. IMOTO** holds a bachelor's degree (1979) in forest management science from Colorado State University. He has been with the Division since 1979.

Acknowledgments:

We thank Gerald D. Pickford, formerly of the Hawaii Division of Forestry, who established most of the growth plots in the older plantations. We also thank personnel of the Forest Service's Institute of Pacific Islands Forestry, and the Division of Forestry's Districts for assistance in field work, planning, and support during the period of the study.

Research in Hawaii by the Division of Forestry and Wildlife, Hawaii Department of Land and Natural Resources, is conducted in cooperation with the Forest Service, U.S. Department of Agriculture.

Cover: A 40-year-old tallowwood eucalyptus (*Eucalyptus microcorys*) plantation grows in the Kalopa section of the Hamakua Forest Reserve on the island of Hawaii.

Publisher

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

December 1982

Growth of 11 Introduced Tree Species on Selected Forest Sites in Hawaii

Michael G. Buck   Roger H. Imoto

CONTENTS

IN BRIEF...

Buck, Michael G.; Imoto, Roger H. **Growth of 11 introduced species on selected forest sites in Hawaii.** Res. Paper PSW-169. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 12 p.

Retrieval Terms: Hawaii, *Pinus, Eucalyptus*, growth, biomass, hardwoods

To assess growth of tree species introduced to Hawaii, trees on 25 plots representing 11 major species were observed and measured over a 21-year period. Species studied were Australian toon (*Toona ciliata* var. *australis* F. Muell. C. DC.), tropical ash (*Fraxinus uhdei* [Wenzig] Lingelsh.), silk-oak (*Grevillea robusta* A. cunn.), Norfolk-Island-pine (*Araucaria heterophylla* [Salisb.] Franco), redwood (*Sequoia sempervirens* [D. Don] Endl.), slash pine (*Pinus elliottii* Engelm.), loblolly pine (*Pinus taeda* L.), tallowwood eucalyptus (*Eucalyptus microcorys* F. Muell), blackbutt eucalyptus (*Eucalyptus pilularis* Sm.), robusta eucalyptus (*Eucalyptus robusta* Sm.), and saligna eucalyptus (*Eucalyptus saligna* Sm.).

All live trees were recorded and measured at 5-year intervals for diameter-at-breast-height (d.b.h.), bark thickness, and sawtimber-poletimber lengths and total heights. Cubic volume for all species except pines were computed by Smalian's formula. All stands were unmanaged except for redwood.

On the Australian toon, tropical ash, and silk-oak sites, high-quality sawlogs were produced from trees on certain sites. Rotation age should not exceed 45 years on these sites. Silk-oak was found to grow well on dry sites (890 mm [35 inches] rainfall/year) and could produce sawtimber if the rotation age was lengthened. High rainfall or excessive cloud cover is not suitable for silk-oak. Australian toon showed improved form and volume when grown in mixture with silk-oak rather than in a pure stand.

Norfolk-Island-pine trees on all plots sampled survived well and were healthy. Among the five plots, growth rates (to a 10-cm top outside bark) ranged from 730 to 1050 m^3 per ha (10,500 to 15,000 ft^3/acre). Total volume mean annual increment ranged from 15 to 27 m^3 per ha (210 to 395 ft^3/acre). Sawtimber volume ranged from 600 to 770 m^3 per ha (8000 to 11,000 ft^3/acre). For sawtimber, the data suggest that spacings of 3 by 3 m (10 by 10 ft) are desirable.

On the redwood sites, diameter growth of trees increased consistently, about 2.54 cm (1 inch) per 5 years during the last 15 years. Trees at age 48 had sawtimber cubic volume of 1500 m^3 per ha (21,328 ft^3/acre); total cubic volume was 1780 m^3 per ha (24,460 ft^3/acre), and mean annual increment for sawtimber was 30 m^3 per ha (444 ft^3/acre). Site index values for dominant redwood, by height and age, on Maui plots, would have a California site index of 160. Because redwood trees in Hawaii grow slower than redwood trees in California, site curves developed for northern California do not apply to trees grown in Hawaii. Another difference is that Hawaii-grown redwood is less durable and of lower grade than California-grown redwood and should be considered a general construction and utility softwood.

Due to denser stocking, the average diameter of slash pine at 15 years (20.8 cm [8.2 inches]) was less than that of loblolly pine (21.8 cm [8.6 inches]). Despite the smaller average diameter, slash pine stands had higher volume growth. At age 15, slash pine had 290 m^3 per ha (4176 ft^3/acre) volume as compared with 130 m^3 per ha (1860 ft^3/acre) volume for loblolly pine at age 20. Height growth, compared for the two species, indicates that loblolly pine was declining while slash pine maintained vigorous growth. To maximize potential growth, spacings more than 3 by 3 m (10 by 10 ft) should not be used for either species. Early thinnings are recommended when trees are planted closer together. Slash pine should be favored for volume production on marginal sites.

More than 8100 ha (20,000 acres) of eucalyptus species have been planted throughout Hawaii. Among these species, robusta eucalyptus is the more suitable for sawtimber; other species are used mainly for fiber and pulp. For young-growth eucalyptus, best growth at age 18 was a total volume of 650 m^3 per ha (9316 ft^3/acre) and 220 m^3 per ha (3126 ft^3/acre) of sawtimber volume. Total annual increment at age 7 to 18 averaged more than 35 m^3 per ha (500 ft^3/acre) and average diameter increased steadily from 18 to 28 cm (7.1 to 11.1 inches). For old-growth eucalyptus, on the best site, at age 32, the stand's total volume averaged 1425 m^3 per ha (20,358 ft^3/acre) and the average total height of the dominant trees was 60 m (196 ft).

Data from this report show that 10 of the 11 tree species investigated grow fast enough to warrant more extensive plantings that could supply timber or wood fiber for a forest products industry in Hawaii.

During the past 50 years, a wide variety of tree species have been introduced to Hawaii. Some have grown remarkably well and have shown great potential as a source of wood products.

In 1961, the Forest Service's Institute of Pacific Islands Forestry, Honolulu, Hawaii, began a study to determine growth rates within selected stands of 11 introduced timber species grown under tropical forest conditions. The study was done in cooperation with the Hawaii Division of Forestry and Wildlife. Of 42 growth plots established, 25 were selected for this report. Number of growth plots for each species is as follows:

Species	Plots
Australian toon (*Toona ciliata* var. *australis* [F. Muell.] C. DC.)	7
Tropical ash (*Fraxinus uhdei* [Wenzig] Lingelsh.)	7
Silk-oak (*Grevillea robusta* A. cunn.)	7
Norfolk-Island-pine (*Araucaria heterophylla* [Salisb.] Franco)	5
Redwood (*Sequoia sempervirens* [D. Don] Endl.)	1
Slash pine (*Pinus elliottii* Engelm.)	1
Loblolly pine (*Pinus taeda* L.)	1
Tallowwood eucalyptus (*Eucalyptus microcorys* F. Muell.)	2
Blackbutt eucalyptus (*Eucalyptus pilularis* Sm.)	1
Robusta eucalyptus (*Eucalyptus robusta* Sm.)	1
Saligna eucalyptus (*Eucalyptus saligna* Sm.)	6

The growth and volume data provided do not represent yields for whole stands or for a typical cross section of planted stands in Hawaii. They depict growth on sample areas. The yields, therefore, indicate the potential for growth of forests on better-than-average sites. Except for redwood, these are yields for completely unmanaged forests.

Because the plots are unique in site, spacing, and species, specific management practices based on data provided cannot be recommended. The data, however, supply a base for inferences that are given as general observations for each species.

This paper reports results and observations of a 21-year study of growth for 11 major tree species in Hawaii. All live trees on each of the 25 plots were recorded, and their growth measured at 5-year intervals. Each species is described in terms of history, size and growth rates, volume, wood characteristics, and potential uses.

PROCEDURES

Circular (0.04-ha) growth plots were established in forest plantations of selected species showing good vigor and low mortality. All live trees were recorded and their growth measured at 5-year intervals. Diameter-at-breast-height, 1.4 m (4.5 ft) above ground, was measured directly with diameter tapes, bark thickness with bark punches, and sawtimber-poletimber lengths and total heights with relaskops.

Sawtimber volume inside bark was calculated for lengths of stems from 30 cm (1 ft) above the base of the tree to a minimum 23-cm (9-inch) top diameter outside bark. Total volume inside bark was calculated for the main stem length, ignoring forks, to a 10-cm (4-inch) top diameter outside bark. Total volumes for pines were calculated for stem lengths from the base to the tip of the tree.

Cubic volume of all species except pines was obtained by Smalian's formula:

$$\text{Cubic volume} = \frac{B + b}{2} L$$

in which:

B = cross-sectional area inside bark at large end of stem

b = cross-sectional area inside bark at small end of stem

L = stem length

Cubic foot volume for pines was computed by these equations (McClure 1977):

Loblolly Pine

Total cubic foot volume inside bark =

$$0.5960 + 0.002115\,(D^2TH)$$

Slash Pine

Total cubic foot volume inside bark =

$$0.0255 + 0.002184\,(D^2TH)$$

D = d.b.h. in inches (outside bark)

TH = total height from ground level to tip of the main stem in feet.

SPECIES

Australian Toon

Australian toon was introduced to Hawaii in 1914, and planted in small scattered stands on all the islands. A small amount of toon timber in Hawaii has been cut and appears to be an excellent utility hardwood because it is easy to work and resistant to termites. Australian toon may have special applications in home construction as house siding and interior paneling (Skolmen 1974).

Two plots of Australian toon are located in the Kalopa section of the Hamakua Forest Reserve on the island of

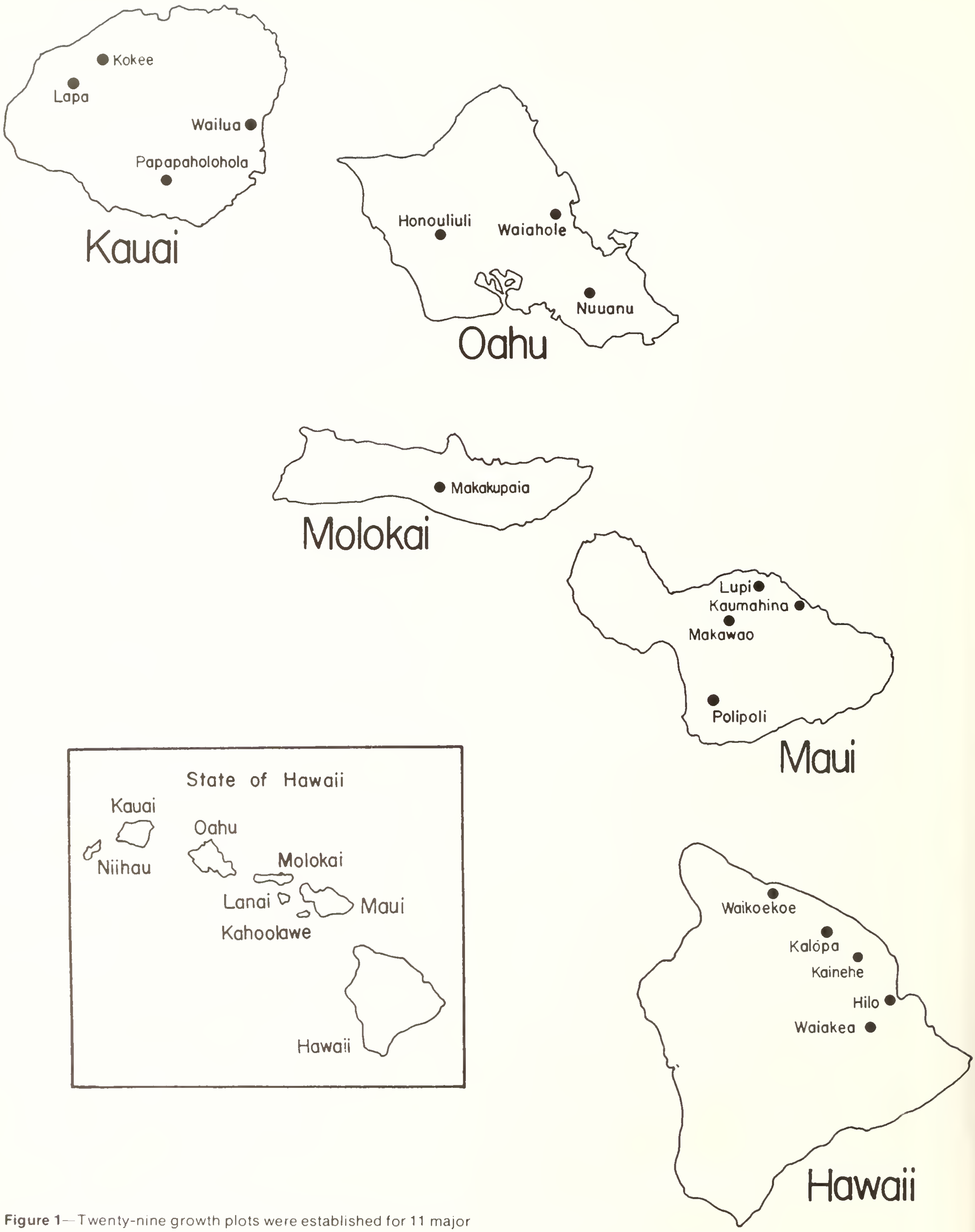


Figure 1—Twenty-nine growth plots were established for 11 major introduced tree species on five islands in Hawaii.

Hawaii (*fig. 1*). One is a pure stand, the other consists of alternating rows of toon and silk-oak (*fig. 2*).

The pure toon plot contained 395 m^3 per ha (5666 ft^3/acre) of sawtimber volume at age 43 (*table 1*). Mean annual increment (MAI) for total volume was 11 m^3 per ha (160 ft^3/acre). Diameter-at-breast-height ranged from 17 to 66 cm (6.7 to 25.9 inches), and averaged 43 cm (17.1 inches), with an average sawtimber stem length of 11 m (35 ft).

The six 43-year-old Australian toon trees on the toon silk-oak plots ranged from 35 to 57 cm (13.7 to 22.6 inches) d.b.h., averaging 47 cm (18.4 inches). Sawtimber stem length averaged 15 m (49 ft).

Tropical Ash

Tropical ash is a Mexican species that was introduced to the island of Oahu in the late 1800's. It was planted in small stands on all the islands and grew well in some locations. The Division of Forestry began planting ash on a larger scale in the Waiakea Forest Reserve near Hilo, for timber production, but its growth was poor. Tropical ash planting there has since been deemphasized.

Figure 2—Forked Australian toon (*Toona ciliata* var. *australis*) is in the background and silk-oak (*Grevillea robusta* A. cunn.) in the foreground in this mixed stand at Kalopa, island of Hawaii, at age 45.

Tropical ash wood is blond, moderately fine in texture, and straight grained. Because of the early growth habit of the tree, the butt log is often clear of knots to the pith and saws out a high yield of high-grade lumber. It is primarily a furniture and cabinet wood and has been used for furniture parts and finished furniture (Skolmen 1974).

Two tropical ash—silk-oak growth plots are in the Kalopa section of the Hamakua Forest Reserve on the island of Hawaii (*table 1, fig. 3*). Diameters of the 42 tropical ash trees on these plots ranged from 7.0 to 94 cm (2.8 to 37.0 inches) at 43 years, and averaged 33.0 cm (13.0 inches). Average sawtimber stem length was 12.5 m (41 ft).

Silk-oak

In about 1880, silk-oak was introduced to Hawaii from Australia, and planted on all the main Hawaiian Islands. The tree produces a straight, erect stem even when open-grown, and grows well in plantations, achieving excellent growth on all soils when annual rainfall is 1525 to 2030 mm (60 to 80 inches). Silk-oak also grows on drier sites, 760 mm (30 inches) annual rainfall, but slower. It has become widely naturalized and reproduction is often girdled or poisoned on pasture land, where it is considered a noxious weed (Nelson 1960).

Silk-oak has cream-colored sapwood about 2.5 cm (1 inch) thick, and changes abruptly to a pale pinkish-brown heartwood. It has been used successfully for furniture, paneling, and flooring. Because of its relatively light weight, the wood was found acceptable for pallets used in handling air cargo. Silk-oak is well suited as face veneer and is known by the name of lacewood (Skolmen 1974).

Three growth plots were established in pure silk-oak stands, two plots in silk-oak—tropical ash stands, and one plot in a silk-oak—Australian toon stand. Elevations varied from 440 to 725 m (1450 to 2380 ft) and rainfall ranged from 890 to 4570 mm (35 to 180 inches) (*table 1*). Pure silk-oak plots are located in the Kalopa section of the Hamakua and Waiakea Forest Reserves, island of Hawaii, and the Honouliuli Forest Reserve on the island of Oahu (*fig. 1*).

Of the three pure silk-oak plots, the Kalopa plot had the best growth volume with 490 m^3 per ha (6,971 ft^3/acre) of sawtimber at age 43 (*table 1*). Total volume mean annual increment was 14 m^3 per ha (196 ft^3/acre). Diameters ranged from 19 to 67 cm (7.6 to 26.3 inches) and averaged 40 cm (15.8 inches). Average sawtimber stem length was 16 m (51 ft).

The silk-oak plot in Honouliuli, Oahu, had 350 m^3 per ha (5018 ft^3/acre) of sawtimber at age 49. Diameters ranged from 10 to 52 cm (4.0 to 20.4 inches) and averaged 31 cm (12.2 inches). This is considered a dry site with 890-mm (35-inches) annual rainfall.

The silk-oak plot in Waiakea, Hawaii, had 235 m^3 per ha (3381 ft^3/acre) of sawtimber at age 43. The diameter range was 21 to 47 cm (8.2 to 18.5 inches), with an average diameter of 35 cm (13.9 inches), and average sawtimber

Table 1—*Site and volumetric data of three tree species at seven locations in Hawaii*

Tree species	Site						Species			Volume		
	Plot	Location	Spacing	Elevation	Precipitation	Aspect	Trees in plot	Age	Avg. d.b.h.	Total (10-cm top)	Sawtimber (23-cm top)	Total mean annual increment
			m	*m*	*mm*			*years*	*cm*	*m³/ha*	*m³/ha*	*m³/ha*
Toona ciliata var. *australis*	1	Kalopa, Hawaii	5.5 by 5.5	715	2080	Northeast	14	27	38.6	[1] —	—	—
							14	32	39.4	—	—	—
							14	38	41.4	345	269	9
							14	43	43.4	483	396	11
Toona ciliata var. *australis*	2	Kalopa, Hawaii	4.9 by 4.9	720	2080	East	17	32	37.1	—	—	—
							16	38	41.4	387	262	10
Grevillea robusta							15	43	43.8	713	597	17
Grevillea robusta	3	Kalopa, Hawaii	3.0 by 3.7	660	2080	North	36	26	26.9	—	—	—
Fraxinus uhdei							33	31	27.4	—	—	—
							27	37	26.7	479	284	13
							25	42	26.2	551	367	13
Grevillea robusta	4	Kalopa, Hawaii	3.7 by 4.9	700	2080	Northwest	25	27	36.3	—	—	—
Fraxinus uhdei							25	32	38.4	—	—	—
							25	38	38.4	619	441	16
							24	43	39.1	906	688	21
Grevillea robusta	5	Kalopa, Hawaii	4.9 by 4.9	725	2080	North	19	27	32.3	—	—	—
							19	32	33.5	—	—	—
							15	38	37.6	329	231	9
							13	43	40.1	590	488	14
Grevillea robusta	6	Honouliuli, Oahu	2.7 by 3.7	445	890	Northeast	30	38	26.9	—	—	—
							27	43	27.9	482	308	11
							26	49	31.0	550	351	11
Grevillea robusta	7	Waiakea, Hawaii	3.4 by 7.6	445	4600	Level	16	38	34.5	—	—	—
							16	43	35.3	360	237	8

[1] No data

stem length of 9 m (30 ft). This is considered a wet site with 4570-mm (180-inches) annual rainfall.

The 43-year-old mixed silk-oak—Australian toon plot in Kalopa had 11 silk-oak and six Australian toon trees. The silk-oak diameter range was 9 to 57 cm (3.4 to 22.4 inches), average diameter 42 cm (16.4 inches), and average sawtimber stem length of 14 m (47 ft). Average height of the seven dominant silk-oak trees was 32 m (105 ft), compared with 30 m (97 ft) for the six dominant Australian toon trees. All Australian toon trees on the plot were in the dominant crown class with no mortality.

The two silk-oak—tropical ash growth plots in Kalopa included 15 silk-oak trees. At age 43, they had diameters ranging from 18 to 43 cm (7.1 to 17.1 inches) and averaged 33 cm (13.0 inches), with an average sawtimber length of 12 m (39 ft). The average height of dominant silk-oak on the two plots was 29.5 m (97 ft) and of tropical ash was 29.3 m (96 ft). Among the trees of each species, 40 percent were in the dominant crown class.

General observations of growth plot data for Australian toon, tropical ash, and silk-oak are as follows:

- Mortality ranged from 0 to 28 percent. Cull and defects such as multistems, spike branches, sweeps, and crooks were observed on all plots. Few trees had a clean stem for 14.6 m (48 ft). On the one exposed site in Kalopa, windthrow and broken tops were common.
- All stand conditions in these plots, except Honouliuli, were deteriorating. Overstory canopies were opening, and weedy vegetation was entering the understory. If stands are going to be unmanaged as these were, rotation ages for high quality sawlogs on the Kalopa and Waiakea sites should not exceed 45 years. Diameter growth could have been increased on the larger stems by thinning the stand to reduce competition.
- The ability of silk-oak to grow acceptably and with good form on sites as dry as Honouliuli (890 mm [35 inches] rainfall/year) could be utilized by lengthening the rotation age on these dry sites. Growth of silk-oak in Waiakea, where rainfall was 4570 mm (180 inches) per year, was poor, suggesting that high rainfall or heavy cloud cover associated with this high rainfall is not suitable for silk-oak.
- Australian toon showed better form and volume in mixture with silk-oak than in the pure stand. In the mixed plot, average sawtimber stem length of Australian toon was 15 m (49 ft), as compared with 11 m (35 ft) for the pure plot.

Norfolk-Island-Pine

Norfolk-Island-pine and Cook-pine (*Araucaria columnaris*) were introduced to Hawaii in about 1860. The two species probably hybridized, and the hybrids were subsequently dispersed throughout the islands. Norfolk-Island-pine in Hawaii is probably *A. heterophylla xcolumnaris.* All juvenile seedlings today show *A. columnaris* traits.

Norfolk-Island-pines are used as Christmas trees that are marketable locally and on the mainland. Most of the timber harvested is used for residential framing and sheathing, and the lowest grade is used for pallets. Some knotty-pine paneling has been produced and used effectively. The wood is also used to a limited extent in the craft industry (Skolmen 1974).

Generally, forest plantations of Norfolk-Island-pine in Hawaii have been established at 2.4- by 2.4-m to 4.6- by 4.6-m (8- by 8-ft to 15-by 15-ft) spacings at elevations below 610 m (2000 ft). Trees in cooler temperatures at higher elevations do not grow well.

Five plots were established in representative areas. One is on the island of Hawaii on the land of Waikoekoe, near Waipio Valley, one on Kauai in the Papapaholahola Spring Forest Reserve near Kalaheo, and three on Oahu (two at different elevations in Nuuanu Valley and one on a ridge at Waiahole on the windward side of the island) (*fig. 1*). Elevations range from 90 to 550 m (300 to 1800 ft) and annual rainfall from 1300 to 3175 mm (50 to 125 inches) (*table 2*). Spacings range from 3 by 3 m to 4.3 by 4.6 m (10 by 10 ft to 14 by 15 ft).

The greatest total volume per acre found in a single stand was on the land of Waikoekoe, with more than 1050 m^3 per ha (15,000 ft^3) at 38 years (*table 2*). This stand also had the most sawtimber cubic foot volume per acre with 750 m^3 per ha (10,815 ft^3) and the highest total volume mean annual increment of 27 m^3 per ha (395 ft^3). This plot had the closest spacing of 3 by 3 m (10 by 10 ft) and the highest elevation at 550 m (1800 ft).

Because no trees died in any plot, the initial planting spacings represent the present stocking level. Spacings ranged from 3 by 3 m (10 by 10 ft) for plot 1 (420 trees acre) to 3.7 by 3.7 m (12 by 12 ft) for plot 5 (300 trees acre) (*table 2*).

Trees on the sparsely-stocked plots (2 and 5) had the largest diameter growth. The largest d.b.h. was 60 cm (23.6 inches) for a 47-year-old tree in plot 5.

Figure 3—Tropical ash (*Fraxinus uhdei* Wenzig Lingelsh.) grows with silk-oak (*Grevillea robusta* A. cunn.) in this 44-year-old stand at Kalopa, island of Hawaii. Note the poorer form of the tropical ash

Table 2—*Site and volumetric data of Norfolk-Island-pine* (Araucaria heterophylla) *at five locations in Hawaii*

Plot	Location	Spacing	Elevation	Precipitation	Aspect	Trees in plot	Age	Average: Diameter	Average: Height of dominant codominant	Volume: Total (10-cm top)	Volume: Sawtimber (23-cm top)	Volume: Total annual increment
		m	*m*	*mm*			*years*	*cm*	*m*	*m³/ha*		
1	Waikoekoe, Hawaii	3.0 by 3.0	550	2030	Northwest	42	28	29.5	[1]			
						41	32	31.8				
						41	38	32.8	34.4	1050	757	28
2	Nuuanu, Oahu	3.7 by 4.0	215	2540	Northwest	38	25	35.8				
						25	43	39.4	22.6	641	514	15
						25	47	40.6	26.8	868	732	18
3	Waiahole, Oahu	3.4 by 3.7	90	2540	North	37	34	31.2				
						33	42	33.3	29.6	862	617	20
						33	46	34.0	30.5	989	743	21
4	Papapahola-hola, Kauai	3.7 by 3.7	305	2080	Southwest	31	49	36.8	25.3	546	452	11
						31	54	38.9	29.3	793	565	15
5	Nuuanu, Oahu	4.3 by 4.6	365	3175	South	21	42	37.1	23.2	524	442	12
						21	47	40.6	27.7	733	592	16

[1] No data

Tree height growth was most vigorous on plots 1 and 3, indicating these were probably the best sites. At age 38, dominant and codominant trees of plot 1 averaged 34 m (113 ft) tall, with the tallest tree measuring 43 m (142 ft).

General observations of the Norfolk-Island-pine growth plots are the following:

- Among the five Norfolk-Island-pine plots, growth rates (to a 10-cm top outside bark) ranged from 730 to 1050 m^3 per ha (10,500 to 15,000 ft^3/acre), and total volume mean annual increment ranged from 15 to 27 m^3 per ha (210 to 395 ft^3/acre).
- Sawtimber volume ranged from 600 to 770 m^3 per ha (8000 to 11,000 ft^3/acre).
- These yields were obtained in stands that were planted 28 to 49 years before they were measured. The ages at which maximum yields can be obtained cannot be determined during this short period of measurement, but the stands appear to be thriving and continuing to grow at high rates.
- For Norfolk-Island-pine sawtimber, spacings of 3 by 3 m (10 by 10 ft), with thinning, appear to be desirable.
- Although some plots showed slower growth rates, trees on all sites sampled had excellent survival and health. Of those sampled, plot 1 at Waikoekoe was the best site for Norfolk-Island-pine.

Redwood

Redwood is established on the islands of Maui, Kauai, and Hawaii. Maui, the island on which most redwood has been planted, has 113 ha (280 acres) of planted redwood containing 6.2 million board feet of sawtimber (Wong and others 1969). Redwood is difficult to establish in plantations because young trees grow slowly and need weeding to remove competing vegetation.

The main problems of Hawaii-grown redwood lumber are its low durability and grade; therefore, it is not a good substitute for top-grade redwood lumber imported from California. Hawaii-grown redwood should be considered a general construction and utility softwood suitable for house framing and similar uses (Skolmen 1974).

The redwood growth plot is located at 1750-m (5700-ft) elevation at Polipoli, in the Kula Forest Reserve on the island of Maui (*fig. 1*). Annual rainfall is 890 mm (35 inches) and afternoon fog and cloud cover are common. Soil on the site is a deep light-brown silty clay loam with no rocks.

The stand was planted in 1930, at 3- by 3-m (10- by 10-ft) spacings with seed from California. Six suppressed trees were removed in 1958, and the remaining 38 stems were pruned.

The average tree diameter for 48-year-old trees was 48 cm (18.8 inches). Diameter growth has been increasing consistently, about 2.54 cm (1 inch) per 5 years during the last 15 years (*table 3*).

At age 48, trees had a sawtimber cubic volume of 1500 m^3 per ha (21,328 ft^3/acre), and total cubic volume was 1780 m^3 per ha (24,460 ft^3/acre). The mean annual increment for sawtimber was 30 m^3 per ha (444 ft^3/acre) at age 48, and the current annual increment during the last 6 years was 110 m^3 per ha (1604 ft^3/acre).

The largest tree on the plot at age 48 was 87 cm (34.1 inches) at d.b.h. and 61 cm (24 inches) diameter on top of the first 5-m (16-ft) log, 20 m (67 ft) to a 23-cm (9-inch) top outside bark, and a total height of 37 m (120 ft).

In comparison to site index values of California redwood, redwood trees on the Maui plot would have a California site index of 160 (Lindquist and Palley 1963). Site indexes for redwood in northern California range from a high of 100 to 240. The low site index of the Maui redwoods might be caused by the slower start of planted stock in Hawaii as compared with the frequent coppice origin of young-growth redwood in California, or perhaps by a reaction of the tree's physiology to day-length differences in Hawaii. Redwood trees in Hawaii are growing slower in height, but more rapidly in diameter than redwood in California. Site curves developed for northern California, therefore, do not apply well to trees grown in Hawaii.

Loblolly Pine and Slash Pine

Hawaii has no native conifers. During the past 100 years, however, more than 45 species of pine have been planted experimentally. A few species have grown well in certain locations. Some have been planted fairly extensively (162

Table 3—*Growth of redwood* (Sequoia sempervirens) *at Poli-Poli, Maui, during 16 years of measurement*[1]

Age (years)	Average: Diameter-at-breast-height (d.b.h.)	Average: Height dominant codominant	Volume: Total (10-cm top)	Volume: Sawtimber (23-cm top)	Sawtimber: Mean annual increment	Sawtimber: Periodic annual increment
	cm	*m*	*m³/ha*			
32	39.6	24.4	—[2]	—	—	—
36	43.2	27.1	—	—	—	—
42	45.2	31.4	1173	819	20	—
48	47.8	31.7	1781	1492	31	112

[1] 3.0- by 3.0-m spacing (38 plot trees), Kula Forest Reserve.
[2] No data.

Figure 4—A loblolly pine (*Pinus taeda* L.) plantation at 2.4 by 2.7 m (8 by 9 ft) spacing on the island of Molokai. Trees on this plot are age 17.

ha [400 acres] loblolly and slash pines) on the island of Molokai (*fig. 4*).

Wood from slash pine grown near Olinda proved to be suitable for millwork and pattern stock, but not for construction (Bohr 1958). Its specific gravity was lower than normal for slash pine, indicating low strength. Exploratory tests of slash pine suggested that growth conditions in Hawaii might produce unusual variations in wood quality (Skolmen 1963).

Two growth plots are located in stands of loblolly and slash pines on Makakupaia Ridge, island of Molokai (*fig. 1*). Annual rainfall is 1000 mm (40 inches) and slope 0 to 5 percent with a north aspect. The soil is a strongly acidic silty clay loam. The loblolly pine stand was planted in January 1957, with 3.6- by 4.6-m (12- by 15-ft) spacings (598 trees/ha). Slash pine was planted in January 1962, with 2.4- by 2.7-m (8- by 9-ft) spacings (1494 trees/ha). Because no trees died in either plot, stocking is represented by the original spacing.

Despite the denser stocking of slash pine, its average diameter at 15 years—20.8 cm (8.2 inches)—was slightly less than that of loblolly pine—21.8 cm (8.6 inches) (*table 4*). The largest diameter for loblolly pine was 36 cm (14.1 inches) and 31 cm (12.1 inches) for slash pine.

A comparison of volume growth of the two species indicates a higher productivity for the slash pine plot, which corresponds with its closer spacing (*fig. 5*). The loblolly pine 3.6- by 4.6-m (12- by 15-ft) spacings do not seem to fully utilize the site potential. Slash pine had 290 m^3 per ha (4176 ft^3/acre) volume at age 15, as compared with 130 m^3 per ha (1860 ft^3/acre) volume at age 20 for loblolly pine (*table 4*).

Average height growth for slash pine was 13 m (43.8 ft) at 15 years, greater than the loblolly pine with 12 m (39.8 ft) at 20 years. The tallest slash pine was 17 m (56 ft) and the tallest loblolly pine was 15.5 m (51 ft). A comparison of height growth between the two species indicates that loblolly pine is decreasing while slash pine is maintaining vigorous growth (*fig. 6*).

Loblolly pine in a similar study at Olinda, Maui (Whitesell 1974), had better d.b.h. and total height growth rates at similar or denser spacings (2.4 by 2.4 m [8 by 8 ft]) than the Molokai loblolly pines (3.7 by 4.6 m [12 by 15 ft]). Another study (Schubert and Korte 1969), shows the growth of slash pine at 9 years as slightly faster than that of loblolly at 1.8- by 1.8-m (6- by 6-ft) and 2.7- by 2.7-m (9- by 9-ft) spacings at the Olinda site. The Olinda site has greater annual rainfall and better soil than the Molokai site.

For conifer plantings on marginal sites similar to the Molokai pine growth plots, slash pine seems to be a more desirable species than loblolly pine for maximum sawtimber and cubic volume growth per acre. As sites improve, growth differences between the two species lessen. The Olinda site may be ideal for either species.

To maximize potential growth, spacings more than 3- by 3-m (10- by 10-ft) should not be used for slash or loblolly pine. Early thinnings are recommended when trees are planted closer. For loblolly spacing, Whitesell (1974) recommended 3- by 3-m (10- by 10-ft) spacings for sawtimber and 2.4- by 2.4-m (8- by 8-ft) spacings for posts, poles, or fuelwood. Early thinnings in the closer spacings would increase growth rates and improve the quality of residual trees.

Table 4—*Growth of loblolly* (Pinus taeda) *and slash* (Pinus elliottii) *pines to age 20, on Molokai, by stand age*

Stand age (years)	Loblolly pine[1] Average Diameter-at-breast-height (d.b.h.)	Loblolly pine[1] Average Height	Loblolly pine[1] Total volume	Slash pine[2] Average Diameter-at-breast-height (d.b.h.)	Slash pine[2] Average Height	Slash pine[2] Total volume
	cm	*m*	*m^3/ha*	*cm*	*m*	*m^3/ha*
5	[3]—	—		11.7	6.1	40
10	16.3	7.8	55	18.0	10.0	153
15	21.8	10.2	95	20.8	13.4	292
20	21.6	12.1	130			

[1]3.7- by 4.6-m spacing (25-plot trees).
[2]2.4- by 2.7-m spacing (57-plot trees).
[3]No data.

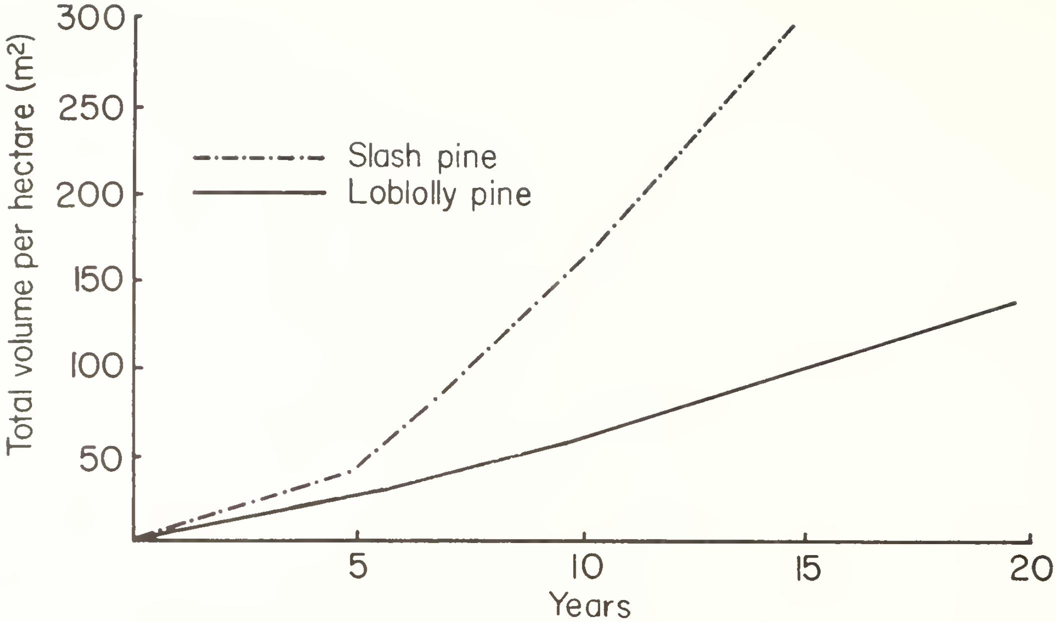


Figure 5—Volume growth compared for loblolly (*Pinus taeda* L.) and slash pine (*Pinus elliottii* Engelm.) shows a higher productivity for slash pine, which corresponds with its closer spacing. Loblolly pine spacing: 3.6 by 4.6 m (12 by 15 ft); slash pine spacing: 2.4 by 2.7 m (8 by 9 ft).

Eucalyptus Species

Eucalyptus species were introduced to Hawaii in the late 1860's to early 1900's. Their rapid growth on a variety of sites has made them a desired species for reforestation on all the main islands. More than 8100 ha (20,000 acres) of eucalyptus have been planted throughout the State.

Wood uses for eucalyptus are species-dependent. Robusta eucalyptus is more suitable for sawtimber than for fiber products. Its wood has been used for house siding, flooring, and paneling. The main uses for the other species have been for fiber and pulp.

This report covers 10 eucalyptus growth plots: one group with three plots representing a young age group from 7 to 18 years, and seven others representing an older age group from 25 to 45 years.

Young Eucalyptus Growth Plots

The younger group of growth plots was established in 7-year-old stands of saligna eucalyptus. Two were located

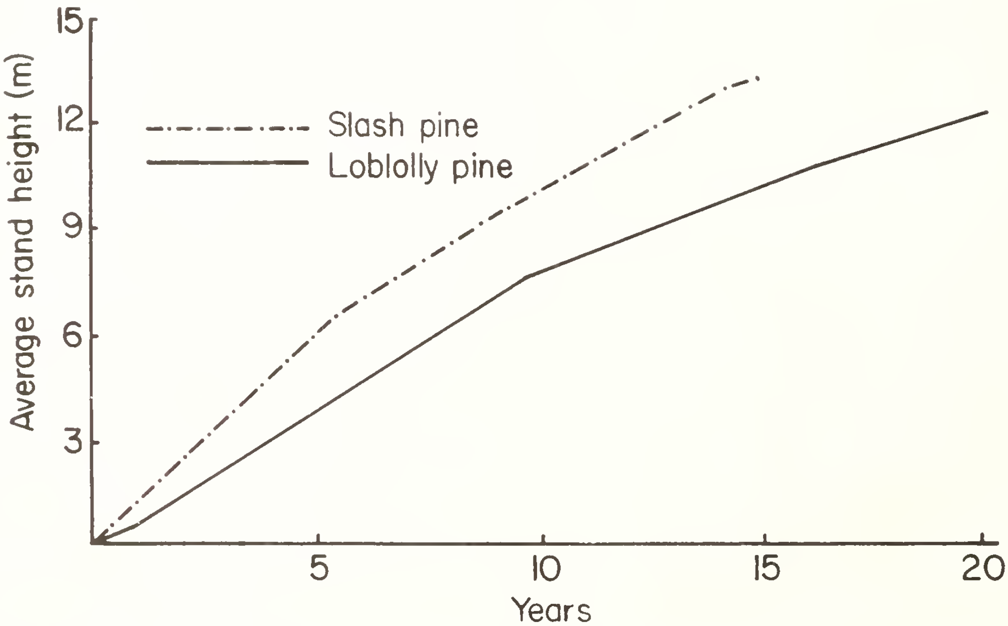


Figure 6—Height of loblolly pine (*Pinus taeda* L.) decreased as slash pine (*Pinus elliottii* Engelm.) maintained vigorous growth. The loblolly pine spacings (3.6 by 4.6 m [12 by 15 ft]) did not seem to fully utilize the site potential.

in the Lupi and Kaumahina sections of the Koolau Forest Reserve on the island of Maui, and the third was in the Waiakea Forest Reserve on the island of Hawaii (*fig. 1*). Data on elevations, rainfall, and spacings for each plot are provided (*table 5*).

The Kaumahina plot showed the best growth of the three plots. At age 18, it produced a total volume of 650 m^3 per ha (9316 ft^3/acre) and 220 m^3 per ha (3126 ft^3/acre) of sawtimber volume. The total measurement of mean annual increment at age 7 to 18 averaged more than 35 m^3 per ha (500 ft^3/acre) and average diameter increased steadily from 18 to 28 cm (7.1 to 11.1 inches).

Average total height of the 13 dominant and codominant trees on the plot at age 18 was 48 m (156 ft). The largest tree on the plot was 58 cm (23.05 inches) at d.b.h., 34 m (113 ft) to a 23-cm (9-inch) top, and 51 m (167 ft) tall.

A 15-year-old spacing study was done in Kaumahina which showed growth rates for the similar spacing slightly higher than those measured in the growth plots (Walters 1980). A significant feature reinforced by our growth plot data is the peaking of the mean annual increment volume at age 7. This peaking indicates that harvesting for optimal biomass production should be done at age 7.

The Lupi and Waiakea growth plots had lower growth rates than those at Kaumahina (*table 5*). The Lupi site had less than 2500-mm (100-inches) annual rainfall and the Waiakea site had more than 5000 mm (200 inches) per year. Again, the mean annual increment volume peaked at age 7. All sites suffered severe windthrow during the 1980 winter storm.

Older Eucalyptus Growth Plots

Much of this older eucalyptus growth data is historical in nature. Current management practices for eucalyptus favor short rotation and subsequent coppice management for high yields of fiber. The data show site quality for certain planting areas and volume estimates for existing, older eucalyptus plantations.

Seven plots were established in different species of eucalyptus (*table 6*). Six are on the island of Hawaii—three in the Kalopa section, Hamakua Forest Reserve, one each in the Kainehe and Waikoekoe units, Hamakua Forest Reserve, and one in the Hilo Reservoir area of Hilo Forest Reserve (*fig. 1*). The last plot is on Lapa Ridge in the Puu Ka Pele Forest Reserve, on the island of Kauai.

The best site for eucalyptus was the Kainehe unit, island of Hawaii. At age 32, the stand's total volume averaged 1425 m^3 per ha (20,358 ft^3/acre), and the average total height of the dominant trees was 60 m (196 ft).

The largest saligna eucalyptus tree measured was in the Hilo Reservoir plot (*fig. 7*). At age 44, it measured 95 cm (37 inches) d.b.h., 46 m (151 ft) to a 23-cm (9-inch) top, and 65 m (215 ft) in total height.

The blackbutt eucalyptus plot at Waikoekoe produced a total volume of 1590 m^3 per ha (22,687 ft^3/acre) at age 45 (*fig. 8*). It had the largest spacings, 4.9 by 6.1 m (16 by 20 ft), which explains its largest average d.b.h. of 65 cm (25.70 inches). The average total height of the dominant trees was 58 m (190 ft), indicating a very good site.

Biomass Energy Tree Farm Survey

In 1979, the Division of Forestry inventoried statewide the existing young forest plantations under the Biomass Energy Tree Farm Program. More than 1450 ha (3600 acres) of eucalyptus and 650 ha (1700 acres) of pines were included. Groups of plantations or strata were chosen to represent specific species, ages, and planting locations. A dendrometer was used to ensure precise tree measurements. Formal and more detailed island supplement reports have been published, but the additional growth information provided here may be of value (Buck and others 1979, Imoto and Ching 1979).

Total volume of the main stem to a 0.25-cm (0.1-inch) top was computed from the dendrometer measurements. Strata range from 65 to 270 ha (160 to 660 acres) each and represent more realistic volume estimates than the previously described 0.04-ha (0.1-acre) growth plots (*table 7*). Original spacings designed for sawtimber averaged 3 by 3 m (10 by 10 ft). Approximately 10 percent of tree deaths were due to windthrow and competing vegetation. Basal

Table 5—*Site and volumetric data of saligna eucalyptus* (Eucalyptus saligna) *7 to 19 years old, at three locations*

Location	Spacing	Elevation	Precipitation	Aspect	Age	Trees in plot	Average: Diameter-at-breast-height (d.b.h.)	Average: Height dominant codominant	Volume: (10-cm top)	Volume: (23-cm top)	Volume: Mean annual increment
	m	*m*	*mm*		*years*		*cm*	*m*	*m^3/ha*	*m^3/ha*	*m^3/ha*
Waiakea, Hawaii	3.0 by 3.0	550	5080	Northeast	7	44	15.7	18.6	188	25	27
					12	33	22.4	32.9	308	108	26
Lupi, Maui	3.0 by 3.0	250	2540		8	42	17.0	20.1	207	11	29
					13	37	21.3	29.9	288	68	22
					19	34	24.4	38.1	438	200	23
Kaumahina, Maui	2.7 by 3.7	150	3800	Northwest	7	39	18.3	23.5	221	41	36
					12	36	23.1	37.2	393	184	33
					18	30	28.2	47.5	652	219	36

Table 6—*Site and volumetric data for seven Eucalyptus plots over 22 years old*

Tree species	Site						Species				Volume		
	Plot	Location	Spacing	Elevation	Precipitation	Aspect	Trees in plot	Age	Avg. (d.b.h.)	Height dominant/codominant	Total (10-cm top)	Saw-timber (23-cm top)	Total mean annual increment
			m	*m*	*mm*			*years*	*cm*	*cm*	*m³/ha*	*m³/ha*	*m³/ha*
Saligna eucalyptus (*Eucalyptus saligna*)	1	Kainehe, Hawaii	2.4 by 3.7	700	3560	North	38	22	25.1	[1]—	—	—	—
							35	27	26.9	54.6	—	—	—
Tallowwood eucalyptus (*Eucalyptus microcorys*)	1	Kainehe, Hawaii	2.4 by 3.7	700	3560	North	33	32	29.7	59.7	1424	1311	44
Saligna eucalyptus (*Eucalyptus saligna*)	2	Hilo, Hawaii Res.	2.7 by 3.0	370	5720		51	33	24.4	45.4	968	740	29
							49	38	26.9	45.4	—	—	—
							44	43	29.5	49.1	1251	1043	28
Saligna eucalyptus (*Eucalyptus saligna*)	3	Lapa Ridge, Kauai	3.0 by 3.0	880	1020		16	31	41.1	36.3	—	—	—
							16	36	43.9	38.7	782	663	22
							16	41	45.4	38.1	998	893	24
Robusta eucalyptus (*Eucalyptus robusta*)	4	Kalopa, Hawaii	2.4 by 3.0	650	2080	North-east	38	27	29.5	45.4	—	—	—
							38	32	30.5	—	—	—	—
							37	37	31.5	51.2	854	779	23
							32	43	36.6	48.8	1140	967	27
Blackbutt eucalyptus (*Eucalyptus pilularis*)	5	Waikoekoe, Hawaii	4.9 by 6.1	520	1960	North	23	27	49.0	—	—	—	—
							20	32	55.9	55.5	—	—	—
							20	37	59.4	55.8	1162	1119	31
							19	45	65.3	57.9	1587	1534	35
Tallowwood eucalyptus (*Eucalyptus microcorys*)	6	Kalopa, Hawaii	3.0 by 3.7	700	2080	North	26	27	35.8	45.7	—	—	—
							26	32	37.3	44.5	—	—	—
							26	39	38.6	49.7	880	650	23
							26	45	40.1	49.7	1101	901	26
Tallowwood eucalyptus (*Eucalyptus microcorys*	7	Kalopa, Hawaii	3.0 by 3.7	700	2080	North-east	27	28	29.2	44.5	—	—	—
							29	33	30.7	45.7	740	627	22
							29	38	31.8	49.7	—	—	—
							28	43	33.5	53.0	941	764	22

[1]No data.

Table 7—*Total volume and bark volume per hectare by species, age, and location, for 1979 Hawaii biomass inventory*

Species and location	Age	Area inventoried	Volume		Basal area
			Total	Bark	
	years	*ha*	*m³/ha*	*m³/ha*	*m²/ha*
Eucalyptus saligna					
Lupi, Maui	19	69	333	53	23.4
Kaumahina, Maui	18	96	354	67	24.3
Makawao, Maui	16	104	150	30	14.2
Wailua, Kauai	12	212	229	53	17.7
Waiakea, Hawaii	12	269	113	26	8.5
Waiakea, Hawaii	10	144	87	25	6.4
Eucalyptus robusta	12	132	96	32	11.5
Waiakea, Hawaii					
Waiakea, Hawaii[1]	10	65	143	43	15.2
Pinus taeda					
Kokee, Kauai	18	146	138	33	21.6
Pinus elliottii					
Makakupaia, Molokai	17	142	129	23	15.6
Pinus radiata					
Poli Poli, Maui	13	78	50	9	8.0

[1]Coppice.

area values indicate stocking at time of measurement. Biomass plantings with closer spacing and intensive management would yield higher total volume per acre.

The highest saligna eucalyptus volume yield per hectare was the Kaumahina, Maui, stratum with 350 m³ per ha (5055 ft³/acre) at age 18. Its total volume of mean annual increment was 20 m³ per ha (281 ft³/acre). The Wailua, Kauai stratum produced 230 m³ per ha (3277 ft³/acre) at age 12, with a total volume mean annual increment of 19 m³ per ha (273 ft³/acre). The percent bark volume was inversely proportional to age. The 19-year-old Lupi, Maui, stratum averaged 16 percent bark volume and the 10-year-old Waiakea, Hawaii, stratum averaged 29 percent bark volume.

The coppice robusta eucalyptus stratum produced 140 m³ per ha (2044 ft³/acre) at age 10. This was significantly higher than the volume yield of the 12-year-old noncoppice robusta stratum that produced 96 m³ per ha (1377 ft³/acre).

Figure 7—This saligna eucalyptus (*Eucalyptus saligna* Sm.) plot at the Hilo Reservoir, island of Hawaii, contained the largest saligna eucalyptus tree measured. At age 44, it measured 95 cm (37 inches) diameter-at-breast-height (d.b.h.), 46 m (151 ft) to a 23-cm (9-inch) top, and 65 m (215 ft) in total height.

Figure 8—Blackbutt eucalyptus (*Eucalyptus pilularis* Sm.) growing on the Waikoekoe plot, island of Hawaii, had the largest spacings (4.9 by 6.1 m [16 by 20 ft]) and the largest average diameter-at-breast-height (d.b.h.) of 65 cm (26 inches).

MANAGEMENT IMPLICATIONS

Although specific management practices cannot be recommended on the basis of the limited data of this study, some general observations for particular species may be significant.

Australian toon, tropical ash, and silk-oak: In unmanaged stands for high-quality sawlogs, rotation age should not exceed 45 years. Silk-oak can grow acceptably and with good form on dry sites (890 mm [35 inches] per year), but the rotation age should be lengthened. High rainfall or heavy cloud cover associated with high rainfall is not suitable for silk-oak. Australian toon may grow better in mixture with silk-oak than in pure stands.

Norfolk-Island-pine: Spacings of 3 by 3 m (10 by 10 ft) with thinning seem to be desirable for maximum growth. Trees at age 49 are healthy and growing at a rate that suggests rotation age of more than 50 years is possible.

Redwood: Although difficult to establish in plantations because of slow early growth, redwood attains good growth rates in Hawaii. Redwood trees in Hawaii grow slower in height but more rapidly in diameter than redwood in California.

Loblolly Pine and Slash Pine: Both species have been established successfully in plantations on a variety of sites in Hawaii. On dry marginal sites, slash pine is the more desirable species for volume production. As sites improve, growth differences between the two species lessen. To maximize growth, spacings larger than 3 by 3 m (10 by 10 ft) are not recommended for either species.

Eucalyptus: Rapid growth on a variety of sites has made eucalyptus a desired species for reforestation in Hawaii. The mean annual increment for volume peaks at age 7. Sawtimber growth at spacings of 3 by 3 m (10 by 10 ft) has produced volumes up to 1425 m^3 per ha (20,358 ft^3/acre) at age 32. At 3- by 3-m (10- by 10-ft) spacings, coppice volume growth was significantly higher than noncoppice growth at similar ages.

The data reported show that 10 tree species can grow fast enough to warrant more extensive plantings that could supply timber or wood fiber for a forest products industry in Hawaii. Forest managers in tropical countries throughout the world will be able to use the information to improve decisionmaking in selecting trees and in managing plantations.

REFERENCES

Bohr, A. W. **A few strength tests on Pinus elliottii from Hawaii.** 1958. Unpublished draft supplied to authors by Roger G. Skolmen, Pacific Southwest Forest and Range Experiment Station, Honolulu, HI.

Buck, Michael G.; Costales, Patrick G.; Petteys, Edwin Q. P. **Forest plantation survey-Biomass Energy Tree Farm Program.** State of Hawaii, Department of Land and Natural Resources; 1979. 22 p.

Imoto, Roger H.; Ching, Wayne F. **Forest plantation survey supplement.** On file with Hawaii Division of Forestry and Wildlife-Resource Survey Section. 1979. 96 p.

Lindquist, James L.; Palley, Marshall N. **Empirical yield tables for young growth redwood.** Bull. 796. Berkeley, CA. California Agricultural Experiment Station; 1963. 47 p.

McClure, Joe [Letter to Michael G. Buck]. 1977 November 30. 1 leaf. Located at: Division of Forestry and Wildlife, Hawaii Department of Land and Natural Resources, Honolulu, HI.

Nelson, Robert E. **Silk-oak in Hawaii . . . pest or potential timber?** Misc. Paper 47. Berkeley, CA. Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1960. 5p.

Schubert, Thomas H.; Korte, Karl H. **Early growth and development of four pine species in Hawaii.** Res. Note PSW-189. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1969. 4 p.

Skolmen, Roger G. **Wood density and growth of some conifers introduced to Hawaii.** Res. Paper PSW-12. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1963. 20 p.

Skolmen, Roger G. **Some woods of Hawaii . . . properties and uses of 16 commercial species.** Gen. Tech. Rep. PSW-8. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1974. 30 p.

Walters, Gerald A. **Saligna eucalyptus growth in a 15-year-old spacing study in Hawaii.** Res. Paper PSW-151. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1980. 6 p.

Whitesell, Craig D. **Effects of spacing on loblolly pine in Hawaii after 11 years.** Res. Note PSW-295. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1974. 4 p.

Wong, Wesley H. C., Jr.; Wick, Herbert L.; Nelson, Robert E. **Plantation timber on the island of Maui—1967.** Resour. Bull. PSW-11. Berkeley, CA. Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1969. 42 p.

Buck, Michael G.; Imoto, Roger H. **Growth of 11 introduced tree species on selected forest sites in Hawaii.** Res. Paper PSW-169. Berkeley, CA. Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 12 p.

Growth and volume data for trees on 25 plots representing 11 introduced species in Hawaii were recorded during a 21-year period. Trees were measured at about 5-year intervals to determine overall growth and stand development. The sites selected were considered better-than-average in terms of elevation, amount of precipitation, and soil quality. Except for redwood, stands were unmanaged. The data reported suggest that 10 tree species can grow fast enough to warrant more extensive plantings for timber or wood fiber production.

Retrieval Terms: Hawaii, *Pinus*, *Eucalyptus*, growth, biomass, hardwoods

United States
Department of
Agriculture

Forest Service

**Pacific Southwest
Forest and Range
Experiment Station**

Research Paper
PSW-170

Carbaryl Applied at Reduced Dosage Rates for Control of Western Spruce Budworm

George P. Markin David R. Johnson

Authors:

GEORGE P. MARKIN is a research entomologist working with the Station's unit that is studying the biology of insects adversely affecting regeneration and establishment of western forests. He holds three degrees in entomology—a B.S. from Montana State College (1962), an M.S. from the University of Idaho (1964), and a Ph.D. from the University of California at Riverside (1967). He joined the Forest Service in 1973 and the Station's staff in 1976. **DAVID R. JOHNSON**, at the time of this study, was a biological technician with the Station's field evaluation of chemical insecticides research unit at Davis, Calif. He earned a B.A. degree (1972) in biology at California State University, Fresno, and an M.S. in entomology (1976) at the University of California, Davis. He is now a biological technician with the Station's Institute of Forest Genetics, Placerville, Calif. He joined the Forest Service in 1978.

Acknowledgments:

We thank Carol S. Horning for technical assistance in operating the field laboratory; Hubert Myers, Cooperative Forestry and Pest Management, Northern Region, Missoula, Montana; and District Ranger Frank R. Primozic and the staff of the White Sulphur Springs Ranger District, without whose help and support this test would not have been possible.

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

August 1983

Carbaryl Applied at Reduced Dosage Rates for Control of Western Spruce Budworm

George P. Markin David R. Johnson

CONTENTS

IN BRIEF . . .

Markin, George P.; Johnson, David R. **Carbaryl applied at reduced dosage rates for control of western spruce budworm.** Res. Paper PSW-170. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983. 3 p.

Retrieval terms: western spruce budworm, *Choristoneura occidentalis*, spray test, carbaryl, Sevin-4-oil, Montana

Of three chemical insecticides presently registered for control of the western spruce budworm (*Choristoneura occidentalis* Freeman), carbaryl in the formulation Sevin-4-oil is the most extensively used. Since carbaryl was first tested in 1975, all subsequent field tests and eventual operational programs have been at the same dosage rate of 1.12 kg a.i. per hectare (1 lb/acre), the rate at which this insecticide is now registered. To determine the effectiveness of lower dosage rates, an aerial field test was conducted in July 1979, north of the community of White Sulphur Springs in western Montana. Rates of 0.28 and 0.56 kg a.i. per hectare (0.25 and 0.5 lb a.i./acre) were compared with the registered rate of 1.12 kg a.i. per hectare. Each dosage was applied to five randomly selected 20-hectare plots by helicopter with Beecomist nozzles while the larvae were in the fifth and early sixth instars. Branch samples were collected from 15 randomly selected Douglas-fir trees before spraying and at intervals of 5, 10, and 15 days after spraying to determine larval populations. An additional sample was collected when 95 percent pupation had occurred to determine percent loss of current year's foliage due to larval feeding. All three treatments significantly reduced larval populations and the amounts of foliage destroyed when compared with the untreated controls. It appears, however, that the rates of 1.12 and 0.56 kg per hectare provided a comparable degree of population control while the rate of 0.28 kg per hectare was possibly 10 percent less effective.

Control of all treatments would have been slightly higher except 17 percent of the trees had unopened buds at the time of spraying, which would have protected any budworm larvae still in the bud mining stage. Results of the test were recalculated after dropping those trees on which 50 percent or more of the buds were still closed at treatment. The final percent population reductions of budworm larvae were 93.9, 95.5, 85.5, and 43.1 percent, respectively, for the dosages of 1.12, 0.56, and 0.28 kg per hectare and the untreated controls. Under the conditions of our test, the rate of 0.56 kg a.i. per hectare compared favorably with the rate of 1.12 kg per hectare in reducing larval populations of the western spruce budworm and preventing destruction of new foliage in Douglas-fir.

Three chemical insecticides are registered for aerial control of western spruce budworm (*Choristoneura occidentalis* Freeman). Among them, carbaryl in the formulation Sevin-4-oil at the dose of 1.12 kg a.i. per hectare (1 lb a.i./acre) is the most extensively used. The registered dosage is the result of field tests in 1975 in Montana (Flavell and others 1978) and in 1976 in Washington (Mounts and Gregg 1978). In both tests, carbaryl was applied at the single dosage of 1.12 kg a.i. per hectare. Data were not available at the time of its registration or have become available since then to indicate if this is the minimum effective dosage rate. The insecticide was tested at two dosage rates in 1975 on eastern spruce budworm (*C. fumiferana* [Clemens]). The rate of 0.56 kg per hectare (0.5 lb/acre) was almost as effective (92 pct control) as the 1.12 kg per hectare rate (96 pct control) (Millers 1976). Those test results suggest that a lower dosage rate might be as effective as the registered dosage in controlling western spruce budworm. A lower rate not only would be cheaper, but also might reduce some of the undesirable effects, such as on aquatic insects, caused by the registered rate (Shea 1978).

To determine the effectiveness of lower dosage rates of carbaryl, an aerial field test was conducted in July 1979 in Montana. Rates of 0.28 and 0.56 kg a.i. per hectare (0.25 and 0.50 lb a.i./acre) were compared with the registered rate of 1.12 kg a.i. per hectare (1.0 lb a.i./acre).

This paper describes the results obtained at lower dosage rates and compares them with results of previous tests and operational programs in which the registered dosage was used.[1]

METHODS AND MATERIALS

Twenty experimental plots were located north of White Sulphur Springs, Montana, most of them on the Lewis and Clark National Forest, with a few on private land within or adjacent to it. Elevation ranged from 1700 to 2000 m. Stand composition was primarily second-growth Douglas-fir (*Pseudotsuga menziesii* var. *glauca* [Beissn.] Franco), with a scattering of lodgepole pine (*Pinus contorta* Dougl.).

Each plot was a 20-ha square or rectangle located within a topographically similar area. All sampling was done in the center area of the plot, 60 m or more from the plot perimeter, where 15 open-grown Douglas-fir trees were randomly selected. Each sample tree was at least 40 m from any other sample tree and small enough so that a 10-m pole pruner could reach at least 30 percent of the foliage. To eliminate the possibility of cross contamination by spray drift, all plots were located at least 1 km apart. Treatments (three dosage rates and a control) were randomly assigned to the 20 plots.

Carbaryl was received from the manufacturer in 18.94-*l* (5-gal) metal containers in the formulation Sevin-4-oil. Each can was rolled for 5 min before opening to assure resuspension of any settled material, and checked afterwards to see that no residue remained in the can. Carbaryl was applied at three dosages: 1.12, 0.56, and 0.28 kg a.i. per hectare, diluted with no. 2 diesel fuel and sprayed at the rate of 4.67 *l* per hectare. Rhodamine B dye, 0.1 percent by volume, was added to facilitate spray deposit assessment.

Western spruce budworm larval population was determined for each sample tree 24 h before spraying and 5, 10, and 15 days later. Two 40-cm branches were removed from midcrown of each sample tree at prespray and four branches postspray (Carolin and Coulter 1972). Sample branches were collected with a 10-m extendable pole pruner with a 50-cm cloth basket fastened just blow the cutting head. They were kept separately in a marked paper bag and stored in an ice chest until brought to the field laboratory.

In the field laboratory, larvae were removed from the branch samples with a beating barrel and collected in shallow pans (Martineau and Benoit 1973). The laboratory crew then counted buds, identified and counted the larvae, expressing budworm population as larvae per 100 buds on new shoots.

Spray deposit was sampled by placing a 10- by 12.7-cm white Kromekote card and two 15- by 15-cm aluminum plates at ground level in an opening adjacent to each sample tree. Cards and plates were left in place for at least 30 min after spraying before being collected, to assure complete settling and drying of the spray. Cards were analyzed on an Imanco Quantimat 720 image analyzer at the Department of Advanced Instrumentation, University of California, Davis,[2] for drop size (volume median diameter [VMD]), and number of drops per square centimeter. Plates were analyzed by washing the deposit off the plate and analyzing for the fluorescent dye tracer (Yates and Akesson 1963) to determine the volume of spray recovered in liters per hectare.

When 95 percent pupation had occurred, we collected four branch samples from the midcrown of each sample tree to determine current year's defoliation from budworm feeding. Defoliation was assessed by examining 25 shoots per branch and estimating the amount of new foliage consumed or destroyed by budworm feeding. The percentages were averaged to estimate the amount of defoliation of the branches sampled for each tree. Analysis of variance was used to determine if the four treatments (three dosage levels and a control) differed significantly in larval population reduction. Pairwise comparisons (treatment as against control) were conducted with Tukey's test.

---

[1]This publication does not contain recommendations for the pesticide uses reported, nor does it imply that they have been registered by appropriate governmental agencies.

[2]Trade names and commercial enterprises or products are mentioned solely for information. No endorsement by the U.S. Department of Agriculture is implied.

SPRAY APPLICATION

Carbaryl was applied by a Bell 47G-3B-2 helicopter, equipped with a hydraulic spray system, 10-m boom, and three Beecomist nozzles equipped with Wettable Powder sleeves. Two of the nozzles were mounted on the extreme ends of the boom and the third mounted on the rear skid support of the helicopter. The materials were mixed in a 750-*l* mixing tank equipped with both mechanical and recirculating agitation. The compound was mixed immediately before spraying (10 to 30 min) and agitated until all materials had been pumped into the helicopter. It was applied at the rate of 4.67 *l* per hectare (1/2 gal/acre). The helicopter flew 75 km/h, 15 m above treetops, and made a 20-m swathe. Each plot was marked with a treetop banner in each corner to help the pilot locate the plot perimeter.

The plots were sprayed early in the morning of July 6 through July 8, when temperatures ranged from 9° to 18°C, and winds were less than 7 km/h. Rain of less than 0.5 cm fell briefly 4 days before spraying; and at 6 days after spraying, less than 0.1 cm of rain fell. Bud development that spring was slow and quite variable. At the time of spray application, only 83 percent of the trees had buds fully opened. Fifteen percent of the trees had buds that were bursting and 2 percent had buds that were still closed. Carbaryl is best applied against the western spruce budworm when buds are opened because that exposes the larvae to the spray. In waiting for buds to open we found that larval development progressed farther than desirable. At time of spraying 51 percent of larvae were in early sixth instar; normally less than 10 percent of larvae would be in sixth instar.

RESULTS

During the treatments, we observed that none of the plots were missed or double treated. An examination of the spray cards and plates indicated that within the plots no major skips occurred since all trees showed some deposit. The carbaryl provided by the manufacturer was highly viscous, but differed considerably in the tree dosage rates applied—depending on the amount of diesel fuel added. With increased diluent the resulting droplet size decreased and the number of droplets increased (*table 1*).

Table 1—*Spray deposits assessed from Kromekote cards and aluminum plates in plots treated with carbaryl, Montana, 1979*

Dosage (kg a.i./ha)	Volume spray applied	Deposit recovered from plates		Deposit recorded on cards	
	l/ha	*l/ha*	*Percent*	*Drops/cm²*	*VMD (μm)*
1.12	4.67	0.90	19.3	10.1	178
.56	4.67	.73	15.7	15.5	173
.28	4.67	.71	15.3	28.5	161

The recovery at ground level of only 15 to 19 percent of the volume of spray applied was slightly lower than we have encountered in previous tests of this type (20 to 30 percent). This result was not unexpected, however, since the droplet size was smaller (less than 200 μm VMD), allowing the droplets to remain suspended in the air longer. The other 81 to 85 percent of the spray probably could be accounted for by interception by the foliage within the plot or lost from the plot by drift.

All three treatments significantly reduced larval population and the amounts of foliage destroyed when compared with the untreated controls (*table 2*). But the design used could not detect differences among individual treatments. It appeared, however, that the rates of 1.12 and 0.56 kg per hectare provided a comparable degree of population control, and that the rate of 0.28 kg per hectare was possibly 10 percent less effective.

A question remains, however, about the effect that partial bud burst at the time of spraying may have had on budworm mortality. An early study suggested that bud development can be critical on the effectiveness of an insecticide with a short field life (Markin and others 1978). In the present test, approximately 17 percent of the trees being sampled had buds bursting or partially open. Larvae and new foliage on these trees, therefore, were not exposed to the spray. To find evidence of an effect on the resulting population reduction, we examined the larval population on individual trees. We found that trees with the highest survival often were those with the slowest bud development at time of spraying.

Percent population reduction was, therefore, recalculated for each plot by using only larval number from those trees in which more than 50 percent of the buds were open. The total

Table 2—*Population reduction, uncorrected for natural mortality, of western spruce budworm larvae populations after application of three rates of carbaryl, Montana, 1979*[1]

Dosage (kg a.i./ha)	Prespray larvae/ 100 buds	5 days postspray		10 days postspray		15 days postspray		Destruction of new foliage[2]
		Larvae/ 100 buds	Percent reduction	Larvae/ 100 buds	Percent reduction	Larvae/ 100 buds	Percent reduction	
1.12	8.24	2.68	67.5a	1.45	84.0a	0.58	92.8a	29.8a
.56	8.65	1.27	85.2a	.69	92.2a	.58	93.5a	27.5a
.28	9.81	4.26	54.4	1.89	78.8a	1.70	83.1a	32.2a
Control	10.16	9.51	7.3b	7.28	26.3b	5.64	42.3	56.4b

[1]Means are for five plots, each with 15 sample trees. Values followed by the same letters do not differ significantly at 5 percent level of probability.
[2]Current year's foliage at beginning of pupation.

number of trees dropped from each of the five replicates in each dosage rate and the corresponding increase in population reduction was computed (*table 3*). Although none of the increases was large—1 to 3 percent—they do indicate that early spraying, when some of the buds were closed, probably affected overall budworm mortality.

Results of this field test with dosage rates of 1.12 and 0.56 kg per hectare were in the same range as those of previous tests and operational programs (*table 4*), particularly after correction for the effect of bud development. The 0.28 kg per hectare rate, even after correcting for bud development, was almost 10 percent less than that obtained with the higher dosages. Under the conditions of our test, 0.56 kg a.i. per hectare compared favorably with 1.12 kg a.i. per hectare in reducing larval populations of western spruce budworm and preventing destruction of new foliage.

REFERENCES

Carolin, V. M.; Coulter, W. K. **Sampling populations of spruce budworm and predicting defoliation of Douglas-fir in eastern Oregon.** Res. Paper PNW-149. Portland, OR: Pacific Northwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1972. 6 p.

Flavell, Thomas H.; Tunnock, Scott; Barry, John W.; Ekblad, Robert B.; Ciesla, William M. **Western spruce budworm, a pilot control project with carbaryl and trichlorfon, 1975.** Rep. 78-5. Missoula, MT: Northern Region, Forest Service, U.S Department of Agriculture; 1978. 23 p.

Livingston, R. L.; Schwandt, John W.; Preston, John; Ciesla, William; Davidek, Bill; Beckman, David; Spickelmire, Lowen; Johnson, Rex. **1979 western spruce budworm control project, Cascade, Idaho.** Rep. 82-4. Coeur d'Alene, ID: Idaho Dep. Lands, Insect and Dis. Sect., 1982. 64 p.

Markin, George P.; Brewer, J. Wayne; and Batzer, Harold O. **Field life of Orthene, Sevin-4-oil and Dylox bioassay with Douglas-fir tussock moth larvae.** Res. Note PNW-313. Portland, OR. Pacific Northwest Forest and Range Experiment Station, U.S. Department of Agriculture; 1978. 5 p.

Martineau, R.; Benoit, P. **A sampling technique for estimating numerical trends in larvae populations of insect defoliators on conifers. II. Modification and operational use of the technique for extensive sampling of spruce budworm populations in Quebec.** Phytoprotection 54:23-31; 1973.

Millers, Imants. **Evaluation of 1 pound and 1/2 pound Sevin-4-oil applications for spruce budworm control in Minnesota, 1975.** Forest Insect and Dis. Manage./Eval. Rep. S-23-76. Upper Darby, PA. Northeastern Area State and Private Forestry, Forest Service, U.S. Department of Agriculture; 1976. 12 p.

Mounts, J.; Gregg, T. F. **1977 western spruce budworm control project in northcentral Washington State.** Portland, OR. Pacific Northwest Region, Forest Service, U.S. Department of Agriculture; 1978. 33 p.

Parker, Douglas L.; Acciavatti, Robert E.; Lessard, Eugene D. **Western spruce budworm suppression and evaluation project using carbaryl, 1977.** Prog. Rep. 1, 78-11. Albuquerque, NM: Southwestern Region, Forest Service, U.S. Department of Agriculture; 1978. 136 p.

Shea, Patrick J. **Environmental safety.** In: Brooks, Martha H.; Stark, Robert W.; Campbell, Robert W., eds. The Douglas-fir tussock moth: a synthesis. Tech. Bull. 1585. Washington, DC: U.S. Department of Agriculture; 1978:122-129.

Yates, Wesley E.; Akesson, Norman B. **Fluorescent tracers for quantitative microresidue analysis.** Trans. Soc. Eng. 6:104-7; 1963.

Table 3—*Effect of bud development at time of carbaryl spraying on reduction of western spruce budworm larvae population 15 days after spraying*

Dosage (kg a.i./ha)	Reduction uncorrected for bud development	Buds open at spraying	Trees dropped from 75 observed	Reduction corrected for bud development	Change in larval population reduction due to correction
	Percent	*Percent*		*Percent*	*Percent*
1.12	92.4	91.7	7	93.9	1.1
.56	93.4	85.6	12	95.5	2.1
.28	83.1	75.2	16	85.3	2.2
Control	42.3	79.4	15	45.1	2.8

Table 4—*Reduction in western spruce budworm population achieved by application of carbaryl, western United States, 1976-1979*

Year, type of test	Location	Hectares sprayed	Average reduction[1]: Treated plots	Average reduction[1]: Control	Source
			Percent	*Percent*	
Preregistration test:[2]					
1975	Montana	1,412	84.4	14.7	Flavell and others (1978)
1976	Washington	3,103	96.2	—	Mounts and Gregg (1978)
Registered use:[2]					
1977	Washington	144,455	91.7	59.0	Mounts and Gregg (1978)
1977	New Mexico	15,168	93.1	44.5	Parker and others (1978)
1979	Idaho	40,000	97.0	55.5	Livingston and others (1982)
Reduced dosage test:					
1979[2]	Montana	100	92.8	45.0	
1979[3]	Montana	100	93.5	45.0	

[1]Uncorrected for natural mortality. [2]Dosage 1.12 kg/ha. [3]Dosage 0.56 kg/ha.

Markin, George P.; Johnson, David R. **Carbaryl applied at reduced dosage rates for control of western spruce budworm.** Res. Paper PSW-170. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983. 3 p.

Carbaryl is registered for control of the western spruce budworm (*Choristoneura occidentalis* Freeman), at the dosage rate of 1.12 kg per hectare. That rate and two lower ones were field tested in western Montana in July 1979 to determine if a lower rate would be as effective as the registered dosage. Each dosage was applied to five randomly selected 20-ha plots by helicopter with Beecomist nozzles while larvae were in the fifth and early sixth instars. Reduced dosages of 0.28 and 0.56 kg a.i. per hectare resulted in 83 and 93 percent population reduction, respectively, compared with 93 percent population reduction for the registered dosage of 1.12 kg a.i. per hectare.
Retrieval terms: western spruce budworm, *Choristoneura occidentalis*, spray test, carbaryl, Sevin-4-oil, Montana

United States
Department of
Agriculture

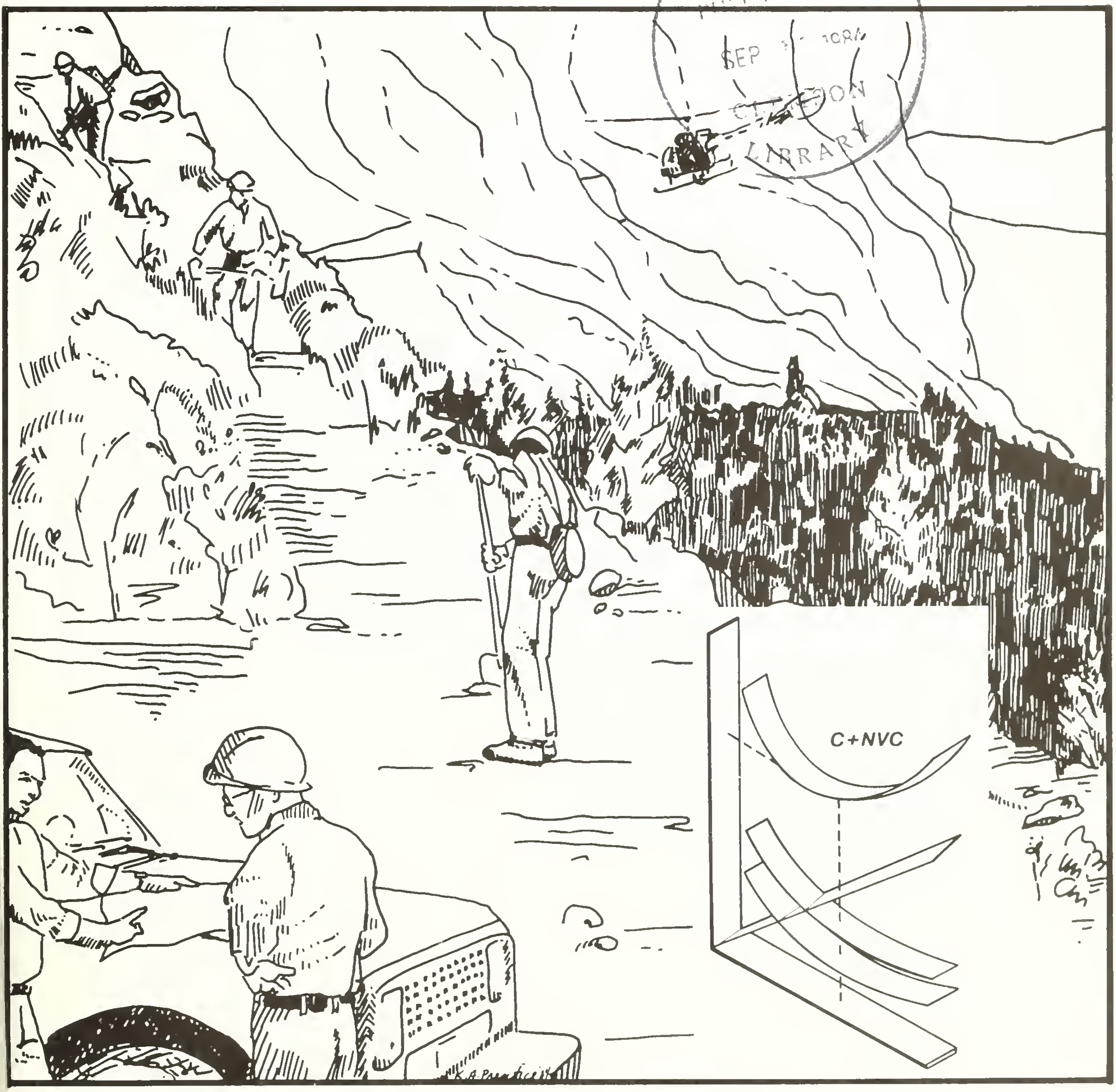
Forest Service

**Pacific Southwest
Forest and Range
Experiment Station**

Research Paper
PSW-171

Costs of Fire Suppression Forces Based On Cost-Aggregation Approach

Armando González-Cabán Charles W. McKetta Thomas J. Mills



Authors:

ARMANDO GONZÁLEZ-CABÁN is an economist with the Station's fire management planning and economics research unit, with headquarters at the Forest Fire Laboratory, Riverside, Calif. He holds two degrees from the University of Puerto Rico: bachelor of business administration (1969), and master of planning (1971). He joined the Forest Service and the Station's staff in 1980. **CHARLES W. MCKETTA** is an economist with the College of Forestry, Wildlife, and Range Sciences, University of Idaho, Moscow. He earned bachelor's (1966) and master's (1969) degrees in forestry at the University of Michigan. **THOMAS J. MILLS,** at the time this paper was prepared, was forest economist in charge of the Station's fire management planning and economics research unit. He is now group leader, Renewable Resources Economics, on the Forest Service's Forest Resources Economics Research Staff, Washington, D.C. He is a graduate of Michigan State University (bachelor of science, forestry, 1968; and master of science, 1969, and doctorate, 1972, in forest economics). He joined the Forest Service in 1972.

González-Cabán, Armando; McKetta, Charles W.; Mills, Thomas J. **Costs of fire suppression forces based on cost-aggregation approach.** Res. Paper PSW-171. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1984. 16 p.

A cost-aggregation approach has been developed for determining the cost of Fire Management Inputs (FMIs)—the direct fireline production units (personnel and equipment) used in initial attack and large-fire suppression activities. All components contributing to an FMI are identified, computed, and summed to estimate hourly costs. This approach can be applied to any FMI by any organization with fire protection responsibility. Significant cost differences were found not only among the three State fire organizations studied, but among the three administrative regions within the Forest Service. Hourly suppression cost estimates ranged from $40 per hour for a small engine and 2-person crew in the Southwestern Region to $595 per hour for a 20-person Category II crew in the Pacific Northwest Region. The overhead, basic training, facilities, and equipment cost components were responsible for most of the cost variations.

Retrieval Terms: fire management costs, economic costs, fire economics, suppression costs, Fire Economics Evaluation System (FEES)

Publisher

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

July 1984

Costs of Fire Suppression Forces Based On Cost-Aggregation Approach

Armando González-Cabán Charles W. McKetta Thomas J. Mills

CONTENTS

IN BRIEF

González-Cabán, Armando; McKetta, Charles W.; Mills, Thomas J. **Costs of fire suppression forces based on cost-aggregation approach.** Res. Paper PSW-171. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1984. 16 p.

Retrieval Terms: fire management costs, economic costs, fire economics, suppression costs, Fire Economics Evaluation System (FEES)

Current cost estimates available for long-term planning of fire management do not provide accurate information nor are they in a form suitable for use in the Forest Service's Fire Economics Evaluation System (FEES) now under development. The FEES simulation model is being designed to analyze the economic efficiency necessary to meet the requirements of the new fire management policy adopted in 1981. That policy includes an economic efficiency criterion for evaluating fire suppression activities. In response to this directive a procedure was developed to estimate the economic cost of Fire Management Inputs (FMIs)—the direct fireline production units used in initial attack and large-fire suppression. The procedure was evaluated in three Regions of the Forest Service, U.S. Department of Agriculture, and three State forestry agencies. The three Regions were: Northern (Region 1) (Montana and northern Idaho), Southwestern (Region 3) (Arizona and New Mexico), and Pacific Northwest (Region 6) (Oregon and Washington). The three State agencies were the California Department of Forestry (CDF), Oregon Department of Forestry (ODF), and Montana Division of Forestry (MDF). The procedure uses a cost-aggregation approach in which all the components contributing to the cost of an FMI are identified, computed, and summed to estimate the FMI total economic cost on an hourly basis. This approach can be applied to any FMI by any organization with fire protection responsibility.

Nine cost components were identified for each of the FMIs: implements and durable supplies, FMI team members' pay, on-fire supervision, subsistence, training, special training for specialized FMIs, overhead, equipment, and facilities. Each of these components was estimated for 12 standardized FMIs identified in the study ranging from Category I handcrews through smokejumpers to engines and bulldozers and their attached personnel.

Attempts to standardize the cost component categories and FMI type and structure to represent a typical fire organization were not totally successful because real differences among organizations led to slightly different FMI compositions. California and Montana fire organizations, for example, staffed their helitack teams with four persons, rather than three, as did the Forest Service's Pacific Northwest and Southwestern Regions, and Oregon, or two, as did the Northern Region. Differences among organizations also existed in their tour-of-duty hours and the length of time used in their depreciation method. All organizations studied used a straight-line depreciation method.

The cost estimates varied significantly for each FMI among organizations. Forest Service Pacific Northwest Region costs were consistently higher than those of the Northern and Southwestern Regions. At the State level no organization showed cost estimates consistently higher than any other.

Within organizations, Forest Service FMI cost estimates ranged from $595 per hour for a 20-person Category II handcrew in the Pacific Northwest Region to as little as $40 per hour for a small-engine 2-person FMI in the Southwestern Region. State FMI cost estimates showed the same kind of variation. The pay and overhead cost components' (the general continuing costs involved in running a business) contribution to total hourly cost was consistently the most significant in all FMIs. Their combined total was always more than 50 percent, and usually more than 70 percent of total FMI cost.

The primary source of the FMI cost differences among Forest Service Regions and State agencies resulted from the overhead cost component even more than from pay differences. Facilities, basic training, and equipment cost components are also responsible for part of the cost differences among Forest Service Regions and State organizations. Other significant factors contributing to the FMI cost differences were variations in FMI composition and staffing, and variations in the length of time used in their depreciation method.

Differences in the economic cost of the FMI among the various categories of deployment status, that is, availability, travel to fire, suppression on small fires, and suppression on large fires were significant. Transportation and equipment costs added considerably to the total hourly cost of the FMI teams during travel status. The hazard-pay adjustment, subsistence, and on-fire supervision costs charged when an FMI was on a fire contributed considerably to the cost differences by deployment status.

The unit cost estimates from this procedure are higher than figures sometimes used for long-term planning purposes but must be compared cautiously. Various studies have differing objectives and were done for different base years. The estimates may differ further in how the fixed costs (costs that do not necessarily increase or decrease as the total volume of production increases or decreases) are allocated among FMIs, by FMI configuration, and by differences in what costs were included in the various cost estimation procedures.

The differences in the FMI economic cost estimates among Forest Service Regions and State fire organizations, and the differences in deployment status have implications for long-term planning and current management decisions. First, previous uses of nationwide cost averages across broad geographical areas and the various fire activity deployment status mask important and real economic cost differences. Second, suppression cost per acre burned will increase substantially as size of the suppression organization increases for a given burned area. Third, during planning of dispatching procedures extra attention should be given to increments in cost beyond the availability status; the extra cost to use an FMI is substantial, even after it has been paid to have it available.

Since 1975, the Forest Service, U.S. Department of Agriculture, and other agencies with fire protection responsibilities have increased their emphasis on analyzing the economic efficiency of fire management programs. Ever-growing budgets without discernible benefits prompted the U.S. Office of Management and Budget (OMB) (Gale 1977), and the U.S. Senate Appropriations Committee to ask the Forest Service to evaluate the costs and benefits of fire management practices (U.S. Senate 1978). State agencies have been faced with similar requests from State legislatures.

In response to the questions raised, the Forest Service made several major changes in its fire management policy. By 1978, fire management policy was revised to require that fire management programs be cost-effective and compatible with land management objectives. In 1981, that policy was amended further to include an economic efficiency criterion for evaluating fire suppression activities: ". . . suppression actions which result in the lowest cost plus net value change, having a reasonable probability of success, and providing for personal stafety should be selected" (U.S. Dep. Agric., Forest Service 1981). The evaluation of this type of analysis is described by Gorte and Gorte (1979) and its use is becoming more common (Bellinger and others 1983). To implement this type of policy change, fire managers need cost estimates for the economic analysis required in long-term planning.

Fire economic studies have addressed fire damage appraisal but few authors have emphasized specific costs for fire management optimization. Sparhawk (1925) called for record-keeping that kept these costs itemized and distinct, but looked only at direct costs of primary protection and suppression. Gale (1977) suggested modification of the USDA Forest Service 5100-29 fire report form to record costs as suppression activity accounts. He recognized five fire management activities and associated costs: fire prevention, fuel modification, fire detection, presuppression activities, and fire suppression. The first four categories reflect Sparhawk's primary protection category. Marty and Barney (1981) designed such a tabular format for expenditure reporting.

Current cost estimates available for long-term planning purposes do not provide accurate economic cost estimates, nor are they constructed in a form suitable for use in the Fire Economics Evaluation System (FEES) (Mills and Bratten 1982). The FEES simulation model is being designed to perform the economic efficiency analysis necessary to meet the requirements established in the new fire management policy.

We developed a cost estimation technique to provide updated and compatible fire management costs for the economic efficiency analysis required in long-term planning. Our cost technique concentrates on only two of the five fire management activities recognized by Gale: initial attack (presuppression) and suppression. Prevention, fuel modification, and detection costs were studied separately. The procedure identifies and aggregates, on an hourly basis, all the component costs of fire management inputs (FMIs), which are direct fireline production units used in initial attack or suppression.

This computational method includes items such as opportunity cost of capital and distribution of overhead and facilities costs to the production units, which are not included in standard budget procedures used at the Federal and State levels, but are necessary considerations for long-term planning and optimization. It does not provide managers, therefore, with data directly usable in their budgetary process. These items are also not included in the current National Fire Management Analysis System used for long-term planning purposes by the Forest Service (U.S. Dep. Agric., Forest Service 1982).

Although developed principally for long-term planning use in the FEES simulation model, the cost components aggregation approach provides sufficient flexibility to be used in other contexts. Cost components not relevant for current operating budget determination such as facilities and overhead costs, for example, can be eliminated from the computation. The numbers resulting can be used in budget development, trespass fire cost estimates, and mutual assistance protection programs' cost determination. An example of how hourly cost estimates can be used in long-term fire management analysis is discussed by González-Cabán (1983).

We included general system costs such as general administration and overhead identified by Davis (1974), but ignored indirect costs of fire pointed out by Zivnuska (1968) and Sutherland (1973) such as watershed damage and forest closure. They are not active costs of FMI activity and are considered part of the net value changes during optimization analysis.

The cost estimation procedure has four basic objectives: (1) to identify appropriate budgetary costs that contribute to the funding or support of specific FMIs and establish a pattern for allocation of aggregated costs; (2) to estimate and incorporate otherwise unaccounted costs that are legitimate economic costs of using the FMIs; (3) to convert fixed costs of an FMI into variable cost rates to facilitate increment evaluation of fire management organizations for long-term planning purposes; and (4) to display the variable costs in distinct categories on a per hour basis to reflect how or when the FMIs are used; for example, the planned availability of FMIs throughout a fire season, or their use on fire during either normal or overtime hours. Availability costs are incurred regardless of whether the FMIs are used during their availability period, except as adjusted for nonfire uses of personnel during availability status.

This paper describes the approach to determining hourly costs for fireline production units—termed Fire Management Inputs (FMIs)—used in initial attack or suppression actions. Application of this approach in collecting and analyzing cost data from fire protection agencies in three Forest Service Regions and in three States is reported.

METHODS

Cost Allocation Procedures

Cost allocation is a problem. Marty and Barney's (1981) cost list indicates a problem in allocation of shared resources, expenditures serving multiple agencies. Martin (1968) also found this problem between the private and public sector in Louisiana while evaluating fire taxes. He suggested that the number of fire origins and the benefits from timber should be the basis for cost sharing rather than the western acreage allocation formulas. Shared costs in FMIs are a minor problem as component costs are assigned to a typical unit regardless of the budgetary function or funding source.

The cost allocation problem addressed by Streeby (1973) was one of allocation between fire management functions. Sackett and others (1967) faced a similar cost allocation in assigning expenditures to particular fires. Expenditures for prevention, capital outlay, training, and detection, were allocated arbitrarily in proportion to acreages protected. Standby and maintenance expenditures were allocated in proportion to number of fires. Sensitivity analysis revealed that the method of allocation was not critical.

Our method for allocating fixed costs is also arbitrary but we found that it may have crucial effects on cost magnitudes. The methods used here link an FMI to its expected use of the items that make up the fixed cost. These costs are constant on a year-by-year basis, but are variable from year-to-year. In a long-term planning context, therefore, fixed costs are more appropriately referred to as long-term variable costs. The overhead cost, for example, is assumed to be a function of fire organization size so it is allocated in proportion to the number of personnel supported by overhead. This means that the FMI overhead charge varies by team personnel size rather than by being equally distributed between FMIs.

Seasonal or annual expenditures and fixed costs that serve large numbers of fire personnel are allocated to the FMIs in proportion to the total number of available person-hours in a season rather than hours they may actually be deployed on fire. The rationale for this allocation is that the actual use of an FMI during subsequent fire seasons is not known at the time the cost is incurred. The organizational necessity of maintaining a certain number of FMIs is determined on the basis of sufficient availability to encompass probable use. Costs allocated on the basis of actual use ignore the insurance function of standing fire organizations. Seasonal, annual, and multiyear costs are allocated to a per hour basis to reflect FMI availability costs.

When supplies, durable goods (such as equipment and facilities), overhead, or other fixed annual expenditures are associated only with the fire initial attack or suppression organization, the cost estimation technique presumes that they serve a function that occurs only during the active fire season. The resultant fixed cost is allocated to an hourly rate on the basis of fire season length. The fire season is defined by the length of time that a fire organization is at 80 percent or more of its peak presuppression strength. If the durable goods are used by nonfire functions at other times of the year, the portion of the total cost allocated to the fire program is a function of its proportional use.

Some fixed costs for the fire organization are spread over the employees served by those expenditures. A central fire cache, for example, is assumed to service all fire personnel equally. The cache costs are allocated over the annual average number of person-years worked directly in fire management, including all regular and temporary personnel in the costed unit. If the number of person-years is not known, it can be approximated from the wages expended and the average hourly wage rate.

When number of person-years is used as the basis for allocation, it is implicitly assumed that costs expand linearly for these components. As the fire force grows, its otherwise fixed overhead would have to grow in direct proportion. This is a simplistic assumption, but only slight evidence supports the hypothesis for economies-of-scale in the overhead function in those areas tested.

Another basic design criterion of the cost procedure is that all costs be allocated to the FMIs on a per hour cost basis to facilitate the economic efficiency evaluation. This is straightforward for hourly costs, such as pay, and for daily costs, such as subsistence costs, once an average day length is assigned. Costs that are incurred once during a season, such as training costs, are allocated on the basis of the number of hours in the fire season.

Allocation of durable items that last several fire seasons, such as equipment or facilities, requires additional data. The annual amortized cost is computed after considering initial cost, salvage cost, useful life, and discount rate. Cost annualization assumes uniform year-to-year use of the durable cost components. The annual equivalent cost is then allocated to an hourly basis, just as season costs are.

Designing Fire Management Inputs

We used a cost-aggregation approach to construct unit cost estimates from basic agency records. This approach required the identification of individual cost components of each FMI, such as supplies, pay, and training. The total fire season cost of each component was estimated and the costs summed to yield a total cost for the FMI. The season total cost was then divided by the number of hours in the season to yield a corresponding hourly cost. The costs of all components necessary to place the FMI on the fireline were included in the calculation.

The first FMI cost estimates were hand-computed to test the procedure in selected fire management organizations. The cost procedure converted an extensive and diverse economic database into cost estimates. FMI composition varied within and among fire management organizations. The variability in cost components and FMI composition made the cost-aggregation approach tedious and expensive in repetitive use when redesigned specifically for each agency. In addition, the lack of a systematic approach resulted in double-counting of some cost components while ignoring others.

The problem was solved by standardizing FMI cost component categories and the data collection procedures so that the same procedures could be applied to any fire organization. The questionnaire[1] used to collect all data included sample data for the Forest Service's Northern Region. The type and structure

[1]A copy of the questionnaire is available upon request to Armando González-Cabán, Pacific Southwest Forest and Range Experiment Station, 4955 Canyon Crest Drive, Riverside, Calif., 92507.

of the FMI team units were standardized to represent a typical fire organization for FEES simulations, but the cost collection method and computerized procedure allow FMI team unit redefinition to accommodate the specific needs of different agencies. The uniformity introduced by the standardization of cost components and procedures permits the use of computer software that streamlines the conversion of a bulky database into large numbers of FMI cost estimates at low cost.

Twelve standardized FMIs were designed for this cost study and were selected on the basis of similarity of costs and fireline production rates (Haven and others 1982):

Unit	Type
1	Category I crew
2	Category II crew
3	Category III crew
4	Project crew
5	Helitack
6	Smokejumper
7	Engine—small
8	Engine—medium
9	Engine—large
10	Bulldozer—small
11	Bulldozer—medium
12	Bulldozer—large

Six of the 12 FMIs were handcrew types, including helitack and smokejumper teams that perform handcrew duties on the fire, but whose form of transportation required specialized training costs as well as specialized transportation costs. Another three FMIs were water delivery systems and personnel combinations. The last three FMIs were personnel and bulldozer combinations. Standard FMI types included regular firefighting forces, hire-as-needed administratively determined (AD) crews, and nonfire agency personnel (*table 1*).

Category I handcrews are fully funded out of fire program dollars for the entire fire season. There are two kinds of Category II handcrews; one is composed of agency regular personnel, such as timber sale administration personnel, who occasionally are organized into a 20-person crew for fire suppression. Another is composed of temporary personnel hired as needed. For clarity purposes, we will refer to the agency regular personnel as Category II crew and the hire-as-needed personnel Category III crew. The two-person project crew is composed of personnel hired to perform nonfire work, but who occasionally assist in initial attack. A timber stand improvement crew is an example. All the engines, FMIs 7 to 9, are water delivery and personnel combinations and are treated as fully fire program funded. All bulldozer combinations, FMIs 10 to 12, have personnel treated as fully fire-program funded.

We computed hourly costs separately for each of these five fire duty statuses:

1. Crew available for assignment
2. Crew on regular time on a small fire (less than 10 acres [4.047 ha])
3. Crew on overtime on a small fire
4. Crew on regular time on a large fire
5. Crew on overtime on a large fire.

During availability, the FMIs are paid at their regular pay rate. When sent to small fires during their tour-of-duty, the FMIs receive a hazard-pay premium, above and beyond their regular pay until the date the fire is controlled, but receive no subsistence or on-fire supervision. That is, no management team is sent to supervise or direct the fire suppression operations. When on small fires during overtime hours, the FMIs draw not only a hazard-pay premium but an overtime premium as well. They may occasionally receive subsistence, but for our purposes, during small-fire activities, they will not receive subsistence.

While on large fires during regular tour-of-duty, the FMI s receive a hazard-pay premium, until the date the fire is controlled, and also extra on-fire supervision and subsistence. During overtime on large fires, they receive a hazard-pay premium, an overtime premium, and extra on-fire supervision and subsistence. Fire duty status causes significant differences between each of the hourly cost categories (*tables 2-4*).

To simplify the analysis and application of the hourly cost estimates, we derived a weighted hourly cost for small-fire suppression and a weighted hourly cost for large-fire suppression. An average percent use of the FMIs on overtime as against regular time during five fire seasons was estimated. The average percent was used to weight the corresponding regular time and overtime rates together. With the same approach, we computed a weighted travel cost for all FMIs.

Table 1—*Composition of 12 standardized units of Fire Management Inputs*

Unit	Type	Composition		Firefighters
		Persons	Equipment	
1	Category I crew	20	Handtools	Regular
2	Category II crew	20	Handtools	Nonfire funded, FS regular
3	Category III crew	20	Handtools	Hired as needed
4*	Project crew	2	Handtools	Nonfire funded, FS regular
5	Helitack	2	Handtools	Regular
6	Smokejumper	2	Handtools	Regular
7	Engine—small	2	Handtools, 250-gal tank	Regular
8	Engine—medium	3	Handtools, 500-gal tank	Regular
9	Engine—large	3	Handtools, 1000-gal tank	Regular
10	Bulldozer—small	2	Light bulldozer	Regular
11	Bulldozer—medium	2	Medium bulldozer	Regular
12	Bulldozer—large	2	Heavy bulldozer	Regular

During the fire season, when there are no on-going fires or the fire danger rating is low, the fire-funded FMIs are generally used to do nonfire work. Nonfire suppression work is any work not directly related to suppression of wildfires or escape prescribed burns—maintenance or building trails, prescribed fire burns, maintenance of campground or campground buildings, or other. Time spent cleaning barracks while waiting to go on a fire is considered fire time. Only the time devoted to actual fire standby or fire activities should be charged as an economic cost to the fire function, regardless of budgetary source. The cost of the average percent time devoted to nonfire suppression activities, therefore, is subtracted from the pay component of the total hourly availability cost. If 10 percent of a Category I crew fire season total time is devoted to prescribed burning or any other nonfire suppression related activity, such as campground maintenance or building of trails, for example, only 90 percent of the pay component is charged as part of the availability cost.

The fire management program in most agencies is built to accommodate the use of nonfire-funded personnel. An economic availability cost is charged for FMI personnel who are not nonfire-funded but who occasionally do fire work during the fire season. The facilities and program management overhead, for example, are used by the additional personnel. The cost for these FMIs is computed in proportion to the average use of the nonfire-funded FMIs during the fire season. If a two-person timber improvement project crew typically spends 10 percent of its time on fire duty during the fire season,

Table 2—*Hourly cost (excluding that of transport delivery and retrieval) of Fire Management Inputs available for assignment, by Forest Service Regions and State forestry agencies, Fiscal Year 1981*

Fire Management Input	Forest Service regions			State forestry agencies		
	Northern	Southwestern	Pacific Northwest	California	Oregon	Montana
			Dollars/hour			
Category I	296	251	351	[1]26	[2]26	—
Category II	35	—	65	[3]35	[4]17	—
Category III	24	[2] 62	—	[5] 7	27	43
Project crew	4	4	7	—	—	—
Helitack	[6] 73	78	94	[7]88	97	[7]83
Smokejumper	39	37	48	—	—	—
Engine—small	30	26	38	[8]41	48	47
Engine—medium	45	41	61	[7]51	73	70
Engine—large	32	[9] 18	[10] 96	[8]41	84	52
Bulldozer—small	49	35	[8] 70	31	53	70
Bulldozer—medium	57	87	[8] 74	31	72	90
Bulldozer—large	—	—	—	—	86	—

[1]Crew of 16 persons, nonfire funded.
[2]Crew of 19 persons, nonfire funded.
[3]Crew of 16 persons, nonfire funded.
[4]Crew of 21 persons, nonfire funded.
[5]Crew of 17 persons, nonfire funded.
[6]Crew of 2 persons.
[7]Crew of 4 persons.
[8]Crew of 3 persons.
[9]Crew of 1 person.
[10]Crew of 5 persons.

Table 3—*Hourly suppression cost (excluding that of transport delivery and retrieval) of Fire Management Inputs on small fires, by Forest Service regions and State forestry agencies, Fiscal Year 1981*

Fire Management Input	Forest Service regions			State forestry agencies		
	Northern	Southwestern	Pacific Northwest	California	Oregon	Montana
			Dollars/hour			
Category I	360	315	418	[1]137	[2]256	—
Category II	411	—	503	[3]178	[4]163	—
Category III	271	[2]220	—	[5]156	266	410
Project crew	42	36	56	—	—	—
Helitack	[6] 82	87	83	[7] 89	100	[7] 87
Smokejumper	47	45	56	—	—	—
Engine—small	39	34	47	[8] 49	50	60
Engine—medium	60	56	93	[7] 61	76	86
Engine—large	45	[9] 25	[10]133	[8] 51	85	77
Bulldozer—small	62	47	[8]100	45	66	70
Bulldozer—medium	78	104	[8]103	52	94	90
Bulldozer—large	—	—	—	—	—	—

[1]Crew of 16 persons, nonfire funded.
[2]Crew of 19 persons, nonfire funded.
[3]Crew of 16 persons, nonfire funded.
[4]Crew of 21 persons, nonfire funded.
[5]Crew of 17 persons, nonfire funded.
[6]Crew of 2 persons.
[7]Crew of 4 persons.
[8]Crew of 3 persons.
[9]Crew of 1 person.
[10]Crew of 5 persons.

for example, 10 percent of its hourly pay is tallied as an availability charge to the fire function. The percent of time that fire-funded FMIs devote to nonfirefighting activities, and percent of time that nonfire-funded FMIs devote to firefighting activities, is estimated by the fire planner or another qualified person using a 5- to 10-year average for all the organizations surveyed. The percentage charged is different for each organization.

Identifying Cost Components

The costs for each FMI are grouped into nine standard components during data collection. We designed these so as to be able to group costs that came from similar sources and were allocated and aggregated in the same way. The components and their subclasses also serve as a checklist to eliminate double-counting and the overlooking of cost components.

The nine cost components are:

1. Implements and durable supplies
2. FMI team members' pay
3. On-fire supervision
4. Subsistence
5. Training
6. Special training for specialized FMIs
7. Overhead
8. Equipment
9. Facilities

The objective is to allocate all component costs required to place an FMI on a fire, and then to sum them into a single hourly cost rate. The FMI cost rate can be compared directly with the fireline production rate of an FMI in the analysis of the economic efficiency of alternative fire management programs. To accomplish this, the cost for facilities, overhead, and on-fire supervision are allocated to specific FMIs. These costs are not direct operating costs of the FMI team unit, but are costs that must be incurred to place an FMI on the fireline.

Identifying all cost components provides flexibility to the economic cost procedure discussed here. Although long-term planning is the primary use of the procedure, for example, some cost components not relevant for current operating budgets, such as facilities or overhead, can be eliminated from the computation. These results can be used for purposes such as budgeting, trespass fire-cost estimates, and mutual assistance protection program cost determination.

Implements and Durable Supplies

The implements and durable supplies assigned to an FMI can be categorized into items carried by each individual, such as fire-resistant clothing and a hard hat, and those assigned to the team as a whole, such as a chain saw. Most of these items have a multiyear service life. The purchase cost and service life of each item is applied to a straight-line amortization calculation to yield an annual cost. Salvage value is assumed to be zero. It is tempting to devote a great deal of time to estimating these costs because they are a visible budget item for which there is close accountability. They make a very small contribution to total hourly costs, however.

FMI Team Members' Pay

This component includes the base hourly salary paid to the FMI's team members. All fire management input teams have a personnel and equipment structure. Although this team structure is fixed for the FEES model, it may be specified by the user by size and wage grades. The pay component can be computed from either of two different pay scales: employees who are regular members of the fire management organization for most of the fire season; temporary personnel who are hired only for a particular fire.

Table 4—*Hourly suppression cost (excluding that of transport delivery and retrieval) of Fire Management Inputs on large fires, by Forest Service regions and State forestry agencies, Fiscal Year 1981*

Fire Management Input	Forest Service regions			State forestry agencies		
	Northern	Southwestern	Pacific Northwest	California	Oregon	Montana
			Dollars/hour			
Category I	442	396	505	[1]188	[2]334	—
Category II	486	—	595	[3]229	[4]250	—
Category III	372	[2]317	—	[5]210	326	473
Project crew	48	39	66	—	—	—
Helitack	[6] 93	102	119	[7]100	100	[7,8]89
Smokejumper	62	60	70	—	—	—
Engine—small	46	40	53	[9] 63	62	61
Engine—medium	93	76	126	[7] 79	91	92
Engine—large	72	[10] 36	[11]176	[9] 66	97	81
Bulldozer—small	85	63	[9]142	65	75	91
Bulldozer—medium	101	119	[9]150	71	102	94
Bulldozer—large	—	—	—	—	126	—

[1]Crew of 16 persons, nonfire funded.
[2]Crew of 19 persons, nonfire funded.
[3]Crew of 16 persons, nonfire funded.
[4]Crew of 21 persons, nonfire funded.
[5]Crew of 17 persons, nonfire funded.
[6]Crew of 2 persons.
[7]Crew of 4 persons.
[8]Does not include equipment cost.
[9]Crew of 3 persons.
[10]Crew of 1 person.
[11]Crew of 17 persons.

In computing the total direct labor costs of an FMI, two types of adjustments are applied to the base hourly salary. The first type of adjustment is for benefits. These benefits are prorated over all the expected work hours in a fire season to reflect the average adjustment as a percentage of the base hourly salary. Annual and sick leave accrual in Federal agencies, for example, are equivalent to a 10 percent increase in the hourly wage paid. This percentage is applied to the appropriate base hourly salary to estimate the entire economic cost of personnel on duty.

The other type of pay adjustment is for special duties, such as overtime or a hazard-duty differential paid when personnel are actually engaged in firefighting or other special missions. This adjustment is applied to the base hourly salary during all hours worked on a calendar day when the special duties are performed.

Supervisory Factor for FMIs

Each FMI is usually linked to its own first-level supervision when assigned to a fire. These division and sector bosses are included in FMI cost estimations as direct costs required to place the FMI on the fireline. A Category II AD crew, for example, may have a full-time liaison officer, 33 percent of a sector boss, and 11 percent of a division boss assigned to it, depending on fire size. If it is common in an agency for FMIs to work independently, without first-level supervision, this category may be ignored—except that the team foreman or crew boss is automatically counted as an integral member of an FMI.

Supervisory personnel are only included in FMI hourly cost estimates when the FMI is engaged in active fire duty. When available, supervisors usually function as fire program staff officers so they are charged as part of the program management overhead. The cost of overhead teams, supervisory and support personnel required for large-fire suppression efforts, are above and beyond this supervision component. Those costs are estimated in a separate large-fire overhead team cost computation.

Daily Subsistence and Per Diem Surplus

Similar to the supervision cost, the cost of food and other consumable supplies is included only when the FMI is enroute to or on a large fire. FMIs are considered self-sufficient when on availability or fighting small fires. The cost of daily consumable items, such as short-lived personal gear supplied by the organization (paper sleeping bags, soap, prorated radio batteries, and other), are most readily estimated on a cost per person per day basis. The cost estimation technique assumes that this cost is allocated on the basis of a standard 8-hour day.

When the FMIs are on a fire, only the per diem costs in excess of the amount charged to the firefighter for food, shelter, and other daily consumables are included in the economic cost. Charging the entire per diem paid would double-count some elements.

FMI Annual and Specialty Training

All firefighters require some form of initial and recurrent fire training. Though training costs are actually fixed, they are allocated over the fire season or multiples of fire seasons, as a contribution to hourly cost.

Two types of training are recognized: annual and specialty. An annual training course in basic firefighting skills and fire behavior is given each FMI. Because training is a prerequisite for the use of any firefighter, the salary during personnnel training is a legitimate cost of that training in addition to associated costs of travel, instructor salary, and training aids. Training expenditures are computed on a per training class basis and then allocated per person back to the FMI.

Some FMIs require additional specialty training. For example, helitack teams' training in helicopter use and rappelling is assumed to be taken by all helitack team members annually. Smokejumper training is another form of specialized training. Initial parachute training is required for all new recruits. The cost of both the initial training and refresher training sessions are amortized over the average service life of a smokejumper and then converted to an hourly rate.

Administrative Overhead

Two types of aggregated overhead costs are identified in the FMI cost estimation procedure: administrative and fire management. Administrative costs are charged for services, such as fiscal and personnel management. Such expenditures are usually budgeted to fire by a proration formula unique to the agency. The indirect overhead costs of general administration are usually a line item in organizational budgets and are used directly for all levels of the organization. The cost estimation procedure assumes that the general administration formula correctly reflects the proportional support given by various administrative services to the fire program. Just as with previous fixed cost, the cost procedure allocates this administrative overhead cost in equal proportions to each person in the fire management organization.

The other overhead costs are the total annual expenditures of the year-round permanent fire management organization, including fire management directors, fire staff, fire control officers, dispatchers, and clerical staff whose salary and operating funds originate in the fire management program. Expenditures for any FMI are deleted from the program management overhead to avoid double-counting. Time spent by fire control staff as division or sector bosses, for example, was excluded from this program management overhead because it was already included in the supervisory component. Similarly, the total program budget is divided between the several fire program activities—fuel management, prevention, detection, initial attack, and aviation—and the nonfire activities performed by fire staff. Some fire staff have responsibility for nonfire activities such as safety or recreation. Only the percentage assigned to initial attack and aviation are included in the program management overhead for these initial attack suppression FMIs.

The administrative overhead cost component is a relatively large contribution to the total cost of most FMIs but is one of the most difficult to estimate accurately. Formulas for allocation of general administration charges, for example, often vary from agency to agency according to different management philosophies that may not really reflect varying degrees of administrative support to the fire program.

Similarly, the fire program overhead is seldom recorded in the manner that is needed for this economic cost computation procedure. The "program management" line item in most accounting budgets, for example, usually considerably underestimates the program management overhead derived here by adding up the salary and the operating expenses of all fire program personnel who support the FMI teams. This is a primary example of the difference between economic costs used in long-term analyses of fire program planning and those used in budgets, which are designed to ensure accountability.

Capital Equipment

All equipment that is an integral part of the FMI and operated by the team in an initial attack or suppression mode is included in the equipment cost component. In general, fixed operating rates and mileage-use rates are converted to an hourly variable cost. All equipment rates excluded operator cost because the operator wages are calculated in the FMI pay component. When fire engines are used in suppression activities, they are assumed to move at an average speed of 5 miles per hour. This is changed to a dollar per hour rate to account for the mileage charges incurred by such a unit. If the agency surveyed uses a direct dollar per hour rate, then this rate is used directly.

One of two calculation procedures for equipment cost is used, depending on whether the equipment is rented or owned. If the fire equipment is rented or contracted, the rental cost for equipment in transit or in place, rather than in fire use, is converted to hourly terms and charged as an availability cost. The operating rate of equipment actually working in a fire suppression task is charged as a fire suppression cost. The operating rate is usually higher than availability cost because of the variable costs of fuel, higher insurance costs, and above average wear-and-tear in fire-related operations.

If the equipment is owned, an equivalent cost is calculated from fleet equipment operating costs. The annual fixed ownership cost of equipment includes items such as depreciation, differential replacement, administrative and management costs, insurance, and capital costs. It represents the cost of the availability of the equipment. The fixed ownership annual cost is allocated to an hourly charge on the basis of fire season length. The use rate, which is added for use on fire suppression, is the sum of costs that vary on a mileage or hourly basis, such as operating costs, fuel, lubrication, and maintenance (U.S. Dep. Agric., Forest Service 1980). Mileage rates are converted to hourly rates on the basis of average vehicle speed on typical system roads.

Estimates of transportation cost for equipment used in wildfire initial attack and large-fire suppression activities have also been developed. Seven different classes of transportation methods, divided into air and ground transport, and currently recognized are these:

Table 5—*Average hourly cost of transportation equipment used in initial attack and large-fire suppression activities, Fiscal Year 1981*

Equipment	Fixed cost	Variable cost	Total
	Dollars/hour		
Air tanker—fixed wing:			
Small (1128 gal)	60	813	873
Medium (1917 gal)	57	1110	1167
Large (2356 gal)	134	1302	1436
Air tanker—rotary wing:			
Small (110 gal)	66	328	394
Medium (450 gal)	224	811	1035
Large (900 gal)	24	1811	1835
Air transport—fixed wing:			
Small (8 passengers)	23	248	271
Medium (12 passengers)	126	376	502
Large (40 passengers)	118	994	1112
Air tansport—rotary wing:			
Small (3 passengers)	81	304	385
Medium (6 passengers)	289	443	732
Large (20 passengers)	103	1708	1811
Truck, tractor, and trailer:			
Small (30,000 pounds GVW[1])	25	19	44
Medium (60,000 pounds GVW)	30	24	54
Large (90,000 pounds GVW)	35	24	59
Truck, stake-side:			
Small (30,000 pounds GVW)	9	22	31
Medium (60,000 pounds GVW)	9	26	35
Large (90,000 pounds GVW)	10	30	40
Bus, passenger:			
Small (10 passengers)	16	17	33
Medium (20 passengers)	18	18	36
Large (33 passengers)	23	18	41

[1]Gross vehicle weight.

Air transport
1. Tanker—fixed wing
2. Tanker—rotary wing
3. Transport—fixed wing
4. Transport—rotary wing

Ground transport

5. Truck—tractor and trailer
6. Bus—passenger
7. Truck—stake-side

Each class of equipment is further divided into three different sizes—small, medium, and large. Because the resultant cost estimate is designed for general use in FEES simulation, no specific equipment identification is necessary (*table 5*). Users, however, could select either an average of vehicles in their own size categories or a representative vehicle for each.

Permanent Facilities

The annual cost of the numerous permanent facilities that house the FMIs and the fire program management staff are included in the facility cost component. The facility cost component is composed of an annual capital cost charge, a facility operating cost, and a maintenance cost. The maintenance and operating costs are sometimes already included in the general administration overhead charge so care is taken to avoid double-counting. If maintenance and operating costs are not already included there, they can be readily estimated from budget data.

The annual capital cost is equal to the rental rate for rented facilities and approximated by equivalent rental rates for agency-owned facilities. Equivalent rental rates are used for owned facilities because it is recognized that all facilities have an alternative use value even if their original capital cost is sunk. This treatment of facilities is conceptually parallel with the treatment of equipment costs that have multiyear service. The regional offices of the General Service Administration (GSA) are ready sources for the equivalent rental rates once the square footage and character of the facility is provided by the fire program agency.

The total cost of the facilities only partially occupied by fire program personnel or equipment is prorated to the fire program in relation to the area of proportional use. The facility costs of fire program management are allocated across all FMIs in proportion to the number of personnel in the FMIs. Specialized facilities, such as helitack bases, are allocated only to the FMIs who use them.

Collecting Cost Data

To collect cost data, we relied on written questionnaires and personal interviews. We first telephoned the agency fire planner, explained the purpose of the study, and then mailed copies of the questionnaire. The planner contacted the specialists best qualified to provide the needed information.

A week after the initial telephone call, we conducted the personal interview during which the data were collected. The interview enabled us to clarify the data required, and resolve any differences in interpretation of different accounting and budgeting systems, and in the FMI structure. Each interview took about 2 days. Although we pared the database down to as few items as possible, as many as 1000 separate entries were required for some organizations.

Sources sometimes lacked ready access to the required data. Cost studies of operational fire programs appear to have been done infrequently or are unrecorded. Most sources, however, are familiar with accounting and budgeting costs and can provide data with adequate precision.

To handle large amounts of data as efficiently as possible, we computerized the procedure, thereby easing the efforts at data revision (McKetta and others 1981). With the questionnaire and computer software available, the data for an agency can be evaluated in about 1 person-week.

We tested the cost-aggregation approach by collecting data in three Forest Service Regions and three State fire protection agencies (*table 6*). They were selected to cover a range of presuppression programs in which size varied both in total dollars or acres protected, and in intensity of protection, as reflected in the presuppression budget expended per acre protected. The organizations studied were also selected to evaluate the approach at different organizational levels.

The six organizations in which the data were collected were:

Forest Service:

Northern Region (Region 1, made up of Montana and northern Idaho)

Southwestern Region (Region 3, made up of Arizona and New Mexico)

Pacific Northwest Region (Region 6, made up of Oregon and Washington)

State agencies:

California Department of Forestry

Oregon Department of Forestry

Montana Division of Forestry

We attempted to standardize the cost component categories and the FMI type and structure to represent a typical fire organization. This objective was not fully accomplished be-

Table 6—*Forest Service regions and State forestry agencies in which the cost estimation procedure was applied*

Region or agency	Presuppression budget in 1981[1]	Protection area	Presuppression budget per acre
	Million dollars	*Million acres*	*Dollars/acre*
Forest Service:			
Northern Region (Region 1, made up of Montana and northern Idaho)	14.5	28.0	0.52
Southwestern Region (Region 3, made up of Arizona and New Mexico)	23.8	22.0	1.08
Pacific Northwest Region (Region 6, made up of Oregon and Washington)	29.0	27.0	1.07
State agencies:			
California Department of Forestry	90.2	33.0	2.73
Oregon Department of Forestry	13.7	15.7	.87
Montana Division of Forestry	2.4	41.2	.06

[1]Total Forest Service, U.S. Department of Agriculture, presuppression budget in Fiscal Year 1981 was $142,000,000.

cause real differences among organizations led to slightly different FMI compositions. The California Department of Forestry (CDF), for example, uses a 24 hour per day tour-of-duty during their fire season, just as does a city fire department. The other organizations use an 8 hour per day tour-of-duty. This difference biases CDF estimates downward relative to all other estimates. Also, the staffing level of some FMIs varied. California and Montana fire organizations, for example, staffed their helitack teams with four persons, rather than three as did Oregon and the Pacific Northwest and Southwestern Regions, or two as did the Northern Region. The Pacific Northwest Region staffed its large engine with five persons, the Southwestern Region used one, CDF used three, and Montana, Oregon, and the Northern Region used two persons. Although uniformity was introduced by standardizing the cost component categories and procedure application, the cost collection procedure and software allowed these variations to accommodate the specific needs of different organizations. The implication, however, is that the per unit cost results are not strictly comparable.

Overhead cost was one of the most difficult components of the fire management program to estimate. Only the cost of the time that the year-round permanent fire personnel spent in the actual planning and overall supervision of the initial attack and large-fire organization was charged as program overhead. This was an arbitrary rule for the allocation of fixed costs, but we think it best represents the real cost to the initial attack and large-fire suppression functions. The allocation of overhead costs was crucial because it is one of the main differences between fire organizations. Different allocation rules produce different results.

RESULTS AND DISCUSSION

The cost estimates varied significantly for each fire management input among organizations. Hourly suppression cost estimates ranged from $40 per hour for a small engine 2-person FMI in the Southwestern Region to $595 per hour for a 20-person Category II crew in the Pacific Northwest region while on large-fire suppression actions. Cost estimates for state FMI suppression ranged from $65 per hour for a light bulldozer in California to $473 per hour for a 20-person Category II crew in Montana during large-fire suppression actions. This variation, combined with the FMI's fireline productivity, has implications for the purchase of FMIs. The technical limitations on use, program flexibility to budgetary changes, and arrival times to fires also influence decisions to purchase FMIs.

Cost Differences Between Components

Calculation of cost by component was not only a convenient way to collect data, but it also proved a convenient aid to the analysis of results. The pay and overhead contribution to total hourly cost was consistently the most significant in all FMIs. Their combined total contribution was always more than 50 percent, and usually more than 70 percent of the total FMI cost. The relative importance of the cost components for the Forest Service, and State organizations for two different FMIs—a 20-person Category I handcrew for the Forest Service and Category II for the State, and a medium engine—is demonstrated (*figs. 1-4*). In all labor-intensive FMIs, such as handcrews, pay, overhead, basic training, and facilities are the most significant components. In those capital intensive FMIs, like a medium engine, equipment replaces basic training as one of the most relevant cost components. Average hourly unit costs were broken down into cost components (*tables 7-9*).

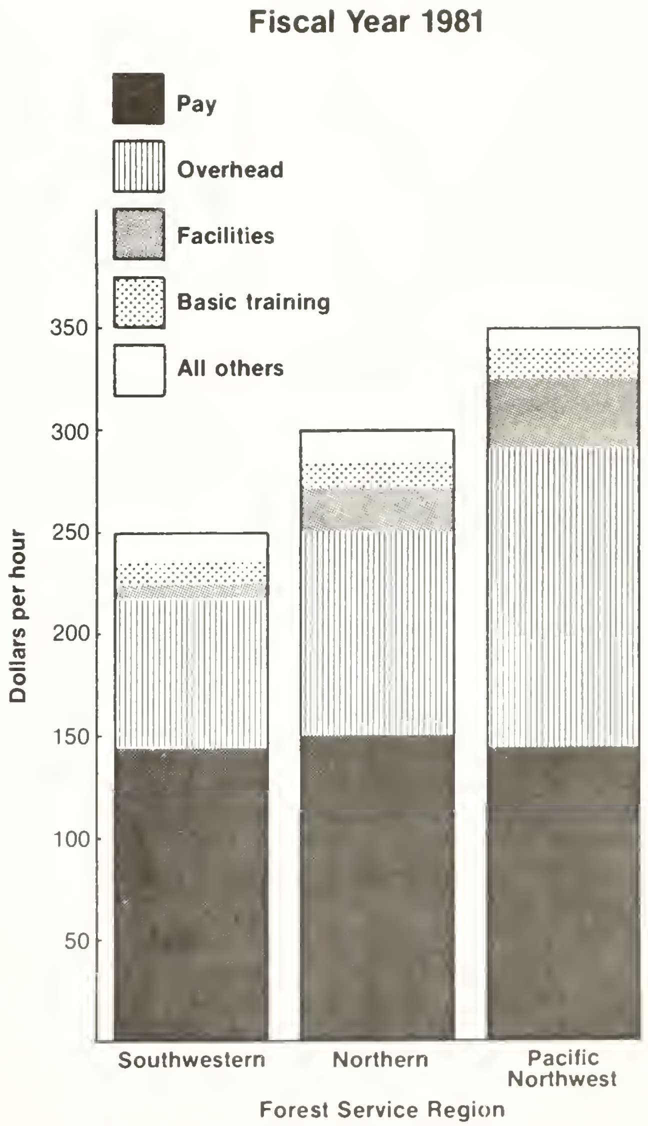


Figure 1—Contribution of Category I crew cost components to total hourly cost during availability for fire assignments, in Forest Service's Northern, Southwestern, and Pacific Northwest Regions.

Cost Differences Between Organizations

The FMI's per unit hourly cost estimates among the various fire organizations differed signficantly. Among Forest Service Regions, the Pacific Northwest's Region cost estimates were consistently higher than those of the Northern Region, and Northern Region cost estimates were consistently higher than those of the Southwestern Region. A 20-person Category I handcrew hourly cost estimate during availability status in the Pacific Northwest Region, for example, was $351 as against $296 (16 percent less) in the Northern Region, and $251 (28 percent less) in the Southwestern Region. The cost estimate of a medium engine was also higher in the Pacific Northwest Region than in the Northern and Southwestern Regions: $63 in the Pacific Northwest Region as against $45 (29 percent less) in the Northern Region and $42 (33 percent less) in the Southwestern Region. The same general cost differences persisted for all FMIs studied (*tables 2-4*).

The primary source of the FMI's cost differences among Forest Service regional organizations was the overhead cost component more than the pay differences. The pay component of a 20-person Category I handcrew, for example, varied from $149 in the Northern Region to $144 in the Pacific Northwest Region and $143 in the Southwestern Region (*fig. 1*). The overhead component, however, varied from a low of $84 in the Southwestern Region, to $100 in the Northern Region, and $145 in the Northern and Pacific Northwest Regions. Facilities and basic training were also responsible for part of the cost differences among regions. The same cost contribution pattern

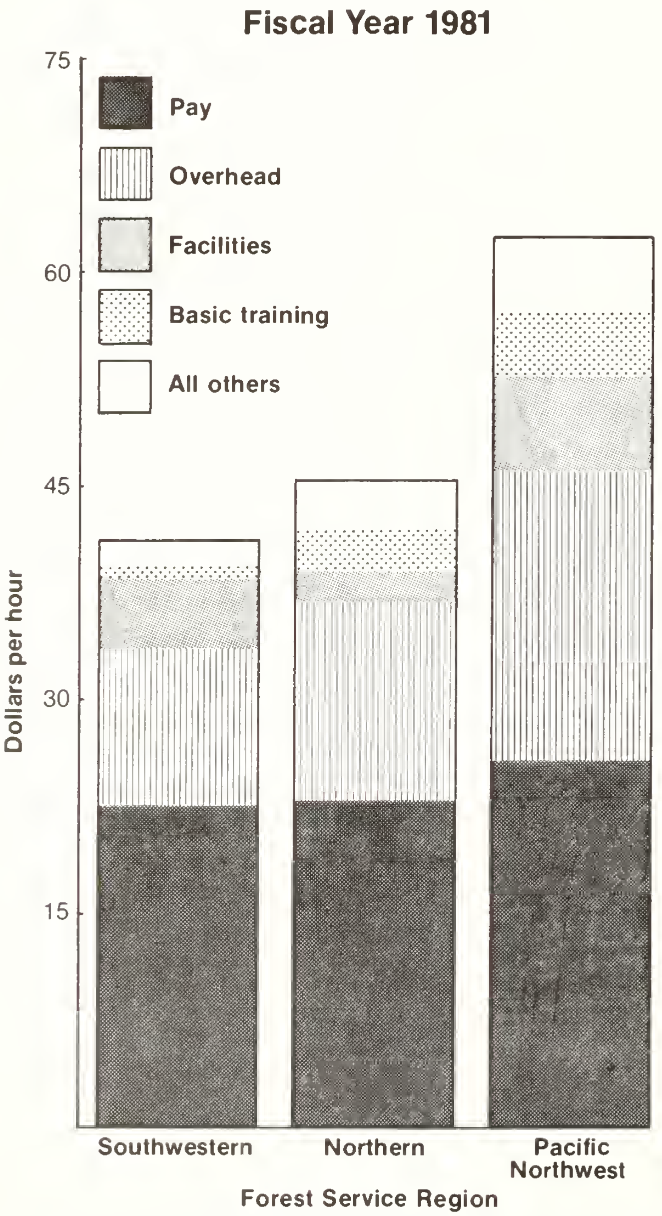


Figure 2—Contribution of medium engine team cost components to total hourly cost during availability for fire assignments, in Forest Service's Northern, Southwestern, and Pacific Northwest Regions.

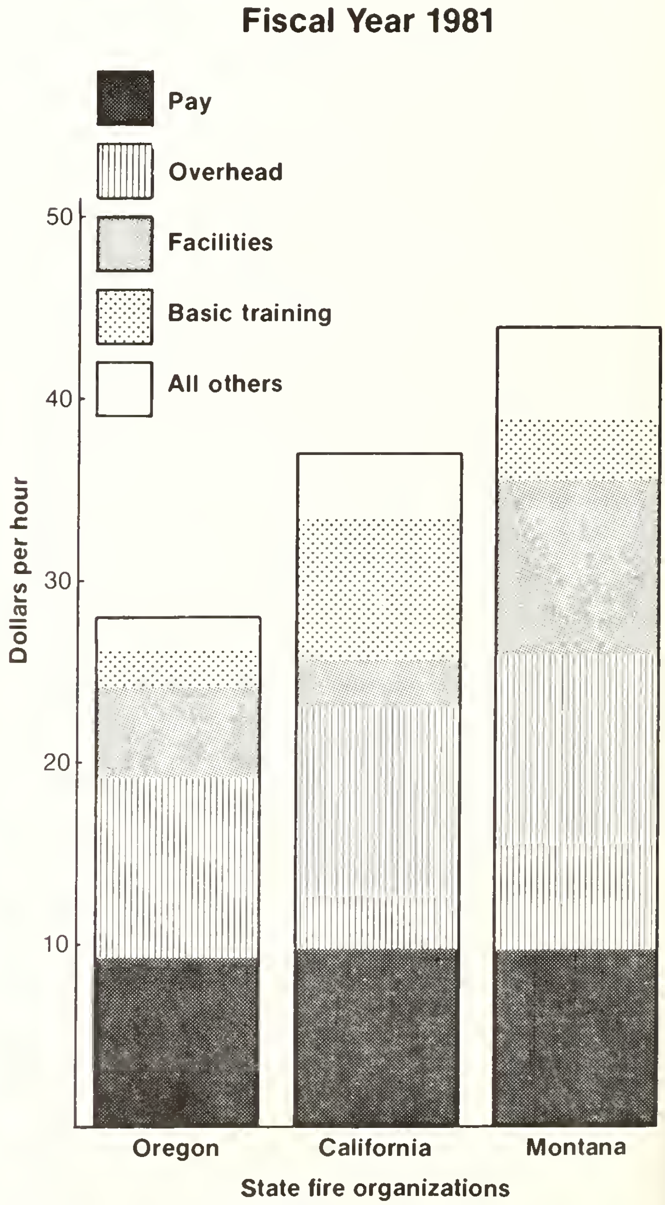


Figure 3—Contribution of Category II crew cost components to total hourly cost during availability for California, Oregon, and Montana fire agencies.

was repeated in the cost estimates for a medium engine (*fig. 2* and *tables 7-9*). Although the pay differences were higher than in the Category I handcrew, the overhead costs component contributed the most to the hourly cost differences. Equipment and facility differences were other contributing variables.

None of the cost estimates of the State fire organization was consistently higher than any of the cost estimates from other States. The hourly cost estimate of a Category II handcrew during availability, for example, was $43 in the Montana Division of Forestry, $36 in the California Department of Forestry, and $27 in the Oregon Department of Forestry. But the cost of a medium engine was $73 in Oregon, $70 in Montana, and $51 in California (*figs. 3, 4*). Again, the overhead and pay components contributed more than 50 percent of the total hourly cost in all FMIs, except in the medium engine team in Oregon where the equipment component was the greatest (*fig. 4*).

Other significant variables contributing to the FMI's cost differences were variations in FMI composition and staffing, and in length of time used in computing depreciation charges. California's 24 hour per day tour-of-duty, for example, resulted in a smaller pay and equipment cost component. The personnel pay and equipment depreciation was computed on a 24-hour basis, yielding a lower per hour cost estimate than would an 8 hour per day tour with depreciation. California's estimate could be computed on an 8 hour per day tour to increase comparability, but would not provide a realistic estimate for the California organization. Differences in staffing patterns— the number of personnel on an engine or in a helitack team—also accounted for real cost differences between organizations.

A higher percentage of the total State's per hour costs was overhead than was the situation for the Forest Service samples. The highest Forest Service overhead contribution to per hour cost during availability status, averaged across the three Regions, was 37 percent for a 20-person Category I handcrew. The corresponding State average overhead cost contribution for a similar handcrew during availability status was 43 percent (*tables 7-9*). Overhead cost compared with organization size, where size was represented by total labor hours, showed a weak correlation. This implies that no economies-of-scale exist in the fire protection organizations studied.

Cost by Deployment Status

The economic cost of the FMIs among the various categories of activity deployment status—availability, travel to fire, suppression on small fires, and suppression on large fires—differed significantly. Availability as used here is being available at the normal duty station. Hourly cost of a Category I handcrew at the Northern Region was $299 when on availability as against $347 on travel status to a fire, $330 during suppression activities of small fires, and $420 during suppression activities of large fires (*fig. 5*). The same cost pattern reappears for all FMIs (*fig. 6* and *table 10*). Deployment status is further compared: *table 2*— FMI hourly availability cost; *table 3*—FMI hourly suppression cost on small fires; *table 4*—FMI hourly suppression cost on large fires.

Transportation and equipment costs add considerably to the total hourly cost of the FMI teams during travel status. As examples, the hourly cost of a 30-passenger bus to transport a

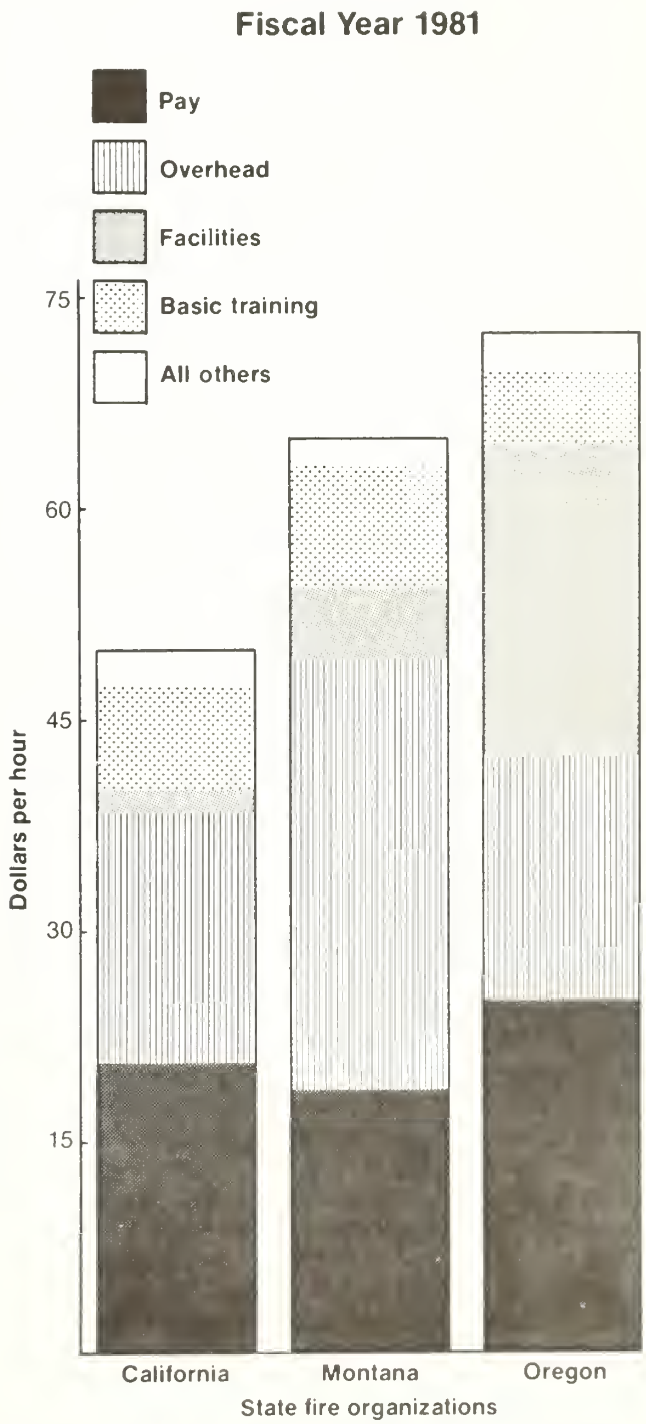


Figure 4—Contribution of medium engine cost components to total hourly cost during availability for California, Oregon, and Montana fire agencies. (California depreciates its equipment on a 24-h basis, which translates into a small equipment cost per hour.)

Table 7—*Combined average hourly cost of Fire Management Inputs in Forest Service Northern (R-1), Southwestern (R-3), and Pacific Northwest (R-6) Regions, by cost component (available for fire assignment), Fiscal Year 1981*

Fire Management Input	Supplies		Pay		Training		Special training		Overhead		Equipment		Facilities		Total	Stand. dev.
	Dollars/hour and pct															
	$	*Pct*	*$*	*Pct*	*$*	*Pct*	*$*	*Pct*	*$*	*Pct*	*$*	*Pct*	*$*	*Pct*	*$*	
Category I	6.85	2.29	145.38	48.62	10.71	3.58	[1]5.35	1.79	111.33	37.23	3.93	1.31	18.86	6.31	299	50
Category II	[1]7.29	14.58	[1]19.40	38.80	[1]16.72	33.44	[2]—	—	[1]5.36	10.72	[1].17	.34	[1]1.21	2.42	50	22
Category III	[1]6.71	15.60	[1]17.11	39.79	[1]6.25	14.53	—	—	[1]11.45	26.63	[1].51	1.19	[1].72	1.67	43	24
Project crew	.70	14.00	2.03	40.66	1.29	25.87	—	—	.50	10.00	.07	1.40	.09	1.80	5	2
Helitack	1.00	1.22	19.79	24.13	1.47	1.79	1.34	14.78	14.78	18.02	40.05	49.39	2.51	3.06	82	11
Smokejumper	.98	2.39	17.90	43.66	1.20	2.93	2.50	6.09	10.97	26.76	5.66	13.80	1.88	4.59	41	6
Engine—small	.76	2.42	14.83	47.19	1.04	3.30	—	—	10.97	34.89	1.95	6.21	1.88	5.99	31	6
Engine—medium	1.78	3.62	22.16	44.98	1.55	3.14	.46	.94	16.45	33.39	4.04	8.19	2.83	5.74	49	11
Engine—large	1.75	3.62	20.53	42.43	1.73	3.58	1.25	2.58	16.83	34.79	3.60	7.43	3.52	7.28	48	42
Bulldozer—small	1.32	2.58	22.08	43.27	1.58	3.09	[2].75	1.47	13.39	26.23	9.97	19.53	2.45	4.80	51	18
Bulldozer—medium	1.56	2.15	23.17	31.92	1.60	2.19	—	—	13.39	18.44	30.41	41.90	2.45	3.38	73	15
Bulldozer—large	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

[1]Two observations. [2]No observations. [3]One observation.

Table 8—*Combined average hourly cost of Fire Management Inputs in Forest Service Northern (R-1), Southwestern (R-3), and Pacific Northwest Regions (R-6), by c component during large fire suppression, Fiscal Year 1981*

Fire Management Input	Supplies		Pay		Supervision		Subsistence		Training		Special training		Overhead		Equipment		Facilities		Total	St
	Dollars/hour and pct																			
	$	*Pct*	*$*	*Pct*	*$*	*Pct*	*$*	*Pct*	*$*	*Pct*	*$*	*Pct*	*$*	*Pct*	*$*	*Pct*	*$*	*Pct*	*$*	
Category I	6.85	1.54	210.32	47.16	9.76	2.19	72.08	16.16	10.71	2.40	[1]5.35	1.20	109.67	24.59	7.02	1.57	18.86	4.22	446	
Catetory II	[1]7.29	1.35	[1]284.09	52.51	[1]12.21	2.26	[1]67.63	12.50	[1]16.72	3.09	[2]—	—	[1]122.64	22.67	[1]3.55	.66	[1]26.48	4.89	541	
Category III	6.71	1.95	129.57	37.67	36.70	10.67	61.07	7.75	6.25	1.82	—	—	89.78	26.09	3.00	.87	4.29	1.25	344	
Project crew	.70	1.37	27.08	53.10	6.02	11.80	4.34	8.51	1.29	2.53	—	—	10.97	21.51	2.57	5.04	1.88	3.69	51	
Helitack	1.00	.95	28.65	27.29	6.57	6.26	7.18	6.84	1.47	1.40	1.34	1.28	14.78	14.08	40.50	38.57	2.51	2.39	105	
Smokejumper	.98	1.53	25.85	40.39	8.96	14.00	5.28	8.25	1.20	1.88	2.50	3.91	10.97	17.14	5.66	8.84	1.88	2.94	64	
Engine—small	.76	1.64	21.46	46.32	—	—	6.21	13.40	1.04	2.24	—	—	10.97	23.68	3.77	8.14	1.88	4.06	46	
Engine—medium	1.78	1.81	30.11	30.62	18.75	19.08	9.90	10.07	1.55	1.58	.46	.47	15.86	16.13	14.65	14.90	2.83	2.88	98	
Engine—large	1.75	1.85	29.85	31.53	17.63	18.62	9.31	9.83	1.73	1.83	1.25	1.32	16.83	17.78	13.48	14.24	3.52	3.72	95	
Bulldozer—small	1.32	1.42	29.74	31.98	18.86	18.13	8.28	8.91	1.58	1.70	[3].75	.81	13.38	14.39	19.33	20.79	2.45	2.63	93	
Bulldozer—medium	1.56	1.30	30.23	25.26	16.80	14.04	7.98	6.67	1.32	1.11	—	—	13.38	11.19	45.51	38.03	2.45	2.05	120	
Bulldozer—large	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	

[1]Two observations. [2]No observations. [3]One observation.

Table 9—*Combined average hourly cost of Fire Management Inputs in California, Montana, and Oregon State agencies, by cost component (available for fire assignment), Fiscal Year 1981*

Fire Management Input	Supplies		Pay		Training		Special training		Overhead		Equipment		Facilities		Total	Stand. dev.
	Dollars/hour and pct															
	$	*Pct*	*$*	*Pct*	*$*	*Pct*	*$*	*Pct*	*$*	*Pct*	*$*	*Pct*	*$*	*Pct*	*$*	
Category I	[1]2.58	9.85	[1]5.00	19.07	[1]2.83	10.79	[2]—	—	[1]11.29	43.11	[3]0.13	0.50	[1]4.49	17.14	26	0.1
Category II	[1]2.58	9.92	[1]4.93	18.95	[1]2.09	8.04	—	—	[1]1.80	45.37	[3].13	.50	[1]4.61	17.72	26	13
Category III	3.31	12.81	6.19	23.98	5.17	20.03	—	—	8.97	34.75	[3].09	.35	2.17	8.41	26	18
Helitack	.80	0.89	23.58	26.49	1.21	1.36	10.30	11.57	25.76	28.94	29.04	32.63	8.01	9.00	89	17
Smokejumper	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Engine—small	.78	1.72	15.39	33.91	.93	2.04	.50	1.11	15.36	33.85	7.50	16.52	4.93	10.85	45	4
Engine—medium	1.01	1.57	20.92	32.35	1.30	2.02	.73	1.12	20.81	32.17	11.43	17.67	7.00	10.83	65	12
Engine—large	.90	1.53	15.34	26.04	.93	1.57	.58	.98	15.36	26.08	20.86	35.42	4.93	8.36	59	22
Bulldozer—small	.49	0.96	16.90	32.99	.86	1.67	.38	.74	13.87	27.07	14.71	28.72	4.15	8.10	51	20
Bulldozer—medium	.49	0.77	17.40	27.06	.87	1.35	.38	.58	13.87	21.57	27.26	42.41	4.15	6.46	64	24
Bulldozer—large	[4].11	0.12	[4]20.69	24.04	[4].65	.76	—	—	[4]11.88	13.81	[4]51.00	59.26	[4]1.73	2.01	86	—

[1]Two observations.
[2]No observations.
[3]Does not include equipment for Montana State.
[4]One observation.

Category I handcrew is $36, the total estimated cost of a medium-size helicopter is $732 per hour. Transportation cost estimates for different transportation methods vary (*table 5*). Hazard-pay adjustment, subsistence, and on-fire supervision costs charged when an FMI is on a fire contributed considerably to the cost differences by deployment status. The State organizations and Forest Service regions showed the same pattern of cost by deployment status (*figs. 7, 8*).

Comparison With Other Cost Estimates

These unit cost estimates are higher than figures sometimes used for long-term planning. The Northern Region FMI's daily costs (assuming an 8-hour day) were higher, for example, than costs proposed in the Fire Management Analysis and Planning Handbook (U.S. Dep. Agric., Forest Serv. 1982). The daily Category I handcrew cost during availability, for example, is $2368 by the method described here and $1765 in the Planning Handbook. The cost difference grows even larger during suppression on small fires and suppression on large-fire deployment status (*table 11*).

Comparability of the two estimates is difficult to assess. The estimates differ in how the fixed costs are allocated among FMIs, by the FMI's configuration, and by differences in which costs are included in the daily costs for the two procedures. Overhead costs that were allocated to the per hour cost of the line-building FMIs in the cost procedure provided here, for example, were charged elsewhere in the Planning Handbook Method (Lundeen 1983). The overhead cost computation itself may also be different.

Cost estimates in the National Interagency Reinforcement Crew and Analysis Plan (U.S. Dep. Agric., Forest Serv. 1979) show the same relative results. The cost estimates for compa-

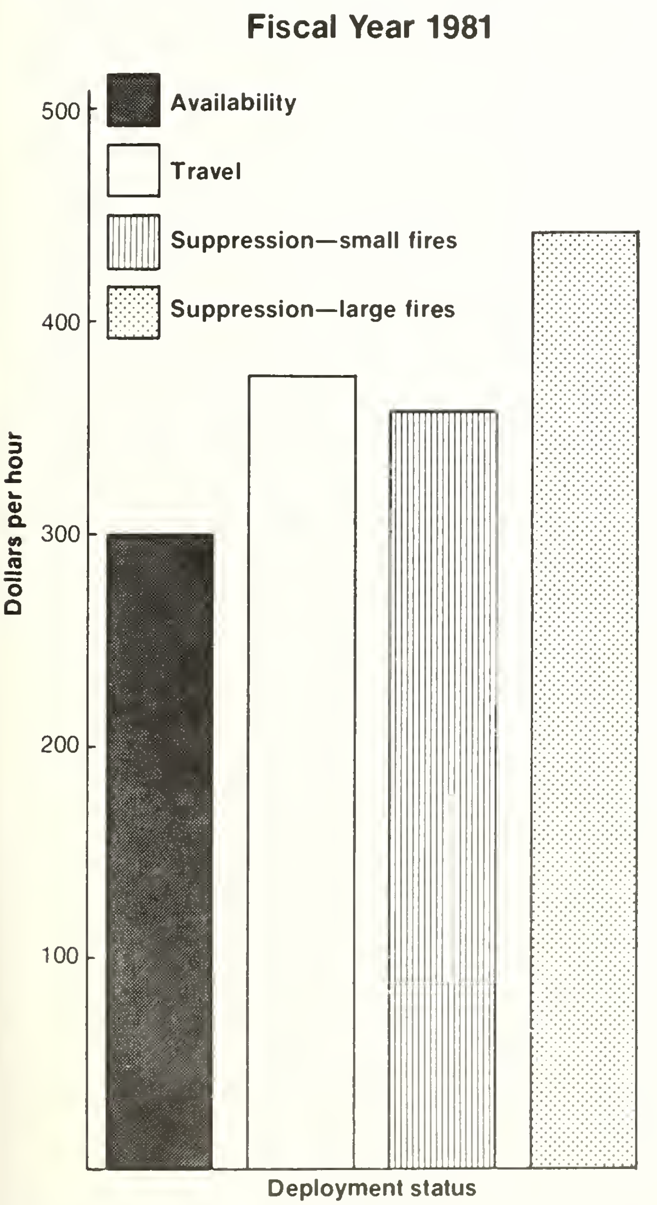


Figure 5—Category I crew cost by deployment status for the Forest Service's Northern Region.

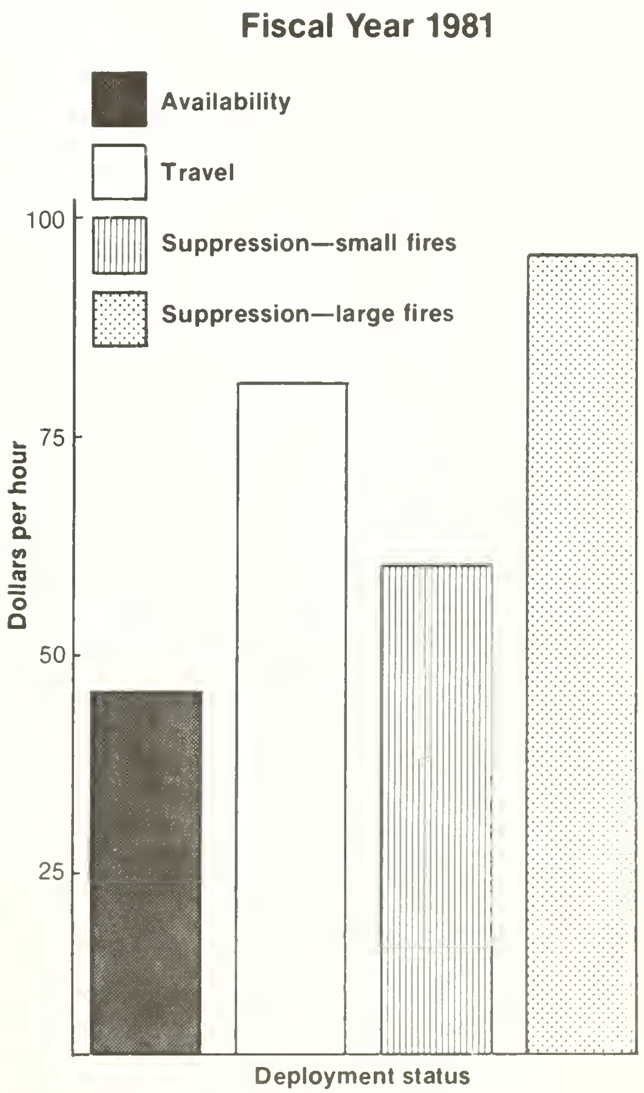


Figure 6—Medium engine team cost by deployment status for the Forest Service's Northern Region.

Table 10—*Hourly cost of Fire Management Inputs, including availability and travel costs, and suppression costs for small and large fires, in the Forest Service's Northern Region, Fiscal Year 1981*

Fire Management Input	Crew available for assignment	Weighted cost, travel to fire[1]	Weighted cost suppression of . . .		Weighted cost, travel as multiple of crew available	Cost as multiple of crew available for . . .	
			Small fires	Large fires		Small fires	Large fires
	Dollars/hour						
Category I	296	[2]372	360	422	1.26	1.21	1.49
Category II	[3] 35	[2]427	414	486	[4]	[4]	[4]
Category III	[3] 24	[2]284	271	372	[4]	[4]	[4]
Project Crew	[3] 4	33	42	48	[4]	[4]	[4]
Helitack	73	[5]234	82	93	3.23	1.11	1.27
Smokejumper	39	[6]109	47	62	2.79	1.21	1.56
Engine—small	30	51	39	46	1.73	1.23	1.47
Engine—medium	45	82	60	93	1.82	1.28	2.02
Engine—large	32	72	45	72	2.25	1.40	2.21
Bulldozer—small	49	95	62	85	1.95	1.27	1.76
Bulldozer—medium	57	110	78	101	1.92	1.36	1.77
Bulldozer—large	—	—	—	—	—	—	—

[1]Includes transportation to fire plus all other components. Percent regular time and percent overtime used as weights.
[2]Assumes transportation of entire crew in a 20-person bus.
[3]Nonfire funded. Value represents an imputed cost to account for the availability of the nonfire FMI for fire use, derived in proportion of total use during fire season.
[4]Nonfire funded; comparisons, as a multiple of availability costs, therefore, are meaningless. See also footnote 3.
[5]Assumes use of small rotary-wing aircraft (3-person capacity), which ferries two helitack teams to fire. Flying cost prorated on a team/hour basis.
[6]Assumes use of small fixed-wing aircraft carrying four smokejumper teams at a time. Flying cost prorated on a team/hour basis.

Table 11—*Daily costs of Fire Management Inputs for the Forest Service's Northern Region, Fiscal Year 1981, compared with those of the Forest Service's Fire Management Analysis and Planning Handbook*

Fire Management Input	Handbook cost[1]	Crew available[2]		Northern Region costs Weighted cost, for suppression of . . .			
				Small fires		Large fires	
		Dollars/day	*Pct difference*	*Dollars/day*[2]	*Pct difference*	*Dollars/day*[2]	*Pct difference*
Category I	1765	2368	34	2880	63	3520	99
Category II	2660	[3] 192	(92)	2144	(5)	2976	32
Category III	2440	[3,4] 280	(89)	[3,4]3288	35	[3,4]3896	60
Bulldozer/plow units	[5] 340	[6] 457	34	622	83	810	138
Engine—small	[7] 270	[8] 244	(10)	311	15	364	34
Smokejumper (each)	130	156	20	188	45	248	91
Helitack (including personnel and equipment)	[9] 310	[10] 584	88	[11]1876	605	[11]1964	639
Airtankers	[12]1210	[13] 424	(65)	[14]9224	762	[12]9224	762

[1]No length period specified.
[2]Assumes 8-hour day; includes all appropriate overhead, hazard, and overtime charges during small and large fires.
[3]This FMI not maintained on standby during fire season. Only a proportion of standby cost assigned, on basis of proportion of use throughout season. Nonfire funded leads to misinterpretable entries.
[4]Forest Service regular nonfire-funded personnel.
[5]Bulldozer nor crew size specified
[6]Medium bulldozer equivalent to a D-6, with a two-person crew.
[7]No crew size specified.
[8]Includes two-person crew.
[9]Helicopter nor crew size specified.
[10]Small helicopter with capacity for three people; includes two-person helitack team.
[11]Assumes 8-hour flying time, including two-person helitack team. Cost prorated on a team/hour basis because two helitack teams ferried.
[12]No plane size specified.
[13]A 1900-gal tank capacity plane.
[14]Assumes 8-hour flying time.

rable handcrews were higher when the method described here was used. Differences in crew configuration and pay grade schedules account for part of the cost differences. The overhead cost computation and allocation may be other sources of differences.

The objectives of the various studies done are quite different. This study estimates total economic cost to the agency of placing an FMI on the fireline. The cost of fringe benefits offered to the employees, such as holidays, annual leave, and sick leave, therefore, are included, but are not included or registered elsewhere in the two other studies cited (U.S. Dep. Agric., Forest Serv. 1980; U.S. Dep. Agric., Forest Serv. 1979). The year of the database also varied among the studies. The crew need study was done in 1979, the Planning Handbook numbers are from 1980, and the data of this study are for fiscal year 1981. In addition, the earlier studies are nationwide approximations, while the current study is regionally specific for three western high fire-activity regions.

The resultant output of the cost-aggregation process is an estimate of the true economic cost of the various FMIs. The final costs may not be consistent with budget estimates because budget costs fail to include some items, such as the annual cost of facilities, or fail to allocate some costs to each FMI, such as fire program management overhead. As a result, these economic costs are usually higher than those with which fire program managers deal. Because the use of cost components as building blocks may ignore unique or unusual costs, the economic cost estimates may actually be conservative.

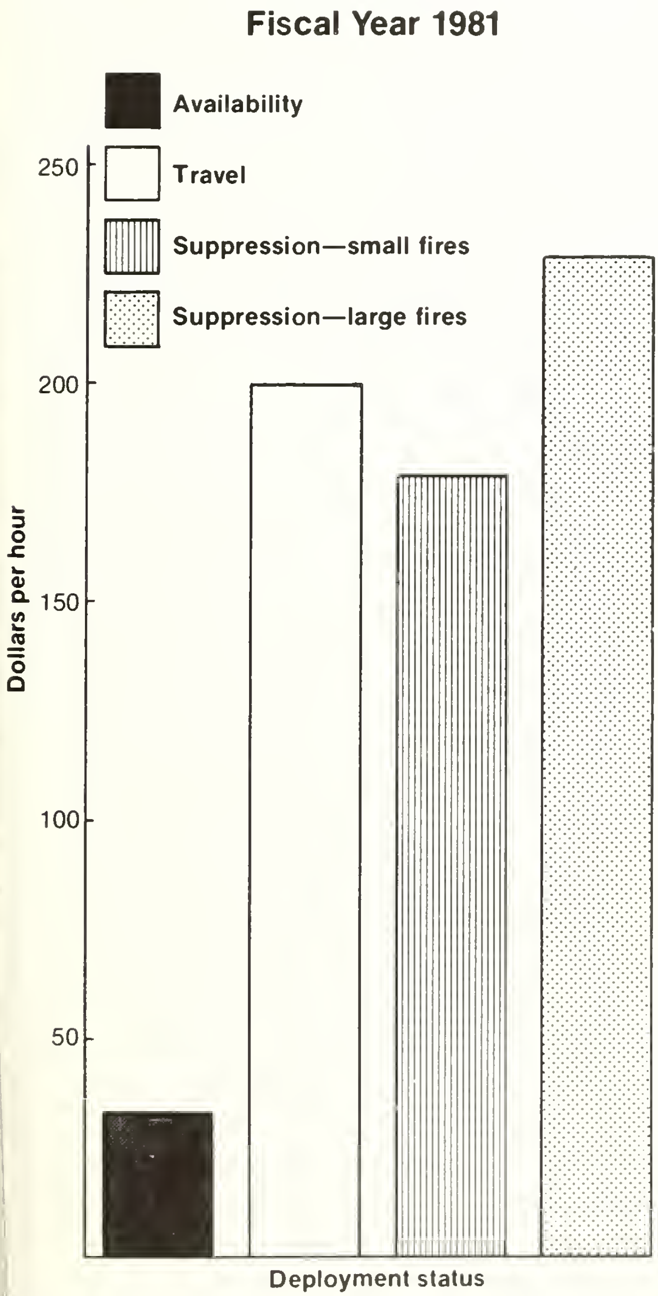


Figure 7—Category II crew cost by deployment status for the California Department of Forestry.

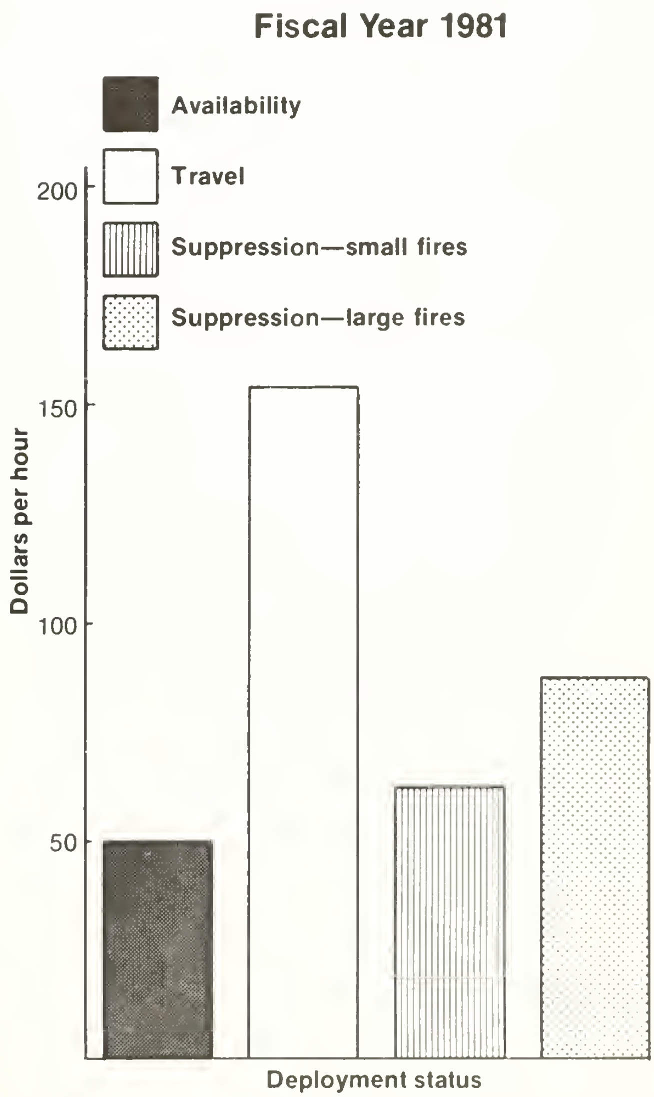


Figure 8— Medium engine team cost by deployment status for the California Department of Forestry.

CONCLUSIONS

With minimum effort, the cost estimates can be updated annually, or whenever organization changes warrant refinements. A full cycle through the procedure—from data collection through analysis of output—can be achieved with a person-week of work.

The cost computation algorithm is sufficiently generalized to be useful to any organization with fire protection responsibilities. Because total comparability between agencies is not possible, the cost collection method and computerized procedure were designed to have enough flexibilty to accommodate the specific needs of different organizations. Because of the procedures and the component nature of the cost, the results may be useful in applications other than long-term planning. Some subset of the cost components, for example, could be used to negotiate mutual assistance contracts among organizations or to determine trespass fire costs.

The magnitude of the cost estimates of this example application are much higher than previously thought, especially the overhead, training, and facilities components. The pay component, although significant, was not as costly as expected. These results have operational implications during constrained budget situations. Sometimes reduction in field personnel is looked upon as the only solution to budget cuts, but this analysis reveals that approach to be only a partial simplistic solution.

This example application of the economic cost procedure also shows that the economic cost of the FMIs among the Forest Service regions and the State fire organizations differ significantly. Part of the cause lies in dissimilar staffing patterns, and in differences in tour-of-duty and length-of-time use in their depreciation schedules. Much of the difference, however, lies in real differences in the overhead, facilities, training, and pay cost components. The economic cost estimates also differ significantly among the different categories of fire activity deployment status; that is, availability, travel to fire, suppression on small fires, and suppression on large fires.

Differences in the FMI's economic cost estimates between Forest Service regions and State fire organizations, and differences between activity deployment status, have implications for both long-term planning and real-time management decisions. The use of nationwide cost averages across broad geographical areas and the various fire activity deployment status mask significant and real economic cost differences. The suppression cost per acre burned will increase substantially as the size of the suppression organization enlarges for a given burned area. The cost during travel status is high and fixed no matter how small the fires are contained; larger suppression organization will contain fires at a smaller size. During planning of the dispatching procedures, attention should be given to the increment in cost above the availability status—the extra cost to *use* an FMI is substantial, even after it has been paid to have the FMI available.

REFERENCES

Bellinger, M.D.; Kaiser, H. Fred; Harrison, H.A. **Economic efficiency of fire management on nonfederal forest and range lands**. J. For. 81(6): 373-375 and 378; 1983 June.

Davis, Lawrence S. **An exploration of the economics of fire management programs in the Rocky Mountains with emphasis on information needs.** 1974. Unpublished draft supplied by author.

Gale, Robert D. **Evaluation of fire management activities on the National Forests**. Policy Analysis Staff Report. Washington, DC: Forest Service, U.S. Department of Agriculture; 1977. 127 p.

González-Cabán, Armando. **Economic cost of initial attack and large-fire suppression**. Gen. Tech. Rep. PSW-63. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983. 7 p.

Gorte, Julie K.; Gorte, Ross W. **Application of economic techniques to fire management. A status review and evaluation**. Gen. Tech. Rep. INT-53. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1979. 26 p.

Haven, Lisa; Hunter, T. Parkin; Storey, Theodore G. **Production rates for crews using hand tools on firelines**. Gen. Tech. Rep. PSW-62. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 8 p.

Lundeen, Charles R. [Telephone conversation with Armando González-Cabán]. 1983 May 30.

Martin, Clifton B. **How should the cost of forest fire protection be shared?** Agricultural Experiment Station Bulletin 625. Baton Rouge, LA: Louisiana State University Agricultural Experiment Station; 1968, 19 p.

Marty, Robert J.; Barney, Richard J. **Fire costs, losses, and benefits: an economic valuation procedure.** Gen. Tech. Rep. INT-108. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1981. 11 p.

McKetta, Charles W.; Ehrenreich, John J.; Clements, Stephen; Overstreet, Joseph. **Fire management cost data collection form and firefighting costs model**. 1981. Unpublished draft supplied by author.

Mills, Thomas J.; Bratten, Frederick W. **FEES: design of a Fire Economics Evaluation System.** Gen. Tech. Rep. PSW-65. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 26 p.

Sackett, S.S.; Webster, H.H.; Lord, W.B. **Economic guides for allocating forest fire protection budgets in Wisconsin**. J. For. 65(9): 636-641; 1967 September.

Sparhawk, W.N. **The use of liability rating in planning forest fire protection.** J. Agric. Res. 30(8):693-761; 1925 April.

Streeby, Larry L. **Foundations of an improved fire damage appraisal system.** Madison, WI: University of Wisconsin; 1973. 158 p. Dissertation.

Sutherland, Charles F. **Cost of forest closure in two Oregon counties**. J. For. 71(10):644-647: 1973 October.

U.S. Department of Agriculture, Forest Service. **National interagency reinforcement crew analysis and action plan**. Washington, DC: U.S. Department of Agriculture, Forest Service [Aviation and Fire Management Staff]; 1979. 281 p.

U.S. Departmet of Agriculture, Forest Service. **FSM 6581.11f—Equipment rental rate development**. Washington, DC; 1980.

U.S. Department of Agriculture, Forest Service. **FSH 5109.19—Fire management analysis and planning handbook**. Washington, DC; 1982.

U.S. Department of Agriculture, Forest Service. **FSM 5130.3—Fire suppression policy**. Washington, DC; 1981.

U.S. Senate. **Report on Department of Interior and related agency appropriations bill**. Rep. 95-1063. Washington, DC; 1978.

Zivnuska, John A. **An economic view of the role of fire in watershed management.** J. For. 66(8):596-600; 1968 August.

United States
Department of
Agriculture

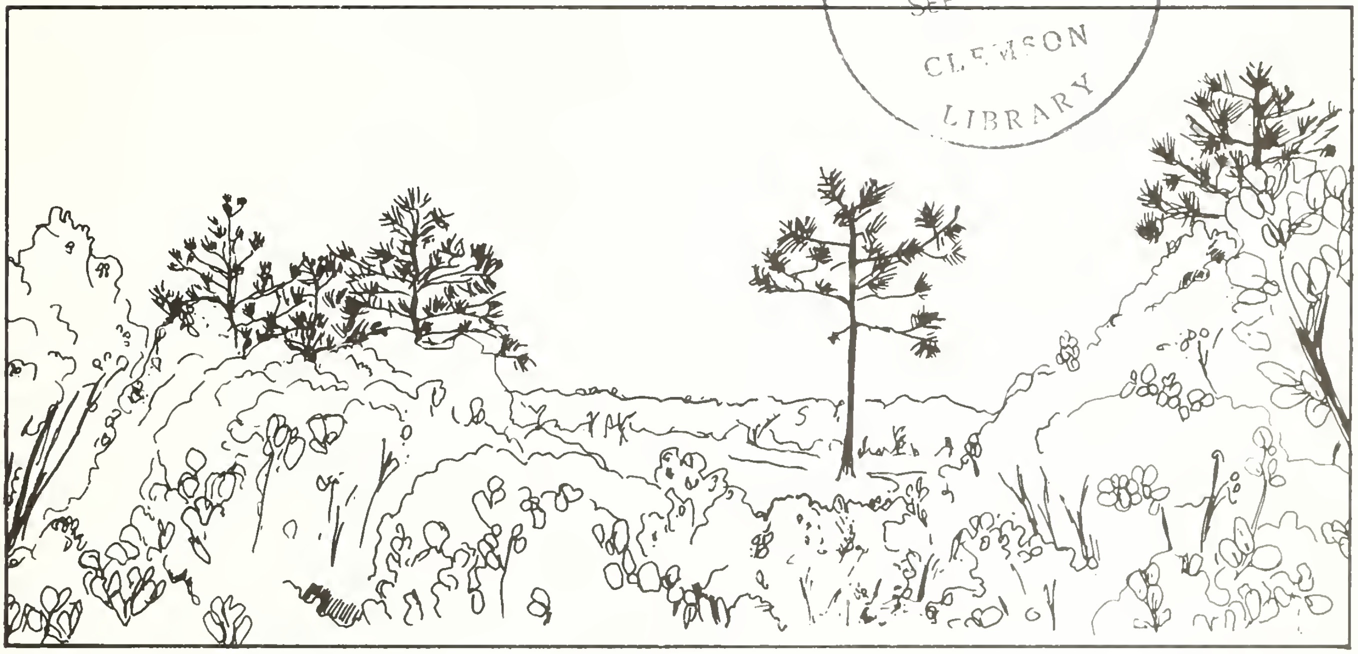
Forest Service

**Pacific Southwest
Forest and Range
Experiment Station**

Research Paper
PSW-172

Brush Reduces Growth of Thinned Ponderosa Pine in Northern California

William W. Oliver



The Author:

WILLIAM W. OLIVER is doing silvicultural research on California conifer types, with headquarters at Redding, California. He earned a B.S. degree (1956) in forestry from the University of New Hampshire, and an M.F. degree (1960) from the University of Michigan. He joined the Station staff in 1962.

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

August 1984

Brush Reduces Growth of Thinned Ponderosa Pine in Northern California

William W. Oliver

CONTENTS

IN BRIEF . . .

Oliver, William W. **Brush reduces growth of thinned ponderosa pine in northern California.** Res. Paper PSW-172. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1984. 7 p.

Retrieval Terms: Pinus ponderosa, Arctostaphylos sp., plantation management, vegetation · management, tree growth, North Coast Range, California

The role of stocking control in increasing the growth and vigor of potential crop trees in young plantations of ponderosa pine (*Pinus ponderosa* Dougl. ex Laws. var. *ponderosa*) is well recognized. Most stocking level recommendations, however, are for stands that contain little or no understory woody vegetation (brush). And yet brush is known to be a common and aggressive competitor that robs ponderosa pines of soil moisture and nutrients. Lack of information on the interrelationships of levels of tree stocking and competing brush quantities impairs the efficiency and even the effectiveness of plantation management.

The effects of tree spacing and brush competition were evaluated on a site of low productivity in California's North Coast Range. Moisture and possibly nutrients were limited by a shallow, skeletal soil. Site index was estimated to be 17 m (55 ft) at 50 years.

Eleven-year-old saplings were thinned to square spacings of 2.1, 2.4, 3.0, and 4.3 m (7, 8, 10, and 14 ft) in each of three blocks. After 5 years, the plots were subdivided into thirds. All, half, and none of the understory brush (principally hoary manzanita [*Arctostaphylos canescens* var. *candidissima* Eastw. Munz]) was manually removed in a split-plot design.

An analysis of variance showed that brush crown cover was significantly ($p < 0.05$) related to periodic annual increment (PAI) in diameter-at-breast-height (d.b.h.), height, and stem volume of the pines. Differences in d.b.h. and height growth were significant among all three brush treatments when all spacings were combined. Stem volume production rose significantly when all brush was removed but not when half the brush was removed. Without brush control, the plantation growth rate declined in all characteristics from the first to the second 5-year period after tree thinning.

Spacing significantly influenced diameter growth only when all brush was removed. Height growth and stem volume production were not significantly influenced by spacing, probably because of the short period of growth monitored after brush treatment and differences in initial tree size among plots.

No relationship between 5-year change in brush crown cover and trees per hectare was found. The ponderosa pines, even when closely spaced at 2.1 by 2.1 m (7 by 7 ft), did not suppress growth of brush. Instead, increasing brush density restricted tree growth, suggesting that brush exploited the site's resources more vigorously than did the pines.

A threshold value of brush crown cover below which brush did not suppress tree growth was not found in this study. A multivariate, nonlinear equation relating brush crown cover and trees per hectare to PAI d.b.h. ($R^2 = 0.90$) suggests that any amount of brush will restrict d.b.h. growth. Only when brush cover is light will spacing exert an influence. At coverages greater than about 30 percent, brush competition overwhelms intertree competition and all trees regardless of spacing grow at the same rate.

Tree death was negligible but insect damage was abundant during the period of observation. The gouty pitch midge (*Cecidomyia piniinopis* Osten Sacken) caused the most noticeable damage associated with brush treatment but not with tree spacing. Larval feeding of this and other unidentified insect species deformed tops and caused loss of foliage. Insect damage tended to exacerbate the growth loss caused by brush competition.

As currently practiced, brush control methods do not eliminate all brush. Unless these methods can be expected to reduce brush coverage substantially over a major portion of early stand life, benefits to tree growth and health will be fleeting, at best. Even small amounts of brush can restrict tree growth markedly, and the major tree growth losses found in this study should prevail in similar plantations on sites of low productivity. Consequently, the cost of brush control should be included as an integral part of the regeneration cost. If, however, brush control is not planned, yields and rotations should be adjusted accordingly.

Stocking control is a cultural treatment commonly applied in young plantations of ponderosa pine (*Pinus ponderosa* Dougl. ex Laws. var. *ponderosa*). Its role in increasing the growth and vigor of potential crop trees is well recognized. Recommended stocking levels for a range of management objectives, sites, and tree sizes are available and are being refined as research continues (Barrett 1979; U.S. Dep. Agric., Forest Serv. 1973).

These stocking level recommendations are for stands that contain little or no understory of woody vegetation (brush). And yet we know brush to be a common and aggressive competitor, robbing ponderosa pines of soil moisture and nutrients. Forest managers estimate that growth loss from competing brush is substantial in nearly one-third of all ponderosa pine plantations in California.[1] Currently, brush is being treated on about 4000 ha (10,000 acres) of these plantations annually.

Lack of information on the interrelationships of levels of tree stocking and competing brush quantities impairs the efficiency and even the effectiveness of plantation management. Competing brush can lengthen the time to first comercial thinning regardless of tree spacings or site productivity. Barrett (1973) estimated that brush control would have saved a decade of time to first commercial entry in a stand of pine poles spaced 5.7 by 5.7 m (18.7 by 18.7 ft) on a medium site in central Oregon. On a highly productive site in California, the equivalent of 3 years' growth in diameter-at-breast-height (d.b.h.) was lost to brush competition after 12 years when trees were planted at about the same spacing (Oliver 1979).

On sites of low productivity, brush competition can exert even stronger effects. After 19 years, planted pines competing with dense manzanita and ceanothus brush were only 27 percent as large in diameter and 35 percent as tall as pines free of brush (McDonald 1982). Part of this size difference resulted from greater damage from frequent insect attacks that destroyed buds and needles. Yields projected from these growth rates fall far short of nominal management objectives (Fiske 1982).

This paper reports the effects of tree spacing and brush growing in a ponderosa pine plantation on a site of low productivity in the North Coast Range of California. Implications for managing pine stands and controlling brush are suggested.

[1]Data on file at the Pacific Southwest Forest and Range Experiment Station, Redding, Calif.

STUDY AREA

The effects of tree spacing and brush competition on planted ponderosa pine are being evaluated on the Trough Springs Ridge 14 km (9 mi) southwest of Stonyford, Colusa County, at 1280-m (4200-ft) elevation on the eastern slope of the North Coast Range (lat. 39° 17′ N., long. 122° 40′ W.). Plots are within a 15-ha (36-acre) area. Almost all slope aspects and gradients up to 20 percent are represented.

Average annual precipitation is 1041 mm (41 inches), about 10 percent of which falls within the April through August growing season. Summers are hot with maximum daily temperatures in July usually about 32° C (90° F).

The soil has been classified as Maymen Series, a Dystric Lithic Xerochrept derived from Pre-Cretaceous metasedimentary rocks. Depth to lithic contact varies from 20 to 33 cm (8 to 13 inches), but some roots can penetrate to an unknown depth along the extensive vertical fractures. Maymen Series, which usually supports chaparral, is found extensively on steep slopes between 300 and 1200 m (1000 and 4000 ft) on the west slope of the Sierra Nevada and on the Coast Range.

The average site index, as measured by naturally established surrounding trees, is estimated to be 17 m (55 ft) at 50 years for trees less than 100 years of age (Powers and Oliver 1978). For older trees, a lower site index, about 14 m (45 ft), is a common phenomenon on shallow soils (Zinke 1959).

The original cover of Pacific Ponderosa Pine–Douglas-fir (Society of American Foresters Type 244) (Eyre 1980) was burned in August 1959. The following April, material remaining after salvage logging was windrowed and the cleared area cultivated with a rangeland disk. Ponderosa pine, stock class 2-0 and 2-1 from the appropriate seed zone, was hand planted at spacings that varied between 1.2 by 1.2 and 1.8 by 2.4 m (4 by 4 and 6 by 8 ft).

Survival was excellent, but tree growth was slowed by a shallow soil with little moisture-holding capacity apparently aggravated by severe brush competition. Eleven years after planting, trees averaged 2.8 cm (1.1 inches) in d.b.h. and 1.8 m (6 ft) tall. Stand density varied from 1422 to 3407 trees per ha (576 to 1380/acre). Manzanita (*Arctostaphylos canescens* var. *candidissima* Eastw. Munz, primarily, and scattered *A. roofii* [Gankin 1966]) formed a uniform understory. Brush crowns averaged 0.7 m (2.3 ft) and covered 30 percent of the area.

METHODS

Tree growth was evaluated at four tree spacings, established by thinning—2.1 by 2.1, 2.4 by 2.4, 3.0 by 3.0, and 4.3 by 4.3 m (7 by 7, 8 by 8, 10 by 10, and 14 by 14 ft). In fall 1970, each spacing was assigned to three 0.10-ha (0.25-acre) plots in a randomized block design. Plots were grouped into three blocks on the basis of small differences in site quality. Three additional plots, one each per block, were lightly thinned, leaving more than 1480 trees per ha (600/acre) as reserve to cover possible plot losses in the future. All plots were surrounded by a buffer strip 6 m (20 ft) wide.

Thinning was from below, leaving as potential crop trees the most vigorous, well-formed specimens as far as this was compatible with reasonably uniform spacing. Slash was left to decay on the site.

Before growth began the next spring, all trees were tagged, described by crown class, measured for d.b.h. to the nearest 0.25 cm (0.1 inch), and noted for insect damage and disease. Also, 20 percent of the trees, randomly chosen in each plot, were measured to the nearest 0.3 m (1 ft) for total height, crown width, and crown length. Upper stem diameters were measured directly on 20 trees per plot to obtain total stem volumes. Selection probability for this sample was proportional to estimated height.

The existing brush understory was measured to explain possible variation in tree growth not attributable to spacing. Three 0.002-ha (0.005-acre) circular brush sampling plots were permanently established at random locations in each tree plot. In each brush sampling plot, the species and mean maximum crown diameter and height of each woody plant were tallied to the nearest 0.03 m (0.1 ft).

Five years later, in fall 1975, when all tree and brush measurements were repeated, growth and vigor of the trees had deteriorated, probably because soil moisture and nutrients were limited by severe brush competition. A brush density treatment, therefore, was superimposed on each stand density plot. Each 0.10-ha (0.25-acre) stand density plot was divided into three equal subplots. All brush tops were manually removed from one-third, left untouched in one-third, and every other brush top, systematically chosen, was manually removed from the final third. Severing the above-ground parts killed most *A. canescens* var. *candidissima* outright because this species does not sprout. But the sprouting *A. roofii* required follow-up cutting. Tree measurements were unaffected except for assigning each tree its appropriate brush subplot. New brush sample plots had to be established, however.

Three brush sampling plots—0.001 ha (0.0025 acre) (half the area of the previous brush sampling plots)—were established at randomly chosen locations in the subplot with full brush. Three more brush sampling plots were established in subplots with half the brush removed. Measurements within the brush sampling plots were the same as in the previous brush sampling scheme. Two growing seasons after the brush was treated, we sampled d.b.h. on 217 trees selected at random within all tree spacings and brush treatments.

Ten years after tree thinning, all measurements were repeated (*table 1*). In addition, annual height growth for the last 5-year period was estimated by measuring internodal distances on a random sample of three trees in each brush-free subplot.

Tree and stand characteristics at the three measurement times were calculated as follows:

• Mean diameter-at-breast-height—d.b.h. of the tree of mean basal area.

• Total height—from a regression of height on d.b.h. calculated from the height sample trees separately on each subplot.

• Crown width and live crown ratio—arithmetic means.

Table 1—*Tree, stand and brush characteristics 5 years after brush treatment in a plantation of sapling ponderosa pines thinned to different spacings*

Tree spacing (m)	Brush Removal	Brush Coverage	D.b.h.	Height	Live crown ratio	Basal area	Total volume
		pct	*cm*	*m*	*pct*	*m²/ha*	*m³/ha*
4.3 by 4.3	None	42	7.6	3.4	65	2.6	4.2
	Half	19	7.0	3.4	64	2.2	3.8
	Full	0	8.4	3.8	77	3.1	5.5
3.0 by 3.0	None	66	6.8	3.2	57	4.2	7.6
	Half	34	7.0	3.3	69	4.1	7.4
	Full	0	7.6	3.5	68	4.3	7.3
2.4 by 2.4	None	39	4.9	2.5	58	3.0	5.7
	Half	19	6.4	3.0	63	4.8	10.0
	Full	0	7.7	3.6	69	6.9	11.9
2.1 by 2.1	None	51	6.4	3.0	59	6.7	10.8
	Half	17	6.6	3.1	62	7.4	12.0
	Full	0	7.3	3.4	65	8.6	16.6

• Stem volumes inside bark in cubic meters from a 0.3-m (1-ft) stump to tip—calculated by Grosenbaugh's (1974) STX computer program.

• Plot volumes immediately after thinning and subsequently were obtained by the following equation:

$$V = \frac{K}{n_j} \bullet \sum_{i=1}^{n_j} \left(\frac{V_{ij}}{est_i} \right)$$

in which

V = plot volume in cubic meters.

K = estimated sum of all tree heights in plot immediately after thinning.

n_j = number of trees measured for upper stem diameters living at time j.

V_{ij} = measured volume of tree i at time j.

est_i = estimated height of tree i.

Periodic annual increments (PAI) during the 5-year period after treating the brush were analyzed statistically (*table 2*). Overall treatment effects on PAI in d.b.h., height, and stem volume were evaluated by a split-plot analysis of variance (*table 3*). Stand and tree responses found statistically significant ($p \leq 0.05$) were evaluated further by multiple range tests or by regressions that included the three additional plots lightly thinned to more than 1480 trees per ha (600/acre).

RESULTS AND DISCUSSION

Without brush control, the plantation growth rate declined in all characteristics from the first to the second 5-year period after tree thinning. Mean PAI of all spacings in the subplots with no brush removal were:

Stand attribute:	*1 to 5 years*	*6 to 10 years*
D.b.h. (cm)	0.38	0.25
Height (m)	0.113	0.073
Basal area (m^2/ha)	0.349	0.308
Volume (m^3/ha)	0.5290	0.5185
Live crown ratio (percent)	−2.2	−2.6

Growth in both diameter and height was only two-thirds of what it had been during the first 5-year period. And basal area and volume growth per hectare, normally expected to increase rapidly at this age, actually declined slightly.

Length of living crown remained almost unchanged during the two 5-year periods. As a result, live crown ratio diminished 2.2 percent annually during the first 5 years, and worsened to 2.6 percent during the second 5-year period. Unless crowns lengthen, in 7 more years the average tree will have only 40 percent of its length in live crown. Ponderosa pine with crown ratios less than 40 percent may experience more growth losses because they apparently lack sufficient foliage to support rapid growth (Hallin 1956).

Brush-Spacing Effects

Analysis of variance showed that 5 years after brush treatment, both tree spacing and brush density, expressed as percent cover of brush crowns, significantly affected PAI of the planted pines (*table 3*).

Diameter Growth

Trees released from brush responded immediately with increased diameter growth. Results of the random sample of trees measured for d.b.h. after two growing seasons indicated a PAI equal to that found after five growing seasons. Average d.b.h. growth regardless of tree spacing was 0.25 cm (0.10 inch) for trees in subplots with full brush, 0.31 cm (0.12 inch) for trees in subplots with half brush, and 0.48 cm (0.19 inch) for trees in subplots with no brush.

Table 2—*Periodic annual increments for 5 years after brush removal in a plantation of sapling ponderosa pines thinned to different spacings*

Tree spacing (m)	Brush: Removal	Brush: Coverage	D.b.h.	Height	Live crown ratio	Basal area	Total volume
		pct	*cm*	*m*	*pct*	*m²/ha*	*m³/ha*
4.3 by 4.3	None	11	0.25	0.07	−2.7	0.15	0.25
	Half	8	.30	.12	−2.1	.16	.29
	Full	0	.61	.19	−1.0	.36	.63
3.0 by 3.0	None	22	.28	.08	−3.1	.30	.60
	Half	12	.32	.11	−1.6	.32	.64
	Full	0	.47	.17	−0.9	.46	.81
2.4 by 2.4	None	10	.22	.07	−2.2	.24	36
	Half	5	.32	.11	1.4	.42	.80
	Full	0	.43	.16	−0.9	.65	1 06
2.1 by 2.1	None	13	.28	.09	2.7	.50	75
	Half	5	.30	.12	2.1	.59	.94
	Full	0	.41	.14	−1.4	.79	1.50

Table 3—*Values of "F" for annual increments during the 5-year period after brush removal in a plantation of sapling ponderosa pines thinned to different spacings*

Source	Df	"F" value when attribute was...		
		D.b.h.	Height	Volume
Block	2	2.18	24.97**	3.33
Trees per ha (T)	3	9.86**	0.92	2.84
Error	6	—	—	—
Brush (B)	2	89.70**	42.16**	7.68**
T × B	6	4.39*	1.08	0.62
Error	12	—	—	—

*Statistically significant at P = 0.05 level.
**Statistically significant at P = 0.01 level.

Periodic annual diameter growth was strongly influenced by both tree spacing and brush cover. Tree spacing had no discernible effect on diameter growth unless all brush was removed (*fig. 1*). When trees were free of brush, differences in annual diameter growth among the spacings were significant between the 0.61 cm (0.24 inch) grown by trees spaced 4.3 m (14 ft) apart and all narrower spacings. The power of the test may have been insufficient to detect further trends.

Diameter growth differences were significant among all three brush treatments when all spacings were combined. Even the overall mean PAI increase of 0.05 cm (0.02 inch) attributable to removing half the brush plants was significant. Removal of all plants increased diameter growth by an additional 0.18 cm (0.07 inch) annually across all spacings.

A significant interaction between tree spacing and brush treatment was detected for PAI d.b.h. (*table 3*). I presume that this statistical interaction is indicative of intertree competition and brush competition working together to suppress diameter growth. Removing brush from around widely-spaced trees allowed trees to grow rapidly because they were free of competition for the site's resources. But removing brush from around closely-spaced trees had less effect on growth because intertree competition still restricted tree growth. In this study, trees spaced 4.3 by 4.3 m (14 by 14 ft) grew 0.36 cm (0.14 inch) more in diameter annually when all brush was removed (*table 2*)—a statistically significant gain. The difference attributable to brush removal narrowed as spacings narrowed until the difference became a nonsignificant 0.13 cm (0.05 inch) annually at the 2.1-m (7-ft) spacing.

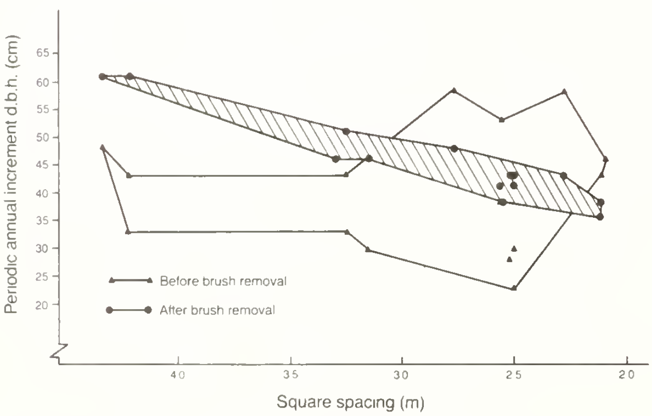


Figure 1—Diameter growth in a sapling ponderosa pine plantation varied widely and was not closely correlated to tree spacing when brush was present.

Another interaction of importance concerns the competitive ability of trees, especially at close spacings, to suppress growth of brush. This question could not be answered by the main analysis of variance. Therefore, 5-year change in both brush crown cover in percent and brush crown volume in the brush subplots were plotted over trees per hectare. No trend of decreasing brush growth with increasing stand density was detected. The reverse was true, however. Increasing brush density restricted tree growth. Apparently, the trees are not exploiting the site's resources to the extent that the site is exploited by the brush.

Because tree spacing, and especially brush treatment, significantly influenced diameter growth, the relationships could be investigated further by regression analysis. Of particular interest was the presence of a threshold value of brush quantity below which brush might not suppress tree growth. But first I had to determine which aboveground attribute of brush was most closely related to tree growth. This question is of significance both to researchers investigating brush effects on tree growth and to forest managers evaluating brush control needs. Bentley and others (1971) expressed brush quantities as crown volume in cubic feet per acre. Dahms (1950) and Barrett (1973) expressed brush quantities as a percent of ground area covered by the vertical projection of their crowns. In this study, both measures were evaluated by comparing their coefficients of linear correlation with PAI d.b.h. of the pines. Crown cover percent yielded a higher correlation (r = 0.71) than did crown volume (r = 0.62). Similar results were found when analyzing the data in a companion study on a highly productive site.[1] Brush crown cover in percent and trees per hectare were the independent variables chosen to predict PAI d.b.h. The equation which fit best and gave biologically defensible solutions was obtained by nonlinear methods:

$$\text{PAI DBH} = \alpha_1 \text{ EXP} \left\{ \frac{\alpha_2 \text{ COV} + \alpha_3}{\text{TPH} + \alpha_4} \right\} + \frac{\alpha_5}{\text{TPH} + \alpha_6}$$

in which

PAI DBH = periodic annual increment in d.b.h. in cm
COV = coverage of brush crowns in percent
TPH = trees per hectare
α_1 = 0.028855
α_2 = −232.920887
α_3 = 7146.815769
α_4 = 2304.065885
α_5 = 3494.315102
α_6 = 13,486.463260

This equation explained 90 percent of the variation for mean diameter growth with a standard error of the estimate of 0.038 cm (0.015 inch).

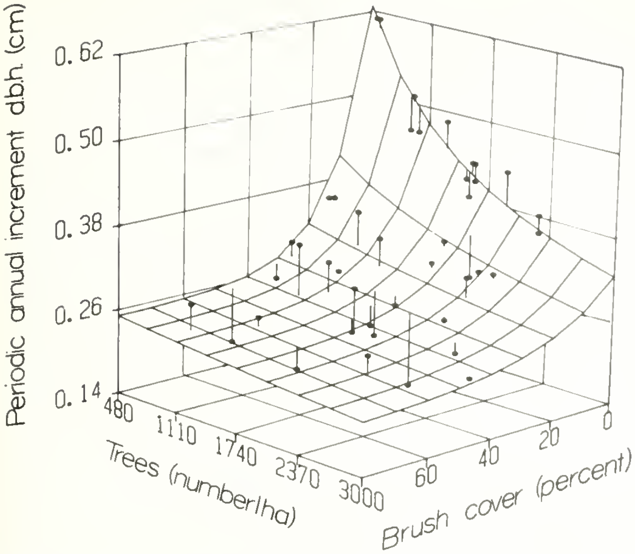


Figure 2—At brush coverages greater than about 30 percent, periodic annual diameter increment of ponderosa pine planted at a poor site was similar regardless of spacing.

A threshold value similar to that reported by Bentley and others (1971) is not apparent from *figure 2*. The equation suggests that, for this plantation at least, any amount of brush will restrict diameter growth, and only when brush cover is light will spacing exert an influence. At coverages greater than about 30 percent, brush competition overwhelms intertree competition and the response surface becomes almost horizontal. Trees at all spacings grow about 0.23 cm (0.09 inch) annually. Thirty percent crown cover was recommended by Kirchner and others (1978) as the density at which brush control efforts should begin. They based their recommendation on comparative heights of pine seedlings in plantations in the southern Sierra Nevada on sites more productive than Trough Springs Ridge.

Height and Volume Growth

In contrast to diameter growth, height growth response was delayed for 2 years after brush removal. Regardless of spacing, trees in brush-free subplots grew 0.11 m (0.36 ft) annually for the first 2 years. Then height growth jumped to 0.19 m (0.63 ft) annually for the next 3 years.

Growth in mean height and stem volume per hectare were not significantly influenced by spacing (*table 3*). The hypothesis that random variation caused the apparent tendency of brush-free trees to grow faster at wider spacings could not be rejected (*table 2*). The strong trend of increasing stem volume growth per hectare with closer spacings usually found in sapling stands was not statistically significant in this study probably because of differences in initial tree size among plots thinned to different spacings.

Brush treatment, however, exerted a statistically significant influence on growth in mean height and stem volume per hectare. Height growth was particularly sensitive to brush removal. Even removing half the brush significantly improved height growth, although the overall difference was only 0.04 m (0.12 ft) per year. Stem volume production per hectare per year rose 0.51 m^3 (7.3 ft^3/acre) overall when all brush was removed, a 29 percent increase in production over untreated brush plots ($p < 0.05$). Removing half the brush, however, did not result in a significant rise in annual production.

Mortality and Damage

Only seven trees died during the two periods reported—too few to relate to tree spacing or brush density. Insect damage was abundant and widespread, however. The larval feeding of many insect species on tree branches, buds, and the main stem deformed tops and resulted in loss of foliage. The two insects causing the most noticeable damage were the Sequoia pitch moth (*Vespamima sequoiae* Hy. Edwards) and the gouty pitch midge (*Cecidomyia piniinopis* Osten Sacken). Many others were not identified.

The larvae of the Sequoia pitch moth bore in the cambial region causing masses of pitch to form (Furniss and Carolin 1977). Indeed, resin flow from injured pines may promote pitch moth attacks (Powers and Sundahl 1973). And, presumably, because more vigorous trees produce more resin, tree thinning and brush removal, by increasing tree vigor, may be expected to promote more pitch moth attacks.

No relationship was found between tree spacing, brush density, or tree vigor (as measured by d.b.h. growth) and Sequoia pitch moth attack. Diameter growth of trees with pitch masses was similar to that of the average tree in each plot. About 74 trees per ha (30/acre) regardless of tree spacing or brush density seem to have been attacked within the past 3 years (as gauged by freshness of pitch masses). This level of attack appears to have been maintained in the plantation for many years.

Larval mining by the gouty pitch midge is the other prominent insect-caused damage. This mining scarred and twisted branches, caused resin exudations, and killed tops.

Deformed tops were counted in an attempt to quantify the amount of damage from attacks of the gouty pitch midge and other insects. The tops were chosen because they are easily measured and are a significant cause of growth loss. Tree spacing was found to be unrelated to incidence of top deformities but brush crown cover was related. The proportion of trees with deformed tops was correlated positively and significantly ($p < 0.01$) with brush crown cover. About 10 percent of the trees in brush-free subplots suffered deformed tops. The incidence doubled to 23 percent in plots with 60 percent brush crown cover.

The results of insect-caused top deformities taken from small plots probably are representative of results expected in practice from large plots. Greater amounts of insect damage with greater amounts of brush were noted in another ponderosa pine plantation (McDonald 1982). At first, I speculated that larger differences may have been masked because insects moved freely into and through adjacent subplots with widely differing brush and tree spacing treatments. Probably, however, these insects successfully attacked trees regardless of vigor, and vigorous trees are better able to withstand larval mining with only minor damage.

MANAGEMENT IMPLICATIONS

The history of the plantation on Trough Springs Ridge is a common one in northern California. A wildfire burned a stand of the Pacific Ponderosa Pine–Douglas-fir forest type on an exposed site with a shallow, skeletal soil. The area was planted with ponderosa pine that survived well, but manzanita brush invaded the plantation almost immediately. Eleven years after planting, brush competition was suppressing tree growth severely.

What options are available to the manager of such a plantation? If nothing is done, brush competition and insect attacks seem likely to continue and, possibly, intensify. Trees in the plantation on Trough Springs Ridge, which should have been growing 0.66 cm (0.26 inch) in diameter and 0.27 m (0.9 ft) in height annually (Oliver and Powers 1978), were growing only 0.38 cm (0.15 inch) in diameter and 0.07 m (0.24 ft) in height. And these rates were decelerating at an age when they should have been accelerating. How long this 10-year trend will continue can be speculated only. But yields certainly will be reduced and rotations lengthened. In projecting McDonald's (1982) data and those of others, Fiske (1982) estimated that trees competing with brush densities rated medium or heavier would take 10 years longer to reach diameters targeted for 55-year-old trees. Basal area targets could be delayed 3 to 5 decades because of higher tree mortality rates in dense brush. In his projection, Fiske assumed that on a medium site, brush would suppress pine growth for 30 years. Older trees were expected to grow at the same rate as trees free of brush. Greater losses are anticipated if current trends are projected. Nineteen-year trends of volume growth of ponderosa pine competing with mountain misery (*Chamaebatia foliolosa* Benth.) were projected to age 50 by Tappeiner and Radosevich (1982). They estimated a 75 percent reduction in net wood production from understory competition.

Investments in cultural treatments such as thinning and fertilizing may be wasted if brush is not controlled. Trees spaced 1.8 by 1.8 m to 4.6 by 4.6 m (6 by 6 ft to 15 by 15 ft) all grew at about the same rate in diameter when brush coverage was greater than 30 percent. Conversely, close spacing of trees did not restrict brush growth effectively. Results suggest instead that brush is better able to exploit the site's resources than is the pine. Nitrogen fertilization, for example, failed to stimulate ponderosa pine growth unless manzanita brush was eliminated (Powers and Jackson 1978).

If the manager elects to control brush, growth may increase dramatically. Depending on spacing, brush-free trees on Trough Springs Ridge grew 45 to 140 percent faster in diameter and 62 to 170 percent faster in height than trees in dense brush. Elsewhere, smaller but consistent growth rate differentials have been maintained for 12 years (Barrett 1973).

Practicable brush control methods do not eliminate all brush. And, unless these methods can be expected to reduce brush coverage substantially over a major portion of the early stand life, benefits to tree growth and health may be fleeting at best. I conclude at Trough Springs Ridge that even small amounts of brush can restrict tree growth markedly. Brush coverage had to be less than 20 to 30 percent before tree growth response was noticeable.

The major growth losses from brush competition experienced at Trough Springs Ridge should prevail in similar plantations on sites of low productivity. If true, the cost of brush control should be included as an integral part of the regeneration cost. If, however, brush control is not planned, yields and rotations should be adjusted accordingly.

REFERENCES

Barrett, James W. **Latest results from the Pringle Falls ponderosa pine spacing study.** Res. Note PNW-209. Portland, OR: Pacific Northwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1973. 22 p.

Barrett, James W. **Silviculture of ponderosa pine in the Pacific Northwest: the state of our knowledge.** Gen. Tech. Rep. PNW-97. Portland, OR: Pacific Northwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1979. 106 p.

Bentley, Jay R.; Carpenter, Stanley B.; Blakeman, David A. **Early brush control promotes growth of ponderosa pine planted on bulldozed site.** Res. Note PSW-238. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1971. 6 p.

Dahms, Walter G. **The effect of manzanita and snowbrush competition on ponderosa pine reproduction.** Res. Note 65. Portland, OR: Pacific Northwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1950. 3 p.

Eyre, F. H., ed. **Forest cover types of the United States and Canada.** Washington, DC: Society of American Foresters; 1980. 148 p.

Fiske, John N. **Evaluating the need for release from competition from woody plants to improve conifer growth rates.** In: Proceedings of the 3d annual forest vegetation management conference; 1981 November 4-5; Redding, CA. Redding, CA: Forest Vegetation Management Conference; 1982: 25-44.

Furniss, R. L.; Carolin, V. M. **Western forest insects.** Misc. Publ. 1339. Washington, DC: U.S. Department of Agriculture; 1977. 654 p.

Gankin, Roman. **A new species of *Arctostaphylos* from Glenn County, California.** Leaflets of Western Botany 10(16): 329-331; 1966.

Grosenbaugh, L. R. **STX 3-3-73: tree content and value estimation using various sample design, dendrometry methods, and V-S-L conversion**

coefficients. Res. Paper SE-117. Asheville, NC: Southeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture; 1974. 112 p.

Hallin, William E. **Pruning ponderosa and Jeffrey pine.** Forest Res. Note 115. Berkeley, CA: California Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1956. 4 p.

Kirchner, W.; Bradley, B.; Griffin, S. **The effect of brush competition on conifer plantation growth on the Sequoia National Forest and recommended release schedules.** 1978; 11 p. Available from: Sequoia National Forest, Porterville, CA 93257.

McDonald, Philip M. **Pest vegetation problems in ponderosa pine management.** In: Executive summaries of the proceedings of the 1981 western forestry conference. Western Reforestation Committee; 1981 December 1-3; Sun Valley, ID. Portland, OR: Western Forestry and Conservation Association; 1982: 45.

Oliver, William W. **Early response of ponderosa pine to spacing and brush: observations on a 12-year-old plantation.** Res. Note PSW-341. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1979. 7 p.

Oliver, William W.; Powers, Robert F. **Growth models for ponderosa pine: I. Yield of unthinned plantations in northern California.** Res. Paper PSW-133. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1978. 21 p.

Powers, Robert F.; Jackson, Grant D. **Ponderosa pine response to fertilization: influence of brush removal and soil type.** Res. Paper PSW-132. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1978. 9 p.

Powers, Robert F.; Oliver, William W. **Site classification of ponderosa pine under stocking control in California.** Res. Paper PSW-128. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1978. 9 p.

Powers, Robert F.; Sundahl, William E. **Sequoia pitch moth: a new problem in fuel-break construction.** J. For. 71(6): 338-339; 1973 June.

Tappeiner, John C., II; Radosevich, Steven R. **Effect of bearmat (*Chamaebatia foliolosa*) on soil moisture and ponderosa pine (*Pinus ponderosa*) growth.** Weed Sci. 30(1):98-101; 1982 January.

U.S. Department of Agriculture, Forest Service. **Forest Service Manual 2476.42—Thinning.** Region 5 Supplement No. 124, 1973. San Francisco, CA: Pacific Southwest Region, Forest Service, U.S. Department of Agriculture; 1973. 7 p.

Zinke, Paul J. **Site quality for Douglas-fir and ponderosa pine in northwestern California as related to climate, topography and soil.** In: Society of American Foresters Proceedings 1958. Washington, DC: Society of American Foresters; 1959: 167-171.

Oliver, William W. **Brush reduces growth of thinned ponderosa pine in northern California.** Res. Paper PSW-172. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1984. 7 p.

The effects of tree spacing and brush competition were evaluated on a ponderosa pine (*Pinus ponderosa* Dougl. ex Laws. var. *ponderosa*) site of low productivity in California's North Coast Range. Eleven-year-old saplings were thinned to square spacings of 2.1, 2.4, 3.0, and 4.3 m (7, 8, 10, and 14 ft), and all, half, and none of the understory brush (principally manzanita [*Arctostaphylos* sp.]) manually removed in a split-plot design. Analysis of variance showed that brush crown cover was significantly related to periodic annual increment in diameter-at-breast-height, height, and volume of the pines. Spacing significantly influenced diameter growth only when all brush was removed. A nonlinear equation relating brush cover and trees per hectare to periodic annual increment in diameter explained 90 percent of the variation. The results suggest that, for the plantation studied, any amount of brush will restrict diameter growth. When cover exceeds 20 to 30 percent, brush competition overwhelms intertree competition, and trees grow at about the same rate regardless of spacing.

Retrieval Terms: Pinus ponderosa, Arctostaphylos sp., plantation management, vegetation management, tree growth, North Coast Range, California

United States
Department of
Agriculture

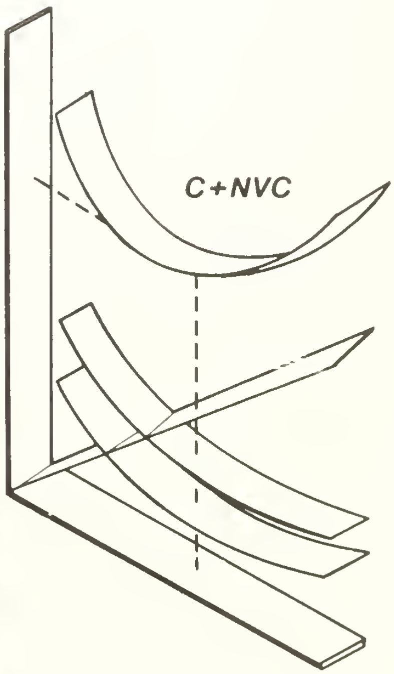
Forest Service

**Pacific Southwest
Forest and Range
Experiment Station**

Research Paper
PSW-173

Estimating Postfire Changes in Production and Value of Northern Rocky Mountain-Intermountain Rangelands

David L. Peterson Patrick J. Flowers



The Authors:

DAVID L. PETERSON is a research ecologist assigned to the Station's Fire Management Planning and Economics Research Unit, headquartered at the Forest Fire Laboratory, Riverside, California. He earned a bachelor's degree in zoology (1976), a master's degree in botany (1977), and a doctor of philosophy degree in plant ecology (1980), all from the University of Illinois, Urbana-Champaign. He joined the Station staff in 1981 after serving on the faculty of the Department of Forestry, University of Illinois. **PATRICK J. FLOWERS** was formerly a research forester with the Station's Fire Management Planning and Economics Research Unit. He is now an economist with the Montana Division of Forestry, Missoula. He earned a bachelor's degree in forestry (1978) and master's degree in forest economics (1981) at the University of Montana, Missoula.

Acknowlegments:

We thank Edward Schrantz and Joyce Simmons for assistance with programming; Gary Carson, William F. Davis, Gardner Fairey, Lisle R. Green, Robert W. Hamner, Billy H. Hardman, and Vern Schultz, for information on various aspects of range management; and Donald J. Bedunah, Melvin D. Bellinger, Carlton M. Britton, Billy H. Hardman, and Henry A. Wright, for helpful comments in reviewing the manuscript.

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

December 1984

Estimating Postfire Changes in Production and Value of Northern Rocky Mountain–Intermountain Rangelands

David L. Peterson Patrick J. Flowers

CONTENTS

IN BRIEF ...

Peterson, David L.; Flowers, Patrick J. **Estimating postfire changes in production and value of Northern Rocky Mountain-Intermountain rangelands.** Res. Paper PSW-173. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1984. 19 p.

Retrieval Terms: fire economics, fire effects, net value change, range management, simulation model, transitory range

A simulation model was used to estimate expected postfire changes in the production and value of grazing lands in the Northern Rocky Mountain–Intermountain region. Ecological information and management policy decisions were used to simulate expected changes in range production following wildfire. An investment analysis procedure was used to calculate the net value change (NVC) of postfire range outputs. Physical output and economic changes were determined by subtracting "with fire" values from "without fire" values for a simulated postfire time stream.

Six major rangeland types were evaluated: permanent forested range (ponderosa pine), transitory range (Douglas-fir, larch, lodgepole pine, western white pine), mountain grassland, sagebrush, pinyon–juniper, and western hardwoods.

The magnitude and duration of postfire changes in production varied widely among these different range types. Transitory rangeland can be grazed for approximately 20 years after a stand replacement fire, with a substantial gain in grass and shrub production during this time. Losses occur later in the postfire time stream because of harvests that occur in the "without fire" situation (that is, harvests that would normally occur in the absence of fire). The early gains weigh heavily in the financial return calculation, however, and NVC is highly negative (that is, a gain in net value) for most situations. Net value change for a seedling–sapling stand utilized at 40 percent of total production and discounted at a rate of 4 percent is –$26.69 per acre. Small losses in net value are found only for recently cutover stands.

In most situations, the production of ponderosa pine range increases immediately postfire. These increases are especially large for older age classes that have high mortality. Removal of the overstory allows understory production to increase. Initial postfire gains again outweigh any subsequent losses in the financial return calculation. A maximum NVC of –$35.96 per acre was calculated for a sawtimber stand with 100 percent mortality (40 percent utilization, 4 percent discount rate). Seedling–sapling and recently cutover stands have small to moderate losses of production and value because the loss of production resulting from grazing deferral is greater than subsequent gains in yield.

Fire effects are shortlived for mountain grassland. Losses in production result from decreased forage and deferred grazing. A maximum decrease in net value of $7.06 per acre was calculated for mountain grassland range that burned in late summer (40 percent utilization, 4 percent discount rate).

Fire produces a substantial increase in forage production of sagebrush range for about 20 years. Removal of the shrub overstory allows grasses to dominate until sagebrush reinvades the site. A maximum NVC of –$16.61 was calculated for sagebrush range (40 percent utilization, 4 percent discount rate).

Long-term increase in production is common for pinyon–juniper range after fire, although annual increases are relatively small. Removal of the overstory allows forage production to remain above prefire levels for about 90 years. A maximum NVC of –$10.87 was calculated for pinyon–juniper range (40 percent utilization, 4 percent discount rate).

A small increase in forage production is common on western hardwoods rangeland after a fire that removes the overstory. Postfire increases last for about 7 years, but are small compared with losses from deferred grazing. As a result, small overall losses occur in production and value. A maximum decrease in net value of $1.38 was calculated for western hardwoods range burned in summer (40 percent utilization, 10 percent discount rate).

The estimates generated in this study allow decision-making on the basis of changes in production, changes in value, or a combination of both. They can be used in fire management planning in the Northern Rocky Mountains and for other aspects of resource management that require estimates of changes in postfire range production and value.

The National Forest Management Act of 1976 requires Forest Service managers to analyze their land management planning activities, formulate and evaluate management alternatives, and select an alternative on the basis of explicit criteria (U.S. Dep. Agric., Forest Serv. 1982). Fire management programs for the National Forests are required to be part of integrated land management and to be economically efficient (U.S. Dep. Agric., Forest Serv. 1979). Agency resource planners, therefore, need data and analytical procedures that will enable them to estimate long-term changes in resource yields and values. And they need to predict accurately any changes in resource outputs and values resulting from wildfire.

Range is one of the major resource categories for which the effects of wildfire must be estimated. In the northern Rocky Mountain–Intermountain area—Idaho, western Montana, western Wyoming, eastern Oregon, eastern Washington—several grassland, shrub, and forest ecosystems are used by cattle for grazing. Although site-specific information on fire effects is available for many rangeland types (for example, Wright and Bailey 1982), considerable time and effort are required to assimilate this information and translate it into a form that is meaningful for range management. Simulation techniques are now available to provide estimates of postfire changes in range production and value in a format compatible with the broad resolution applications required for land management planning (Mills and Bratten 1982). These estimates may also be useful for quantifying resource effects in analyzing escaped fires.

The difficulties associated with the identification and valuation of fire effects were first described by Flint (1924). Since this early review, numerous studies have addressed the theoretical and practical aspects of estimating the physical and financial effects of wildfire (for example, Crosby 1977, Lindenmuth and others 1951, Marty and Barney 1981). Few fire effects studies consider range effects in any detail. One study estimated range values-at-risk by multiplying total annual range production in animal-unit months (AUM), a fee per AUM, and a capitalization factor (U.S. Dep. Agric., Forest Serv. 1971). Another estimated range values-at-risk as the product of total annual range production (AUM) and a fee per AUM (Lewis and others 1979). This study was unique in applying no capitalization factor, and in distinguishing between annual production on wooded and improved pasture. Another study suggested that immediate forage value lost be estimated as the product of AUM destroyed and a fee per AUM (Marty and Barney 1981). The current value of future changes in forage revenues was added to immediate losses to obtain an estimate of the total change in forage revenues resulting from fire. In a study of six National Forests, 7 years of range effects were considered (Schweitzer and others 1982). The 7-year change in AUMs was multiplied by dollars per AUM. The analysis was simplified by assuming that the total 7-year change occurred in the third year, and this sum was then discounted to the present.

All of the studies described consider only the immediate and short-term (that is, less than 20 years) effects of fire on range. This approach is appropriate for only those range types in which timber is not found. In an optimization analysis, Ritters and others (1982) describe the interaction between the joint products of timber and range. This interaction should be considered in the valuation of fire effects. The cycle of range production in timbered areas depends upon the developmental stage of the timber. Forage production in a timbered area, for example, may be high in the seedling–sapling stage of stand development, but diminishes as the stand matures because of canopy closure and increased competition for light and moisture. If timber stand development is altered by fire, the cycle of forage availability is also interrupted. Interruptions in this forage cycle shift the timing of the perpetual series of forage cycles that follow. The shifting or long-term effect has been ignored in previous work of range fire effects and may significantly affect estimates of fire-caused net value change in the range resource.

Fire damage can be estimated as the difference in the value of affected resources before and after fire (Althaus and Mills 1982, Flint 1924). The value of a resource has been described as follows: "...the value of any productive resource equals the sum total of its future economic rents discounted back to the present" (Barlowe 1958, p. 169). Fire-caused value change in range, therefore, is estimated as the net present value of the time stream of economic rents found in the "without fire" situation, less the time stream found in the "with fire" situation.

This paper provides estimates of postfire changes in production and value of grazing lands in Northern Rocky Mountain–Intermountain rangelands. The estimates generated by computer simulation can aid resource managers in fire management planning and in integrating fire management with land management planning.

MODEL DESIGN

A simulation model was used to predict the effects of fire on range production *(fig. 1)*. A set of parameters describes some general features of the simulated rangeland and fire occurrence. The composite generated should be thought of as a generic fire site, or a kind of fire, because it does not describe an actual geographic location. All of the fire and site parameters are used by a fire behavior simulation system (Salazar and Bradshaw, in prep.). This system associates these parameters with historical weather records and calculates fire behavior characteristics such as scorch height (Van Wagner 1973) on the basis of the physical description of fuels and terrain.

Two basic submodels are included in the overall range model: the Timber Submodel simulates the effects of fire on forested areas for grazing, and the Nontimber Submodel simulates fire effects for grassland and shrubland range types. If the cover type parameter indicates a forested rangeland, fire-caused mortality is simulated before the data are used in the Timber Submodel. Percent basal area killed is determined for a simulated stand from the scorch height value generated by the fire behavior simulation (Peterson 1983). Subroutines that have been developed for each individual range type calculate forage production over time both with and without the presence of fire. Forage production is then adjusted on the basis of forage utilization level (in this study, 25 percent and 40 percent of total production are used in simulations). This adjustment can be related to a site parameter such as slope, elevation, or both, or can simply be a default value that is multiplied by forage production.

Range production over time can then be calculated in terms of animal-unit months for the "with fire" and "without fire" situations. The change in range production over time (ΔAUM) is calculated by subtracting "with fire" output from "without fire" output (Mills and Bratten 1982). As a result, *positive numbers represent a loss in grazing output, and negative numbers represent a gain.* After the point at which simulations indicate that "with fire" outputs stabilize at prefire levels, we assume that no change in outputs occurs for the balance of the 200-year analysis period and that no fires occur subsequently.

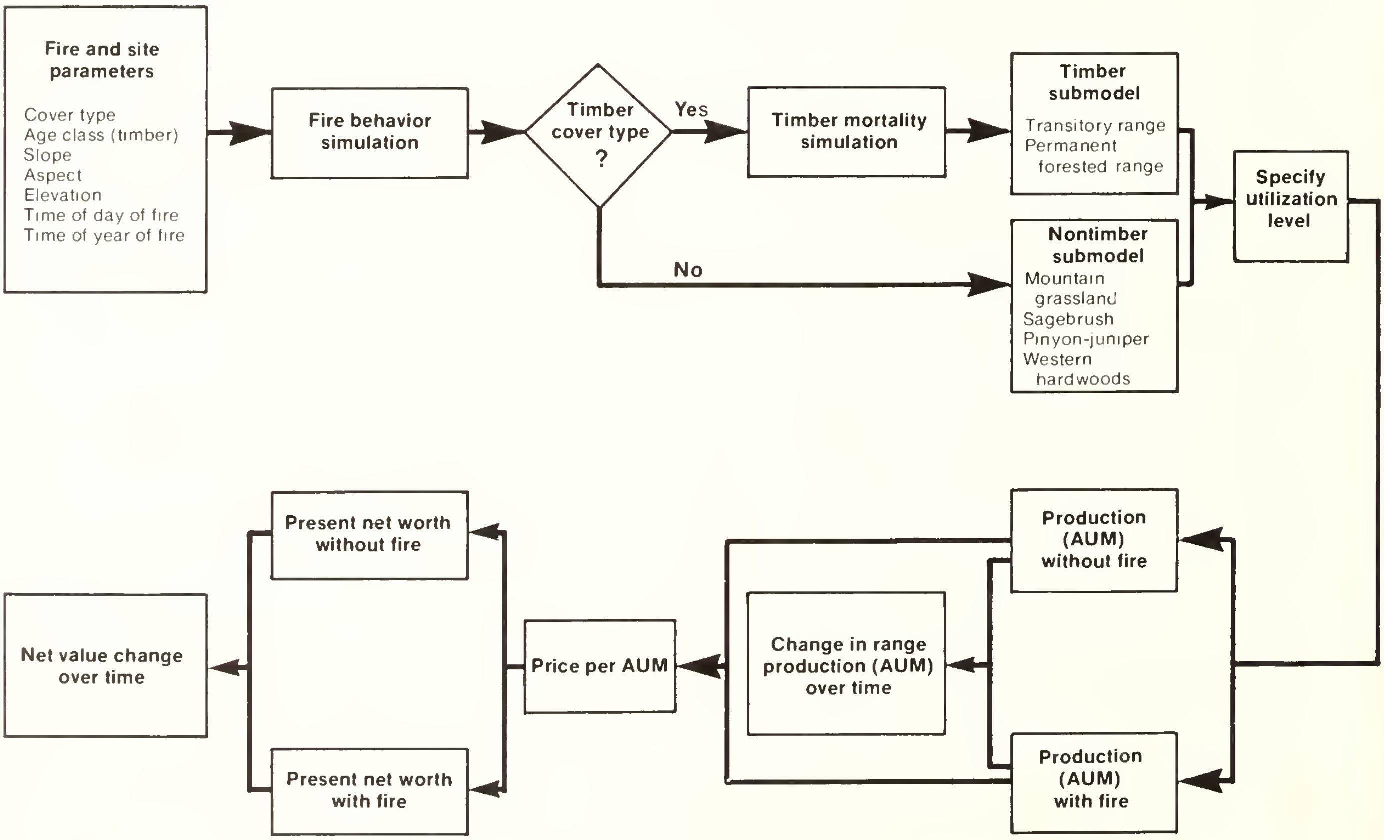


Figure 1—A simulation model was used to estimate the effects of wildfire on rangeland yield and values. The model includes two submodels: one for timber, and the other for nontimber range types.

The net value change of range output is determined through a straightforward financial return calculation. Prices are assigned to "with fire" and "without fire" AUM production values, and a given discount rate is used to calculate present net worth (PNW) for both series of values. Net value change (NVC) of range output is then calculated by subtracting the PNW of the "with fire" series from the PNW of the "without fire" series. Similar to the ΔAUM values, *positive NVC represents a loss in range value, and negative NVC represents a gain.*

Geographic Area and Range Types

The modeling procedures discussed were developed for the Northern Rocky Mountain–Intermountain fire climate zone (Schroeder and others 1964). This region has relatively homogeneous synoptic weather patterns with respect to conditions that affect fire occurrence. Pacific and Northwest Canadian high pressure systems are generally associated with periods of high fire occurrence in this region.

Cover types used to identify rangelands in the model are based on Forest and Range Ecosystem Study (FRES) ecosystem types (Garrison and others 1977). Eleven major ecosystem types are found in the Northern Rocky Mountain–Intermountain climate zone: ponderosa pine, Douglas-fir, lodgepole pine, larch, western white pine, fir–spruce, hemlock–Sitka spruce, mountain grassland, sagebrush, pinyon–juniper, and western hardwoods.

The hemlock–Sitka spruce (mainly western hemlock [*Tsuga heterophylla*] and western redcedar [*Thuja plicata*]), and fir–spruce (mainly subalpine fir [*Abies lasiocarpa*] and Engelmann spruce [*Picea engelmannii*]) timber types are generally not used for grazing (Mueggler 1962, Garrison and others 1977) and are not included in this analysis. Douglas-fir *(Pseudotsuga menziesii)*, lodgepole pine *(Pinus contorta)*, larch *(Larix occidentalis)*, and western white pine *(Pinus monticola)* rangelands are generally grazed only during a 20-year period after timber harvest or a stand replacement fire. These four timber types are grouped as transitory range and are modeled within a single subroutine. Ponderosa pine *(Pinus ponderosa)* rangeland is normally grazed for a much longer period of time than transitory rangeland types and is included in a discrete subroutine. Mountain grassland, sagebrush, pinyon–juniper, and western hardwoods are all modeled in discrete subroutines

Definitions, Assumptions, Decisions

Most of the information and data sources used in the development of this model were derived from literature on the effects of fire on rangeland. A limited amount of reliable quantitative information on some range types was available, however, and literature sources sometimes offered conflicting results. Also, it was sometimes difficult to establish what "typical" range composition and conditions were and what "typical" responses to fire were. These problems were resolved through objective judgments on the relative value of information sources in consultation with experts on range management.

The unit of measure used to express range production is the animal-unit month (AUM), the amount of forage consumed per animal unit per month, with an animal unit defined as a 1000-lb (454-kg) cow. The daily production ration varies depending on type of forage and location. In this study, a daily production ration of 30 lb (14 kg) is assumed for all range types, so an AUM is equivalent to 900 lb (409 kg) of forage—that portion of vegetative production that is usable for consumption by cattle. Forage consumption by wildlife is not considered in the model, although it is recognized that cattle and wildlife interact on some rangelands.

Because it has not been demonstrated that consistent differences exist among most grazing systems with respect to long-term productivity (Currie 1978), grazing systems are not considered in simulations developed for this model. Length of grazing season varies depending on the elevation of the range and the cover type. Two elevation classes are used as values in the model: ≤ 4500 ft (1400 m) and > 4500 ft (1400 m). Grazing seasons were determined through consultation with range experts and are incorporated into individual subroutines for each cover type. We assumed that grazing is distributed equally throughout the grazing season rather than concentrated at any particular time.

In the model, the effects of fire on range are simulated for wildfire only. In the Timber Submodel, burn intensity (expressed as scorch height) determines the proportion of tree mortality, which is then used in the simulation of subsequent forage production. In the Nontimber Submodel, we assumed that wildfires occur only during years when fuels are dry enough to carry a fire, resulting in a high-intensity fire. This assumption is based on inferences from several literature sources and expert opinion. Fire occurrence data from the historical records of Forest Service Northern (R-1), Intermountain (R-4), and Pacific Northwest (R-6) Regions suggest that fires rarely occur in nontimber cover types unless weather and fuel conditions are conducive to high-intensity fires (Bratten 1982). As a result, burn intensity is not an input to the Nontimber Submodel.

Fire effects are simulated for two time-of-year classes: spring and late summer. The specific fire dates used in the model are May 15 and August 15, respectively. The effects of fire on variables such as nutritional value of forage and dispersal patterns of cattle on the range (for example, cattle may concentrate in certain areas) are difficult to simulate and are not considered in this model. Substitution of alternative range sites for grazing is not an option in the model; any loss of range production resulting from fire is considered an actual loss that cannot be compensated for through substitution.

MODELING POSTFIRE CHANGES

Six subroutines in the model simulate the effects of wildfire on the major rangeland types found in the Northern Rocky Mountain–Intermountain region. Ponderosa pine and transitory range—Douglas-fir, lodgepole pine, western white pine, and larch cover types—subroutines are contained in the Timber Submodel. Mountain grassland, sagebrush, pinyon–juniper, and western hardwoods subroutines are contained in the Nontimber Submodel *(fig. 1)*.

Transitory Range

Transitory ranges are forested ranges that are used for grazing for a limited period of time after harvest or a stand replacement fire. Transitory ranges are considered separately from permanent forest range (ponderosa pine) that can be grazed at any stand age.

Information on cover type and age class from the fire and site parameter list, and estimated scorch height from the fire behavior simulation process are inputs to the timber mortality simulation process *(fig. 1)*, which calculates proportion of basal area killed in the stand. Elevation, as it relates to length of grazing season, and time-of-year of fire, are not required inputs. Mortality is simulated for stands based on the Northern Region's timber inventory data, by cover type and age class. The proportion of timber killed determines if a stand is retained or if it is completely salvaged and regenerated. The stand retention decision is based on information obtained from the Northern Region's silviculture staff (Wulf 1982). Stands are retained for these age classes only:

Age class:	Proportion of basal area killed
Seedling–sapling	< 0.85
Pole	$< .70$
Sawtimber	$< .70$

The basal areas indicated are considered to be the maximum losses that can be incurred without reducing stocking below minimally acceptable levels. If the stand is not retained, range production is simulated for the regenerated stand. Also available is a recently cutover age class for which the stand retention decision rules are not used. Recently cutover is defined as 2 years postharvest.

Useful quantities of forage are produced on cutover or burned stands for about 20 years after tree removal (Basile and Jensen 1971, Davis 1982, Hardman 1982). Most studies to date on vegetal development after fire or harvest have evaluated percent cover only (Lyon 1971, Lyon 1976, Lyon and Stickney 1976, Stickney 1980). On the basis of one of the few studies done on forage production after clearcuts (Basile and Jensen 1971), peak understory production is estimated to be 900 lb per acre (1010 kg/ha) for a lodgepole pine stand. Peak understory production on Douglas-fir clearcuts was 1100 lb per acre (1240 kg/ha)(Lewis 1965). Production values are not available for other transitory range types. The value of 900 lb per acre is used in the model to represent lodgepole pine only, but 1100 lb per acre is used for Douglas-fir and for larch and western white pine. Of the understory production in this range type 70 percent is usable forage (Mueggler and Stewart 1980), so 630 lb per acre (710 kg/ha) and 770 lb per acre (860 kg/ha) are considered peak forage production values in this subroutine. Understory production may vary greatly depending on forest type and geographic location. It is reasonable to group transitory range types in this manner, however, because of the broad resolution of the model and the lack of production data.

The pattern of understory production after stand removal is described mathematically as (Basile and Jensen 1971):

$$p = (p_m) \exp [(-0.01667)(a_s - a_m)^2] \qquad (1)$$

in which

p = understory production
p_m = maximum understory production
a_s = stand age after harvest (years)
a_m = age of maximum understory production (years)

A consensus of the studies cited earlier indicates that peak production occurs approximately 10 years after stand removal, so $a_m = 10$. Because forage production (f) equals 0.7 p and $p_m = 900$, forage production for each year after stand removal is:

$$f = (0.7)(900) \exp [(-0.01667)(a_s - 10)^2], \qquad (2)$$

for the values $a_s = 1, 2, 3, \ldots 20$. Because *year 1 of the model output is defined as the year of the fire*, f is calculated through year 21.

Grazing is not permitted in the year of the fire and is generally deferred for years 2 and 3 to permit seedling establishment (Davis 1982). The change in range production (ΔAUM) = 0 for years 1 to 3 because grazing would not have occurred in the absence of fire. For all age classes except the recently cutover class, a net gain in forage occurs for years 4 to 21. The one exception is lodgepole pine in the seedling–sapling age class. In this situation, grazing would have occurred in years 1 and 2 without fire because stand age = 20 for this cover type–age class combination. Consequently, a loss of AUMs occurs in years 1 and 2. Postharvest (or postfire) management actions are summarized as: (a) stand harvested (or salvaged) in year 1, (b) stand regenerated (planting or germination) in year 2, deferred from grazing, (c) stand deferred from grazing in year 3, (d) grazing begun in year 4.

In both the "with fire" and "without fire" situations, physical changes in grazing outputs are evaluated within the 200-year analysis period at appropriate points in time when harvest occurs. Forest planning documentation from the Northern Region indicates that average rotation age is about 125 years for Douglas-fir, western larch, and western white pine, and 100 years for lodgepole pine. The Northern Region's inventory data were used to determine the following mean ages for each age class:

Age class:	Lodgepole pine	Douglas-fir, western larch, western white pine
Seedling-sapling	20	30
Pole	50	60
Sawtimber	80	100

The presence of fire induces a sequence of discrete periods of gain and loss in AUMs for all age classes. In situations in which a stand is not retained, the range production that would have been realized after a future harvest is shifted to an earlier point in time. This shift affects the timing of all future timber harvests and associated grazing. Because the cutover age class is defined as 2 years post-harvest, range production begins in the "without fire" situation in year 2, and continues through year 19. This production results in an initial loss in AUMs followed by a gain, because the "with fire" and "without fire" grazing sequences overlap.

Permanent Forested Range (Ponderosa Pine)

The ponderosa pine cover type can generally be used for grazing if canopy cover is less than 60 percent (Carson 1982). If canopy cover is greater, forage production in the understory is insufficient to support grazing (Jameson 1967, Pase 1958). Mathematical relationships between basal area and understory production, and between canopy cover and understory production have been developed for ponderosa pine by Pase (1958):

$$\log p=3.22-0.00936b \qquad (3)$$

$$\log p=3.33-0.0247c \qquad (4)$$

in which

p=understory production (lb/acre)

b=basal area (ft^2/acre)

c=canopy cover (pct).

If equation 4 is solved for p in which c=60, and is substituted in equation 3, then basal area (b) is calculated to be 146 ft^2 per acre (33 m^2/ha). Forest inventory data from the Northern Region indicate that mean basal area of ponderosa pine is less than 146 ft^2 per acre even at rotation age. It is assumed for modeling purposes, therefore, that ponderosa pine can be used for grazing throughout the life of the stand.

Cover type, age class, and time-of-year of fire are required inputs for this subroutine. Mean basal area and stand age for each age class have been determined from forest inventory data from the Northern Region. The mean values are:

Age class:	Basal area (ft^2/acre)	Age (yrs)
Seedling-sapling	45	30
Pole	55	40
Sawtimber	96	90

Mean rotation age for ponderosa pine is about 125 years, on the basis of silvicultural practices currently used in the Northern Region. Mean basal area at harvest is 120 ft^2 per acre (27 m^2/ha). By using data on basal area and age, we developed a simple relationship:

$$b=12.7a^{0.5}-25.6 \qquad r^2=0.99 \qquad (5)$$

in which

b = basal area (ft^2/acre)(if $b < 0$, the value of b is set equal to 0)

a = age (yrs).

This equation can be used to simulate basal area throughout the growth of the stand *(fig. 2).*

Similar to the decision process of the transitory range subroutine, stand retention depends upon the proportion of basal area killed. The decision rule is the same one used with the transitory range: the stand is retained if basal area killed is <85 percent for the seedling-sapling age class, or <70 percent for pole and sawtimber age classes. If the stand is retained, growth of the stand is simulated until the end of that rotation.

Understory production is estimated from the relationship developed by Pase (1958):

$$p=10^{3.22-0.00936b} \qquad (6)$$

in which

p = understory production (lb/acre)

b = basal area (ft^2/acre).

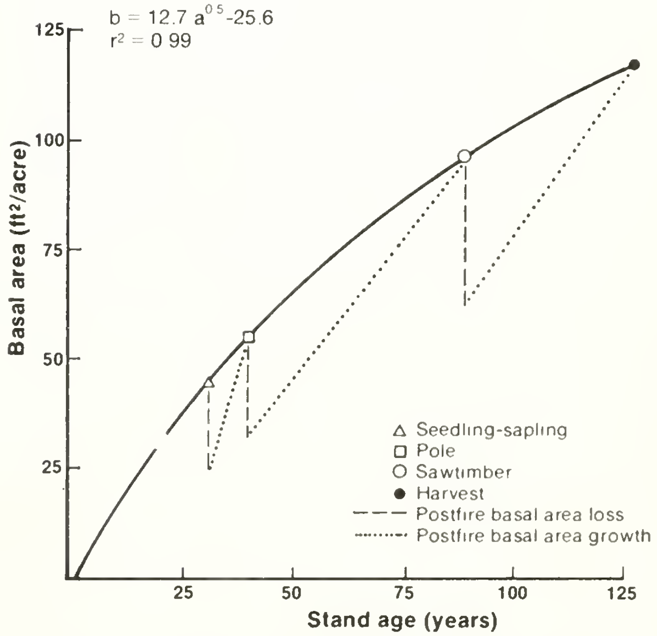


Figure 2—For ponderosa pine, basal area (b) reaches expected levels by the mean age of the next older age class or, if sawtimber, by the end of the rotation.

About 70 percent of understory production in this range type is available forage (Mueggler and Stewart 1980). Because forage production $f = 0.7\,p$, forage production is calculated as:

$$f = (0.7)(10^{3.22-0.00936b}) \qquad (7)$$

Basal area can be calculated for each year in the rotation with equation 5, so f can be determined throughout the growth of the stand.

The calculation of f is fairly simple in the "without fire" situation after harvest or a stand replacement fire. Forage production is determined for values of b along the basal area–age curve (*fig. 2*, eq. 5). The "with fire" situation in which the stand is retained requires an additional step in simulating regrowth. In this situation, some of the basal area of the stand has been lost. We assumed that because the stand still has adequate postfire stocking, basal area will reach expected levels along the basal area–age curve by the mean age of the next older age class or, if sawtimber, by the end of the rotation. Furthermore, we assumed that recovery is linear from the point of the fire to the point at which expected basal area is reached.

This pattern of basal area recovery after fire is illustrated in *figure 2*, in which a portion of stand basal area is lost after fire. In years subsequent to the fire, basal area is determined along straight lines until the basal area–age curve is reached at the mean age of the next older age class. Basal area is determined from the curve for the remainder of the rotation.

Forage production in the "without fire" situation is calculated from equation 7 with appropriate values of b from the basal area–age curve throughout the rotation. In situations in which a stand of ponderosa pine is not retained, the peak forage production realized after a future harvest is shifted to an earlier point in time. This shift affects the timing of all future harvests and the sequence of range outputs for the 200-year analysis period.

Ponderosa pine range is deferred for a short period of time after fire or harvest. After harvest, range is deferred for the year of the harvest and the next 2 years. After fire, range is deferred for the balance of that year and for the next 2 years. The grazing season is defined as June 1 to October 31 for elevations ≤ 4500 ft (1400m) and as June 1 to October 15 for elevations > 4500 ft (1400 m) (Davis 1982, Hamner 1982, Hardman 1982). If fire occurs in spring (May 15), all of year 1 is lost for grazing. If fire occurs in late summer (August 15), 50 percent of the grazing season is lost in year 1 for range in either elevation class.

Mountain Grassland

The mountain grassland ecosystem consists mainly of open, untimbered areas, although it is often adjacent to or surrounded by ponderosa pine, Douglas-fir, or lodgepole pine at moderate elevations. This grassland cover type may include many grasses, especially those in the genera *Agropyron, Festuca, Muhlenbergia, Stipa, Poa,* and *Danthonia*, and forbs such as *Balsamorhiza sagittata*. The mountain meadows ecosystem is also dominated by perennial grasses, but tends to occur on more moist sites (Garrison and others 1977). Mountain meadows are relatively insignificant in terms of total land area in the Northern Rocky Mountains, and literature on fire effects in this range type is scant. It is included, therefore, with mountain grassland for the purpose of modeling the effects of wildfire.

In the mountain grassland type we assumed that *Agropyron spicatum* and *Festuca idahoensis* are the dominant species. Forage production is 1500 lb per acre (1680 kg/ha) based on the mean value for several mountain grassland sites (Paulsen 1975). Substantial literature is available on the effects of fire on *Agropyron* and *Festuca* for both wildfire and prescribed fire conditions (Bailey and Anderson 1978; Clarke and others 1943; Conrad and Poulton 1966; Uresk and others 1976, 1980; Willms and others 1980; Wright and Bailey 1980). Although the results of these studies are not in total agreement, some generalizations can be inferred: (a) *Agropyron spicatum* is resistant to fire and suffers low mortality; and (b) the effect of fire on overall production in mountain grasslands is relatively shortlived, and losses of *Festuca idahoensis* are generally compensated for by increases in production of *Agropyron spicatum* and other species.

Of the studies on fire effects on mountain grassland species, Clarke and others (1943), provide the best analysis of postfire changes in forage production. Because most of the other studies corroborate the results of this paper, it will be the basis for much of the modeling in this range type. With a spring fire (April-June), simulated loss of forage is 50 percent during the year of the fire (year 1) and 15 percent the year after the fire (year 2). Forage production returns to prefire levels in year 3. With a late summer fire (July-September), loss of forage is 30 percent in year 2, and forage production returns to prefire levels in year 3.

An additional loss of forage occurs depending on the time of fire. For a spring fire, the range is deferred from grazing in year 1 until after seed ripening (Davis 1982, Hardman 1982). The date of seed ripening is estimated to be August 1 at elevations ≤ 4500 ft, and August 15 to October 15 at elevations > 4500 ft. The amount of grazing time that is lost depends on the length of the grazing season. Length of grazing season is defined as June 1 to October 31 at elevations ≤ 4500 ft, and June 15 to October 15 at elevations > 4500 ft. Normal grazing patterns are resumed in year 2 after a spring fire. With a late summer fire, grazing is deferred until after seed ripening (August 1 or August 15, depending on elevation class) in year 2. Normal grazing patterns are resumed in year 3.

The effects of fire on mountain grassland are shortlived. Losses in range production in years 1 and 2 occur because of a decline in forage production and deferral of the range from grazing. Forage production reaches prefire levels by year 3, and the range can be fully utilized thereafter.

Sagebrush

Sagebrush is one of the most common range types in the Northern Rocky Mountain–Intermountain region. This range type contains primarily big sagebrush (*Artemisia tridentata*) and perennial grasses, of which *Agropyron* and *Festuca* are most common. The information used to simulate the effects of fire on sagebrush range is derived from long-term studies on sagebrush–grass range in Idaho (Blaisdell 1953, Harniss and Murray 1973, Mueggler and Blaisdell 1958) and Oregon (Hedrick and others 1966, Sneva 1972). Some of the general conclusions of the studies are these: (a) wildfire kills nearly all sagebrush plants; (b) most of the increased grass production after removal of sagebrush is because of *Agropyron* and *Calamagrostis;* (c) reinvasion of the range by sagebrush occurs by seed dispersal because big sagebrush does not sprout; and, as sagebrush increases on a site, perennial grasses decline.

Mean forage production on sagebrush range is 280 lb per acre (310 kg/ha) based on mean forage values for different productivity classes (Garrison and others 1977) and the percentage of existing rangeland that occurs in each class (U.S. Dep. Agric., Forest Serv. 1980). Sagebrush range is deferred from grazing for two growing seasons after fire under current management practice (Carson 1982, Wright 1982). Forage production need not be simulated during these years because no grazing occurs. Loss of range output in year 1 varies depending on elevation and time-of-year of the fire. Grazing season is defined as May 1 to October 31 at elevations $\leq$ 4500 ft, and June 15 to October 31 at elevations > 4500 ft (Carson 1982, Schultz 1982).

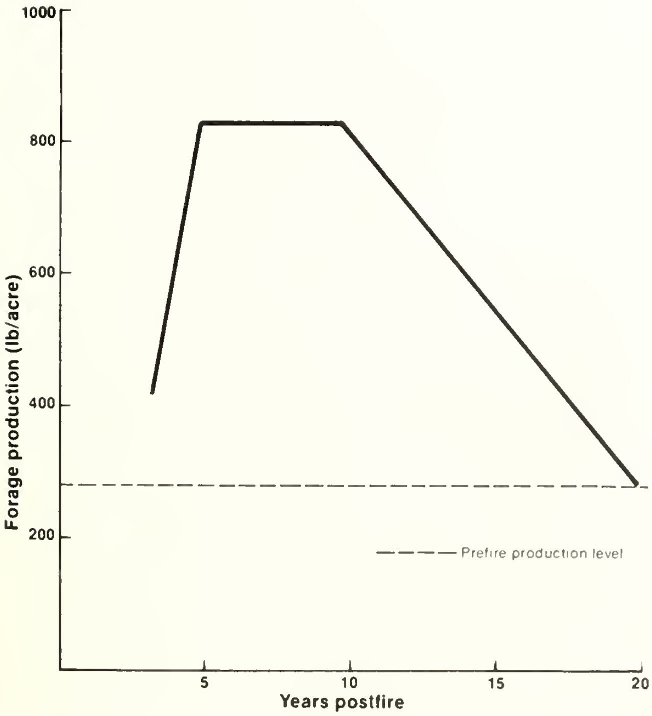


Figure 3—For sagebrush, peak forage production is maintained from years 5 through 10 and then declines until year 20 when it reaches prefire levels.

Forage production increases 50 percent over pretreatment levels 2 years after removal of sagebrush (year 3), 100 percent in year 4, and 200 percent in year 5 (Hedrick and others 1966, Sneva 1972). Peak forage production is maintained through year 10, and perennial grass production begins a gradual decline in year 11 because of the reinvasion of the range by the sagebrush (Blaisdell 1953, Harniss and Murray 1973, Mueggler and Blaisdell 1958). We assumed that this decline is linear from 200 percent greater than prefire production in year 10 to 0 percent in year 20. This decline is described by $p = -55.8y + 1390$, in which p = forage production (lb per acre), and y = years postfire ($10 \leq y \leq 20$). Postfire forage production is summarized (*fig. 3*).

Losses in range output in years 1 and 2 occur because of deferral from grazing. The range is deferred in year 3 in a late summer fire, resulting in an additional year of lost range production. The range can be grazed in year 3 in a spring fire, however, because two growing seasons have passed; a gain in range output occurs because forage production has increased in year 3. Time-of-year of fire has no effect on the gain in AUM in years 4 to 19.

Pinyon–Juniper

The pinyon–juniper ecosystem that is found in the Northern Rocky Mountain–Intermountain region contains only western juniper (*Juniperus occidentalis*) in the overstory. Dominant grasses in the understory are various species of *Agropyron* and *Festuca* and some *Stipa* and *Poa* (Wright and others 1979). In a discussion of the effects of fire on western juniper, Martin (1978) suggests that wildfire normally kills 80 percent of the overstory. Because juniper stands in Idaho have a mean canopy cover of 42 percent (Tueller and others 1979), less than 10 percent canopy cover would remain after wildfire. The best documentation of postfire changes over time in pinyon–juniper is a study of 28 different burns in west-central Utah (Barney and Frischknecht 1974).

Mean forage production for pinyon–juniper range is 130 lb per acre (150 kg/ha) based on mean forage values for four different productivity classes (Garrison and others 1977) and the proportion of land found in each productivity class (U.S. Dep. Agric., Forest Serv. 1980). Decision rules are the same as for mountain grassland because many of the grass species are the same (Davis 1982, Hardman 1982). Grazing is deferred until after seed ripening (August 1 at elevations $\leq$ 4500 ft, August 15 at elevations > 4500 ft) of year 1 for spring fires. Grazing is deferred until these same dates in year 2 for a late summer fire, and the balance of the grazing season in year 1 is lost. Grazing season is defined as May 1 to October 31 at elevations $\leq$ 4500 ft, and

June 15 to October 15 at elevations > 4500 ft (Carson 1982, Schultz 1982).

The study on pinyon-juniper fire effects does not include information on forage production for the first few years after fire (Barney and Frischknecht 1974). Because the perennial grasses in pinyon-juniper are similar to those in mountain grassland range, effects in years 1 to 3 are simulated as for mountain grassland. Forage production is reduced by 50 percent for the balance of year 1 and by 15 percent in year 2 for a spring fire. Forage production during year 2 is reduced by 30 percent in a later summer fire. Forage production equals prefire levels in year 3 for both spring and summer fires. Forage production is 100 percent greater than prefire levels in year 5 (Barney and Frischknecht 1974). It is estimated that forage increases 50 percent (by interpolating between 0 percent and 100 percent) in year 4.

Reinvasion by juniper after fire is relatively slow, and canopy cover does not increase much until about 50 years after fire. During this period, forage production remains fairly stable (Barney and Frischknecht 1974), so forage production for years 5 to 50 is 100 percent greater than prefire levels (or 260 lb/acre). Juniper canopy cover increases steadily after year 50 until prefire levels are reached at about 90 years. During this period, a concurrent decrease in available forage occurs (Barney and Frischknecht 1974). We assumed that the decline in forage from year 50 to year 90 is linear. This decline is described by $p = 3.16y + 414$, in which p = forage production (lb/acre) and y = years postfire ($50 \leq y \leq 90$). Forage production remains at prefire levels for years 90 to 200. Postfire forage production is summarized (*fig. 4*).

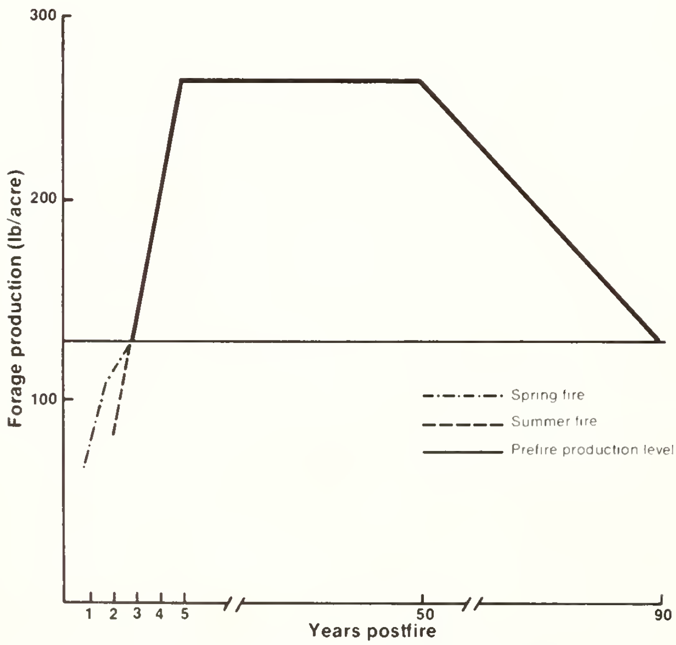


Figure 4—For pinyon-juniper, peak forage production is maintained from years 5 through 50 and then declines until year 90 when it reaches prefire levels. Season of fire affects early postfire production.

Western Hardwoods

The western hardwoods ecosystem in the Northern Rocky Mountains consists primarily of scattered stands of quaking aspen (*Populus tremuloides*) with an understory of grasses, forbs, and shrubs. This cover type is normally relatively open and meadow-like and may occur adjacent to grassland or conifer forest. Most of the information used to simulate the effects of wildfire on western hardwoods is drawn from a series of studies conducted on aspen stands in western Wyoming (Bartos 1978, 1979; Bartos and Mueggler 1979, 1981). These papers discuss the effects of prescribed fire, and classify burn intensity as low, moderate, and high. We assumed that the high burn intensity class can be used to simulate the effects of wildfire. Aspen sucker production increases initially after fire. Production of grasses and forbs increases in the second year after fire and gradually declines thereafter.

Decision rules for deferred grazing after fire are the same as those used for mountain grassland. Grazing is deferred until August 1 (for elevations $\leq$ 4500 ft) or August 15 (for elevations > 4500 ft) of year 1 in a spring fire. Grazing is deferred until the same dates of year 2 in a late summer fire. Grazing season is defined as June 1 to October 31 for elevations $\leq$ 4500 ft, and June 15 to October 15 for elevations > 4500 ft.

Mean understory production on aspen sites studied was1325 lb per acre (1480 kg/ha) and was dominated by various forbs (Bartos and Mueggler 1981). The value of this production for forage could not be determined directly from that study. Forage was estimated by multiplying palatability ratings by the production of each species.[1] Mean forage was calculated by this method to be 350 lb per acre (340 kg/ha), or 27 percent of total production. Understory production 3 years postfire was 2250 lb per acre (2520 kg/ha) on the severely burned sites, 66 percent of which was the unpalatable species fireweed (*Epilobium angustifolium*). Forage production calculated with the use of palatability ratings was 402 lb per acre (450 kg/ha), or only 18 percent of understory production.

Total understory production trends indicate that forage production (assuming the same forage-understory production ratio) was 22 percent of the 402 lb per acre, or 89 lb per acre (100 kg/ha) in the year after fire (Bartos and Mueggler 1981). This value is used for year 1 of a spring fire and for year 2 of a late summer fire. Peak forage production was estimated as 416 lb per acre (466 kg/ha) 2 years postfire (year 3). An interpolated value of 252 lb per acre (282 kg/ha) (the mean of years 1 and 3) was used to express forage production in year 2 for a spring fire. By extrapolating production trends into the future according to a constant linear decline, forage levels approach prefire levels 7 years after fire. This decline is described by

[1]Unpublished data by Lisle R. Green, on file at Pacific Southwest Forest and Range Experiment Station, Riverside, California.

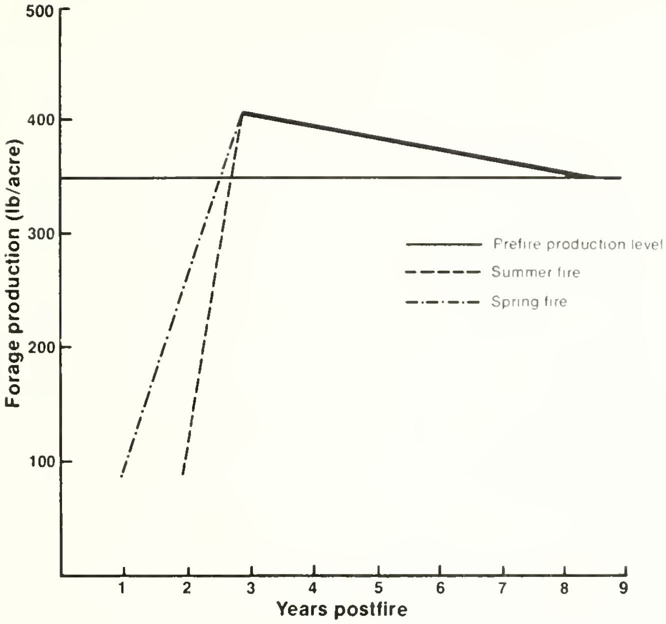


Figure 5—For western hardwoods, peak forage production is reached at year 3 and then declines until year 8 when it reaches prefire levels. Season of fire affects early postfire production.

$p = -12.6\ y + 450$, in which p = forage production (lb/acre) and y = years postfire ($3 \leq y \leq 8$). We assumed that forage production would remain constant thereafter (*fig. 5*).

Forage losses occur immediately postfire, and increases for several years after fire are relatively small. Although a substantial increase in understory production occurs after fire, the forage value of the vegetation is low and results in only a small gain in AUM.

CALCULATING NET VALUE CHANGE

The "with fire" and "without fire" approach to effects valuation is described by the following general form of the range effects valuation equation:

$$NVC = PNV_{w/o} - PNV_{w} \qquad (8)$$

in which

NVC = net value change
$PNV_{w/o}$ = present net value of all future range reventus in "without fire" situation
PNV_{w} = present net value of all future range revenues in "with fire" situation

Equation 8 accounts for long- and short-term effects by valuing changes in the infinite series of future revenues, rather than valuing changes in the revenue series for only a limited number of years. Management costs are omitted on the assumption that wildfire causes no significant variation in those costs. Although costs might be incurred in some situations for items such as fencing or watering facilities, it is difficult to estimate the frequency or magnitude of these costs. We assumed that fires occur only in areas currently managed for range, that required improvements are already in place, and that a fire does not create a new range that requires a high level of management costs. In equation 9, the range net value change calculation is expanded to its computational form.

$$NVC = \left[\sum_{s=o}^{n} \frac{PQ_{w/o,\,s_n}}{(1+i)^{s_n}} + \sum_{f=o}^{n} \frac{PQ'_{w/o,\,f_n}(1+i)^{t-f_n}}{(1+i)^{t}-1} \right] - \left[\sum_{s=o}^{n} \frac{PQ_{w,\,s_n}}{(1+i)^{s_n}} + \sum_{f=o}^{n} \frac{PQ'_{w,\,f_n}(1+i)^{t-f_n}}{(1+i)^{t}-1} \right] \qquad (9)$$

in which

NVC = net value change
P = price in 1978 dollars per AUM
$Q_{w/o,\,s_n}$ = single series annual or periodic forage yield at time s_n in the "without fire" situation
$Q'_{w/o,\,f_n}$ = infinite series annual or periodic forage yield at time f_n in the "without fire" situation
$Q_{w,\,s_n}$ = single series annual or periodic forage yield at time s_n in the "with fire" situation
$Q'_{w,\,f_n}$ = infinite series annual or periodic forage yield at time f_n in the " with fire" situation
i = policy provided discount rate (for example, i = 0.04)
s_n = the years after fire in which single series differences exist between "with fire" and "without fire" forage yields
f_n = the years after fire in which infinite series, cyclic, timber-associated forage yields first occur
t = the number of years between cyclic occurrences of timber-associated forage yields (that is, equivalent to rotation age of associated timber stand)

The first bracketed component of equation 9 represents $PNV_{w/o}$ and the second represents PNV_{w}. Long-term effects are estimated by subtracting the second term in the two bracketed components (that is, the infinite series difference). This long-term effect must be estimated in timber-associated range types because of the cyclical nature of these types. A fire may alter the development of a timber stand and thereby alter the timing of forage yield cycles dependent on that development. The value of this shifting of the infinite series of forage yield cycles represents the long-term, fire-caused financial effect on the range resource.

Short-term effects are estimated by subtracting the first term in the second bracket from the first term in the first bracket (that is, the single series difference). These effects are characteristic of all nontimber range types and of some timber-associated types. Short-term effects are all those associated with fire-caused, single period changes in forage yields, rather than with simple shifts in the timing of postfire yields. Fire, for example, reduces mountain grassland forage yield for only 2 years after fire. Paired "with fire" and "without fire" sites show identical yield beyond that point. Mountain grassland range is subject to only short-term changes, with no infinite series forage cycle shifts occurring. The appropriate terms cancel in equation 9 when only long- or short-term effects occur.

To evaluate the fire effects on range types in this study, we used SASSY, an investment analysis computer package (Goforth and Mills 1975) that performs the equation 9 calculation, given the following information: (a) the timing or investment year of "with fire" and "without fire" forage yields; (b) the yield amount (AUM/acre); (c) a price per AUM; (d) discount rate(s); and (e) in some instances, a cycle or rotation length. The timing and magnitude of forage yields are output of the range simulation model discussed earlier, and the cycle or rotation age information was the same as that used in the simulation model.

A uniform price of $9.72 per AUM was used in the NVC calculations for all range types. This price is a weighted mean of the 1985 Resources Planning Act (RPA) Program prices for 26 National Forests in the Northern Rocky Mountains.[2] The forest-specific RPA Program prices were developed as shadow prices from a linear program developed by Gee (1981). These prices, where available, are being used in forest-level planning. The RPA prices were adjusted to 1978 dollars from the gross national product implicit price deflator. Actual range-use levels were used as weights in developing the mean Northern Rocky Mountain price. The AUM price was assumed to remain constant over time, as evidence was inadequate to justify a real price change assumption.

ESTIMATING POSTFIRE CHANGES

Estimates of changes in range production and value for the six range types were calculated for the postfire time stream during which range output is affected, up to 200 years postfire.[3] Some of the data in the tables are grouped by year, for convenience.

Changes in range production (ΔAUM) are based on the values used for forage production in the individual subroutines described earlier. These default values can be modified with an appropriate multiplier at the discretion of the user if it is determined that the values are too high or too low. The ΔAUM values in *tables 1, 3, 5, 7, 9,* and *11* are the entire change in AUM, that is ΔAUM at a theoretical 100 percent utilization. Although 100 percent utilization is not realistic in actual management, it serves as a reference point that can be modified by users according to the level they think is appropriate. Net ΔAUM (for the entire postfire time stream) for utilization levels of 25 percent and 40 percent of annual production is listed in *tables 2, 4, 6, 8, 10,* and *12.* Forty percent is the maximum utilization level for sustained range production, on the basis of various literature citations and a consensus of opinions from range management experts. Twenty-five percent represents a moderate level of range utilization. As discussed earlier, *positive numbers in the tables indicate a loss in range production and value, and negative numbers indicate a gain in production and value.*

Changes in range production and value are given for all possible situations within each range or cover type. Elevation and time-of year of fire were originally used to stratify some of these situations in the simulation model and are listed in odd-numbered tables. Values in even-numbered tables were aggregated for these parameters if the difference was less than 10 percent between range types for both net ΔAUM and NVC. As a result of the aggregation process, elevation is not listed in any of the even-numbered tables and is not a significant stratifier with respect to net ΔAUM or NVC. Age class and percent mortality are additional stratifiers for the timbered range types. In addition, NVC is calculated for two utilization levels at two different discount rates. The user should cautiously interpolate or extrapolate the data of these tables to fit individual purposes.

Transitory Range

Substantial changes in postfire range production for cover types are included in transitory range *(table 1).* This table should be used only for a stand replacement fire (defined here as $>$ 70 percent of basal area removed) or if the entire stand is removed by salvage. The general effect of wildfire in these types is to shift the periods of grazing use that would have occurred after harvest to an earier point in the time sequence. The same sequence of values is repeated throughout the 200-year analysis period, with gains after fire and harvests in the "with fire" situation, and losses after harvests in the "without fire" situation. The magnitude of ΔAUM is relatively low for the cutover age class

[2]National Forests in Idaho were the Boise, Caribou, Challis, Clearwater, Idaho Panhandle, Nezperce, Payette, Salmon, Sawtooth, and Targhee. National Forests in Montana were the Beaverhead, Bitterroot, Deerlodge, Flathead, Kootenai, and Lolo. National Forests in Oregon were the Deschutes, Fremont, Malheur, Ochoco, Umatilla, and Wallowa-Whitman. National Forests in Washington were the Colville, Okanogan, and Wenatchee. National Forest in Wyoming was the Bridger-Teton.

[3]See *tables 1* to *12* in *appendix.*

because of the overlap of grazing sequences in the "with fire" and "without fire" situations.

The two examples (*table 1*) not only have different sequences of ΔAUM values, but have different sequence timing because lodgepole pine has different mean stand ages and rotation age than Douglas-fir, western larch, and western white pine. Net ΔAUM is large for some age classes but is equal to 0 in others (*table 2*). This demonstrates the effect of the shift of grazing sequences within the 200-year analysis period.

The NVC estimates for all size classes except cutover in the transitory range types show a net benefit resulting from fire (that is, negative NVC estimates). This beneficial effect results from a forward shift in the timing of future expected range yields. In a seedling–sapling stand (age 30), for example, range yields are not expected until the beginning of the next rotation (that is, a 95-year delay, given a 125-year rotation), but if fire destroys the timber stand the next rotation begins in year 1. The fire allows an almost immediate realization of range yields, which was not available for 95 years in the "without fire" situation. The beneficial effect of fire decreases as stand age at time of fire increases. This trend results from a less forward shift in the timing of range yields as fire occurs in older stands. The beneficial effect is more pronounced at a higher utilization level because larger values are differenced there than at the lower utilization level.

The beneficial effects in the transitory range types decrease at a higher discount rate. This result indicates that the "with fire" values are driving the NVC calculation in this instance. A higher absolute decrease occurs in out-year "with fire" range values at a higher discount rate than in out-year "without fire" values.

The losses in the cutover age class result from a fire-caused 2-year delay in range yields. Range yields expected in year 1 for the "without fire" situation are delayed until year 3 in the "with fire" situation. The losses in the cutover age class increase at a higher discount rate, because a higher absolute decrease occurs in the value of future "with fire" yields at a higher discount rate, than occurs in "without fire" values. Losses become more pronounced at higher utilization levels because larger values are being subtracted. This effect of higher utilization levels occurs in all range types.

Permanent Forested Range (Ponderosa Pine)

Change in postfire production of ponderosa pine range varies greatly depending on age class and percent timber mortality (*table 3*). The cutover age class and all seedling-sapling classes have overall losses in production except where mortality is 100 percent. Almost all pole and sawtimber classes have overall gains.

In the cutover age class, the initial losses from deferred grazing are large because the range is highly productive early in the rotation (*table 3*). After the initial loss, small increases occur until the mean seedling–sapling age is reached because the "with fire" rotation is 2 years behind the "without fire" rotation.

The effects of fire on the seedling–sapling age class (*table 3*), are relatively shortlived because the mean age of pole timber is reached in only 10 years. Initial losses from deferred grazing are substantial. Subsequent increases are large only if 100 percent of the stand is removed (this could result entirely from fire or postfire salvage). The 100 percent mortality class has a net gain in AUMs, while the other mortality classes have losses.

Long-term changes in range production are similar across all mortality classes for the pole (*table 3*) and sawtimber age classes. Gains in AUMs are large over a long period of time, especially in the 100 percent mortality class. In this class, the effect of the fire is to shift from a stand with relatively high basal area and low range output to a new rotation with high range output. Large losses in range output are incurred later in the postfire time stream. This results from the harvest of the stand at rotation age in the "without fire" situation, which results in higher range production than the "with fire" situation. The losses incurred later in the time stream tend to compensate for the earlier gains, and total ΔAUM production is about 0 for the 100 percent mortality class of pole and sawtimber (*table 4*).

The NVC estimates for ponderosa pine range follow the same general trend as the estimates of net change in physical output (AUMs). Net losses occur in all cutover classes and in all seedling–sapling classes except where there is 100 percent mortality. Net gains occur in all pole and sawtimber classes.

The net losses in the cutover age classes result from a fire-caused delay in range yields. The detrimental effect of the delay is greater at higher discount rates. The value of delayed future "with fire" yields decreases relative to "without fire" yields at higher rates.

Losses in the net value of seedling–sapling stands at 30 and 60 percent mortality result from a 2- or 3-year fire-caused deferral of grazing (*table 4*). The larger spring losses result from the loss of 3 years grazing as against 2 years for a summer fire. Evaluating NVC at a higher discount rate results in the same increase in losses that occurred in the cutover classes.

Net gains occurred at 100 percent mortality in seedling–sapling stands despite the 2- or 3-year grazing deferral. The "with fire" yields subsequent to the delay were sufficiently larger than "without fire" yields to offset the losses resulting from the delay. The fire-caused gains decrease at higher discount rates because early losses become relatively more significant than later gains at higher rates. Time-of-year of fire has a minimal effect on the NVC for all age classes.

The net gains in range values associated with fires in all pole and sawtimber age stands (*table 4*) results from fire-caused reductions in basal area. These reductions facilitate earlier increases in range production than would occur in the "without fire" situation. Future expected range yields are shifted forward in time and realized sooner in the "with fire" situation. Higher mortality levels are associated with greater net gains because of the range production response to removal of increasing amounts of basal area.

The gains in pole and sawtimber age stands decline at a higher discount rate for the same reason the decline took place in the transitory type. The early "with fire" yields are driving the the NVC calculation. The absolute decreases in annual range values that occur with the application of higher discount rates are larger in "with fire" values than in "without fire" values.

Mountain Grassland

The effects of wildfire on mountain grassland range are shortlived because production returns to prefire levels in year 3 (*table 5*). Losses are relatively high, however, because this range type is normally highly productive. A large proportion of the loss results from the deferral of the range from grazing after fire. Fires that occur in late summer result in slightly higher total ΔAUM losses than spring fires (*table 6*).

Mountain grasslands show the largest value losses of all the range types (*table 6*), along with the cutover and seedling–sapling age classes of ponderosa pine. The effect of time-of-year on NVC is generally the same as was described for physical output. NVC losses are smaller at a higher discount rate because of the relatively great magnitude of the "without fire" values.

Sagebrush

Sagebrush shows a substantial long-term gain in range production after fire (*table 7*). An initial loss of production occurs because the range is deferred from grazing, and elevation and time-of-year of fire affect range yield in years 1 to 3. Range production is maintained at 200 percent greater than prefire levels during years 5 to 10. Production gradually declines during the next decade as sagebrush increases and grass production decreases. The many years of gain in AUMs more than compensate for the initial years of loss. Elevation and time-of-year of fire have little effect on net ΔAUM (*table 8*) because of the long-term gain in range production.

The net value gains in the sagebrush type also vary slightly by time-of-year or elevation (*table 8*). The NVCs decline at a higher discount rate because of the great magnitude of the "with fire" values relative to the "without fire" values.

Pinyon–Juniper

The pattern of postfire range production for pinyon–juniper range is similar to that for sagebrush: an initial loss in production is followed by a long-term gain (*table 9*). Small losses of AUMs occur in years 1 to 2, with elevation and time-of-year of fire having only a minor effect. Range production is maintained at 100 percent greater than prefire levels during years 5 to 50. Although this increase is relatively small (0.14 AUM) on an annual basis, the long-term net ΔAUM is substantial (*table 10*). Production begins a gradual decline after year 50 as juniper increases and grass production decreases. Prefire conditions are not reached until year 90. Pinyon–juniper range is normally unproductive for range management. Wildfire can make it substantially more productive over a long period of time.

All NVC estimates represent net gains resulting from fire that are consistent with gains in physical output (*table 10*). NVC estimates vary slightly by elevation or time-of-year, and the NVC gains decrease at higher interest rates. This decrease results from the relatively large magnitude of the "with fire" values.

Western Hardwoods

The dominant influence on range production of western hardwoods is deferred grazing during years 1 to 2 (*table 11*). Losses of production in these years are substantial for all elevation and time-of-year classes, and yields in year 2 are affected to some extent by decreased forage production. Production increases in years 3 to 7 are small, and are not large enough to compensate for losses in years 1 to 2. Net ΔAUM indicates a small loss in range production (*table 12*). Although wildfire affects range production of western hardwoods for several years, the long-term effect is relatively small.

The net effect of fire on western hardwoods range values is also small (*table 12*). A slight difference in NVCs results from time-of-year. This difference occurs because the first year postfire value in the "with fire" situation is consistently smaller after a summer fire than after a spring fire. NVCs increase at a higher discount rate because early range output reductions in the "with fire" situation become relatively more significant than later increases.

APPLICATION

The estimates of postfire change in production and value that are provided represent a broad spectrum of possible situations for common range types in the Northern Rocky Mountain–Intermountain area (*tables 1-6*). Postfire changes range from substantial long-term gains to moderate losses in production and value. In addition, the duration of fire effects varies widely among range types.

The information provided here can be used for several different aspects of decisionmaking. The timestream of postfire outputs includes estimates of both long- and short-term changes in range production. In some situations, change in output in the first few years may be a major concern. In long-term land management planning, the entire analysis period during which effects can be measured should be considered. Net value change estimates are provided for use in economic assessments. These estimates can be used as the sole criterion for decisionmaking or can be used in combination with estimates of physical output change.

The estimates of fire effects on range production developed by this study have several potential applications. They summarize the effects of wildfire on several ecosystems that are managed for cattle grazing. They can be used in a broad resolution sense to predict increases or decreases in range production after fire, on the basis of ecological information and management policies. More valuable, however, is the use of these fire effects estimates within the context of land management planning. Until recently, it has been difficult to incorporate fire management programs in the planning process because of insufficient methods for estimating postfire changes in resource yields. Estimates provided in this study can help solve this problem and can facilitate the integration of fire management with land management planning for Northern Rocky Mountain rangelands. Net value change estimates may also be useful as part of escaped fire situation analyses if a NVC criterion is part of the decisionmaking process.

Because of the nature of the simulation process used to generate changes in range production after fire, several limitations of this study are evident. Information available for some range types on which to base relationships useful for modeling purposes was scant. Quantitative information from the literature was often poor or had to be extrapolated to fit the broad resolution design of the current study. In addition, some critical points in the simulations were provided by assumptions drawn from the literature or by a consensus from range management experts. Although these assumptions do not affect the overall design of the model, they may be significant if fire effects estimates are used in site-specific situations. The broad resolution categories for which values have been generated may be difficult to correlate with some of the existing classification systems used in planning and site-specific analysis.

The design of the model that was used to produce estimates of changes in range production and value after wildfire should be adequate for the broad resolution needs of fire management planning. Some refinements could improve estimates used for site-specific applications, however. The range types considered here are broadly defined and could be subdivided on the basis of discrete combinations of forage species. Different species groups have different production levels and different responses to wildfire. More research is needed to determine the effect of fire on production levels in different range ecosystems. The model could also be modified to have more flexibility with respect to management actions. Management decisions such as length of grazing deferral after fire, length of grazing season, and utilization level can have a major effect on range output in some situations. The availability of a wider range of options could increase the likelihood of identifying a range or cover type that is applicable to a site-specific situation.

APPENDIX

Table 1—*Estimated postfire change in animal-unit months (ΔAUM) in transitory range production over time for four age classes of (A) Douglas-fir, western larch, and western white pine, and (B) lodgepole pine cover types*[1]

Year	Age classes			
	Seedling-sapling	Pole	Sawtimber	Cutover
	ΔAUM/acre			
	(A) Douglas-fir, western larch, western white pine			
1	0	0	0	0
2	0	0	0	0.38
3	0	0	0	.46
4	-0.38	-0.38	-0.38	.18
5	- .46	- .46	- .46	.20
6	- .56	- .56	- .56	.17
7	- .66	- .66	- .66	.13
8	- .73	- .73	- .73	.11
9	- .79	- .79	- .79	.06
10	- .84	- .84	- .84	0
11	- .86	- .86	- .86	- .06
12	- .84	- .84	- .84	- .11
13	- .79	- .79	- .79	- .13
14	- .73	- .73	- .73	- .17
15	- .66	- .66	- .66	- .20
16	- .56	- .56	- .56	- .18
17	- .46	- .46	- .46	- .17
18	- .38	- .38	- .38	- .16
19	- .29	- .29	- .29	- .13
20	- .22	- .22	- .22	- .22
21	- .16	- .16	- .16	- .16
29 to 46			10.40	
69 to 86		10.40		
99 to 116	10.40			
127 to 146				10.40
129 to 146	-10.40	-10.40	-10.40	
154 to 171			10.40	
194 to 200		4.44		

Year	Age classes			
	Seedling-sapling	Pole	Sawtimber	Cutover
	ΔAUM/acre			
	(B) Lodgepole pine			
1	0.18	0	0	0
2	.13	0	0	0.31
3	0	0	0	.38
4	- .31	-0.31	-0.31	.15
5	- .38	- .38	- .38	.16
6	- .46	- .46	- .46	.14
7	- .54	- .54	- .54	.11
8	- .60	- .60	- .60	.09
9	- .65	- .65	- .65	.05
10	- .69	- .69	- .69	0
11	- .70	- .70	- .70	- .05
12	- .69	- .69	- .69	- .09
13	- .65	- .65	- .65	- .11
14	- .60	- .60	- .60	- .14
15	- .54	- .54	- .54	- .16
16	- .46	- .46	- .46	- .15
17	- .38	- .38	- .38	- .14
18	- .31	- .31	- .31	- .13
19	- .24	- .24	- .24	- .11
20	- .18	- .18	- .18	- .18
21	- .13	- .13	- .13	- .13
24 to 41			8.51	
54 to 71		8.51		
84 to 101	8.51			
102 to 109				1.39
104 to 121	-8.51	-8.51	-8.51	
110				0
111 to 121				-1.39
124 to 141			8.51	
154 to 171		8.51		
184 to 200	8.38			

[1] Δ AUM = 0 for years not listed. Time intervals not applicable for a particular age class are indicated by blanks.

Table 2—*Estimated postfire net value change (NVC) in transitory range production for (A) Douglas-fir, western larch, and western white pine, and (B) lodgepole pine cover types*

Age class	Utilization level	Net production change	NVC (1978 dollars/acre) (rate)	
	pct	*ΔAUM/acre*	*4 pct*	*10 pct*
(A) Douglas-fir, western larch, and western white pine				
Seedling-sapling	25	-2.60	-16.68	-10.02
	40	-4.16	-26.69	-16.03
Pole	25	-1.49	-15.76	-10.00
	40	-2.38	-25.21	-16.00
Sawtimber	25	0	-10.68	-9.10
	40	0	-17.09	-14.55
Cutover	25	0	1.39	2.10
	40	0	2.23	3.37

Age class	Utilization level	Net production change	NVC (1978 dollars/acre) (rate)	
	pct	*ΔAUM/acre*	*4 pct*	*10 pct*
(B) Lodgepole pine				
Seedling-sapling	25	0.04	-13.22	-7.87
	40	.07	-21.16	-12.60
Pole	25	0	-12.17	-8.13
	40	0	-19.47	-13.01
Sawtimber	25	0	-7.70	-7.64
	40	0	-12.32	-11.17
Cutover	25	0	1.15	1.72
	40	0	1.85	2.75

Table 3—*Estimated postfire change in ponderosa pine range production over time for (A) cutover, (B) seedling-sapling, (C) pole, and (D) sawtimber age classes*[1]

Year	ΔAUM/acre	Year	ΔAUM/acre
(A) Cutover age class			
1	0	9	-0.09
2	1.29	10	-.08
3	1.29	11 to 20	-.68
4	-.08	21 to 30	-.50
5	-.15	31 to 40	-.30
6	-.13	41 to 50	-.12
7	-.11	51 to 100	-.10
8	-.10	101 to 150	-.42

Year and season of fire[2]		Mortality of . . . 30 pct	60 pct	100 pct
(B) Seedling-sapling age class				
1	Spring	0.49	0.49	0.49
	Summer	.24	.24	.24
2	Either	.48	.48	.48
3		.46	.46	.46
4		-.11	-.23	-.85
5		-.09	-.19	-.85
6		-.07	-.15	-.78
7		-.06	-.12	-.72
8		-.04	-.08	-.66
9		-.03	-.05	-.62
10		-.02	-.03	-.58

Year and season of fire[2]		Mortality of . . . 30 pct	60 pct	100 pct
(C) Pole age class				
1	Spring	0.38	0.38	0.38
	Summer	.19	.19	.19
2	Either	.38	.38	.38
3		.37	.37	.37
4		-.15	-.36	-.93
5		-.15	-.35	-.92
6		-.14	-.34	-.86
7		-.14	-.32	-.80
8		-.13	-.30	-.74
9		-.13	-.29	-.70
10		-.13	-.28	-.66
11 to 20		-1.32	-2.45	-4.92
21 to 30		-.86	-1.48	-3.32
31 to 40		-.34	-.55	-2.40
41 to 50		-.12	-.20	-1.76
51 to 100		0	0	5.92
101 to 150		0	0	11.04
(D) Sawtimber age class				
1	Spring	0.16	0.16	0.16
	Summer	.08	.08	.08
2	Either	.16	.16	.16
3		.15	.15	.15
4		-.12	-.33	-1.14
5		-.11	-.31	-1.14
6		-.11	-.29	-1.06
7		-.10	-.27	-.99
8		-.10	-.25	-.93
9		-.09	-.24	-.88
10		-.09	-.22	-.84
11 to 20		-.61	-1.45	-6.51
21 to 30		-.26	-.56	-4.60
31 to 40		-.03	-.06	-3.88
41 to 50		0	0	5.72
51 to 100		0	0	10.84
101 to 150		0	0	1.96

[1]ΔAUM = 0 for years not listed.

[2]Season of fire for year 2 and all subsequent years is spring or summer.

Table 4—*Estimated postfire net value change (NVC) in ponderosa pine production for (A) cutover, (B) seedling-sapling, (C) pole, and (D) sawtimber age classes*

Mortality class (pct)	Season of fire	Utilization level	Net production change	NVC (1978 dollars/acre) (rate)	
		pct	*ΔAUM/acre*	*4 pct*	*10 pct*
			(A) Cutover		
—	Either	25	0.10	3.13	3.88
—		40	.16	5.01	6.21
			(B) Seedling-sapling		
30	Spring	25	.25	2.52	2.54
		40	.40	4.03	4.06
	Summer	25	.19	1.92	1.94
		40	.30	3.08	3.11
60	Spring	25	.14	1.62	1.85
		40	.23	2.60	2.96
	Summer	25	.08	1.03	1.25
		40	.13	1.65	2.01
100	Either	25	- .94	-6.80	-4.37
		40	-1.50	-10.88	-6.98
			(C) Pole		
30	Spring	25	-0.62	-1.54	0.26
		40	- .99	-2.47	- .42
	Summer	25	- .68	-2.01	- .21
		40	-1.07	-3.22	- .33
60	Spring	25	-1.45	-6.41	-2.48
		40	-2.32	-8.47	-4.55
	Summer	25	-1.50	-6.88	-2.95
		40	-2.39	-11.01	-4.72
100	Either	25	0	-20.89	-10.17
		40	0	-33.42	-16.27
			(D) Sawtimber		
30	Spring	25	-0.29	-1.44	-0.46
		40	- .46	-2.30	- .74
	Summer	25	- .31	-1.63	- .66
		40	- .49	-2.61	-1.06
60	Spring	25	- .88	-5.30	-2.84
		40	-1.40	-8.47	-4.55
	Summer	25	- .90	-6.88	-2.95
		40	-1.44	-8.79	-4.86
100	Either	25	- .75	-22.48	-14.30
		40	-1.20	-35.96	-22.88

Table 5—*Estimated postfire change in mountain grassland range production over time*[1]

Year	Season of fire	Elevation (ft)	ΔAUM/acre
1	Spring	≤4500	1.16
2	Spring		.25
1	Summer		.83
2	Summer		.97
1	Spring	>4500	1.25
2	Spring		.25
1	Summer		.83
2	Summer		1.08

[1]ΔAUM = 0 for years not listed.

Table 6—*Estimated postfire net value change (NVC) in mountain grassland range production*

Season of fire	Utilization level	Net production change	NVC (1978 dollars/acre) (rate)	
	pct	*ΔAUM/acre*	*4 pct*	*10 pct*
Spring	25	0.36	3.51	3.48
	40	.58	5.62	5.56
Summer	25	.46	4.41	4.28
	40	.74	7.06	6.85

Table 7—*Estimated postfire change in sagebrush range production over time*[1]

Year	Season of fire[2]	Elevation[3] (ft)	ΔAUM/acre
1	Spring	≤4500	0.29
1	Summer		.13
1	Spring	>4500	.31
1	Summer		.16
2	Spring	Either	.31
2	Summer		.31
3	Spring		- .15
3	Summer		.31
4	Either		- .31
5			- .62
6			- .62
7			- .62
8			- .62
9			- .62
10			- .62
11			- .56
12			- .50
13			- .43
14			- .37
15			- .31
16			- .25
17			- .19
18			- .12
19			- .06

[1]ΔAUM = 0 for years not listed.
[2]Season of fire for year 4 and all subsequent years is spring or summer.
[3]Elevation for year 2 and all subsequent years is ≤4500 or >4500 ft.

Table 8—*Estimated postfire net value change (NVC) in sagebrush range production*

Elevation	Season of fire	Utilization level	Net production change	NVC (1978 dollars/acre) (rate)	
		pct	*ΔAUM/acre*	*4 pct*	*10 pct*
Either	Either	25	-1.56	-10.38	-6.18
		40	-2.48	-16.61	-9.88

Table 9—*Estimated postfire change in pinyon-juniper range production over time*[1]

Year	Season of fire[2]	Elevation[3] (ft)	ΔAUM/acre
1	Spring	<4500	0.10
2	Spring		.02
1	Summer		.06
2	Summer		.09
1	Spring	>4500 ft	.11
2	Spring		.02
1	Summer		.07
2	Summer		.09
3	Either	Either	0
4			-.07
5			-.14
6			-.14
7			-.14
8			-.14
9			-.14
10			-.14
11 to 20			-1.40
21 to 30			-1.40
31 to 40			-1.40
41 to 50			-1.40
51 to 60			-1.21
61 to 70			-0.85
71 to 80			-0.52
81 to 89			-0.15

[1]ΔAUM = 0 for all years not listed.
[2]Season of fire for year 3 and all subsequent years is spring or summer.
[3]Elevation for year 3 and all subsequent years is ≤4500 ft or >4500 ft.

Table 10—*Estimated postfire net value change (NVC) in pinyon-juniper range production*

Elevation	Season of fire	Utilization level	Net production change	NVC (1978 dollars/acre) (rate)	
		pct	*ΔAUM/acre*	*4 pct*	*10 pct*
Either	Either	25	-2.28	-6.79	-2.36
		40	-3.64	-10.87	-3.76

Table 11—*Estimated postfire change in western hardwoods range production over time*[1]

Year	Season of fire[2]	Elevation[3] (ft)	ΔAUM/acre
1	Spring	<4500	0.32
2	Spring		.12
1	Summer		.19
2	Summer		.34
1	Spring	>4500	.34
2	Spring		.12
1	Summer		.19
2	Summer		.35
3	Either	Either	-.07
4			-.06
5			-.05
6			-.04
7			-.01

[1]ΔAUM = 0 for years not listed.
[2]Season of fire for year 3 and all subsequent years is spring or summer.
[3]Elevation for year 3 and all subsequent years is ≤4500 ft or >4500 ft.

Table 12—*Estimated postfire net value change (NVC) in western hardwoods range production*

Elevation	Season of fire	Utilization level	Net production change	NVC (1978 dollars/acre) (rate)	
		pct	*ΔAUM/acre*	*4 pct*	*10 pct*
Either	Spring	25	0.06	0.66	0.71
	Spring	40	.08	1.05	1.14
	Summer	25	.08	.84	.87
	Summer	40	.12	1.34	1.38

REFERENCES

Althaus, Irene A.; Mills, Thomas J. **Resource values in analyzing fire managment programs for economic efficiency.** Gen. Tech. Rep. PSW-57. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 9 p.

Bailey, Arthur W.; Anderson, Murray L. **Prescribed burning of a *Festuca-Stipa* grassland.** J. Range Manage. 31:446-449; 1978.

Barlowe, Raleigh. **Land resource economics.** 4th ed. New Jersey: Prentice-Hall, Inc.; 1958. 585 p.

Barney, Milo A.; Frischknecht, Neil C. **Vegetation changes following fire in the pinyon-juniper type of west-central Utah.** J. Range Manage. 27:91-96; 1974.

Bartos, Dale L. **Modeling plant succession in aspen ecosystems.** In: Proceedings of the First International Rangeland Congress; Denver, CO: Society for Range Management; 1978: 208-211.

Bartos, Dale L. **Effects of burning on the aspen ecosystem.** In: Wyoming shrublands. Proceedings of the Eighth Wyoming Shrub Ecology Workshop; 1979 May 30-31; Laramie, WY: Range Management Division, University of Wyoming: 1979: 47-58.

Bartos, Dale L.; Mueggler, Walter F. **Influence of fire on vegetation production in the aspen ecosystem in western Wyoming.** In: Boyce, M.S.; Hayden-Wing, L.D., eds. North American elk ecology, behavior, and management. Laramie, WY: University of Wyoming; 1979: 75-78.

Bartos, Dale L.; Mueggler, Walter F. **Early succession in aspen communities following fire in western Wyoming.** J. Range Manage. 34:315-318; 1981.

Basile, Joseph V.; Jensen, Chester E. **Grazing potential on lodgepole pine clearcuts in Montana.** Res. Paper INT-98. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1971. 11 p.

Blaisdell, James P. **Ecological effects of planned burning of sagebrush-grass range on the upper Snake River Plains.** Tech. Bull. 1075. Washington, DC: U.S. Department of Agriculture, Forest Service; 1953. 39 p.

Bratten, Frederick W., Operations Research Analyst, Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Riverside, CA. [Conversation with David L. Peterson]. December 1982.

Carson, Gary, Range Management Specialist, Bureau of Land Management, U.S. Department of the Interior, Boise, ID. [Telephone conversation with David L. Peterson]. May 1982.

Clarke, S.E.; Tisdale, E.W.; Skoglund, N.A. **The effects of climate and grazing on shortgrass prairie vegetation.** Tech. Bull. 46. Canadian Dominion Department of Agriculture; 1943.

Conrad, C. Eugene; Poulton, Charles E. **Effects of a wildfire on Idaho fescue and bluebunch wheatgrass.** J. Range Manage. 19:138-141; 1966.

Crosby, John S. **A guide to the appraisal of: wildfire damages, benefits, and resource values protected.** Res. Paper NC-142. St. Paul, MN: North Central Forest and Range Experiment Station, Forest Service. U.S. Department of Agriculture; 1977. 43 p.

Currie, Pat O. **Cattle weight gain comparisons under seasonlong and rotation grazing systems.** In: Proceedings of the First International Rangeland Congress; Denver, CO: Society for Range Management; 1978: 579-580.

Davis, William, Range Management Specialist, Intermountain Region (R-4), Forest Service, U.S. Department of Agriculture, Ogden, UT. [Telephone conversation with David L. Peterson]. April 1982.

Flint, Howard R. **The appraisal of forest fire damages.** J. For. 22(2): 154-161; 1924.

Garrison, George A.; Bjugstad, Ardell J.; Duncan, Don A.; Lewis, Mont E.; Smith, Dixie R. **Vegetation and environmental features of forest and range ecosystems.** Agric. Handb. 475. Washington, DC: U.S. Department of Agriculture; 1977. 68 p.

Gee, C.K. **Estimating economic impacts of adjustments in grazing on federal lands and estimating federal rangeland forage values.** Tech. Bull. 143. Fort Collins, CO: Colorado State University Experiment Station; 1981. 11 p.

Goforth, Mark H.; Mills, Thomas J. **A financial return program for forestry investments; including sensitivity of results to data errors.** Agric. Handb. 488. Washington, DC: U.S. Department of Agriculture; 1975. 18 p.

Hamner, Robert W., Range Management Specialist, Pacific Northwest Region (R-6), Forest Service, U.S. Department of Agriculture, Portland, OR. [Telephone conversation with David L. Peterson]. April 1982.

Hardman, Billy H., Range Planner, Northern Region (R-1), Forest Service, U.S. Department of Agriculture, Missoula, MT. [Telephone conversation with David L. Peterson]. April 1982.

Harniss, Roy O.; Murray, Robert B. **Thirty years of vegetal change following burning of sagebrush-grass range.** J. Range Manage. 26:322-325; 1973.

Hedrick, D. W.; Hyder, D. N.; Sneva, F. A.; Poulton, C. E. **Ecological response of sagebrush-grass range in central Oregon to mechanical and chemical removal of *Artemisia*.** Ecology 47:432-439; 1966.

Jameson, Donald A. **The relationship of tree overstory and herbaceous understory vegetation.** J. Range Manage. 20:247-249; 1967.

Lewis, B. P. **Forage production and utilization in western Montana clearcuts.** Missoula, MT: University of Montana; 1965. 101 p. Dissertation.

Lewis, Joe; Johnson, Lionel R.; Mobley, Hugh; Davis, Jim; Cumbie, Richard; Duckett, Dave. **An assessment of values-at-risk relating to fire protection in Alabama.** Montgomery, AL: Alabama Forestry Commission; 1979. 45 p.

Lindenmuth, A. W., Jr.; Keetch, J. J.; Nelson, R. M. **Fire damage appraisal procedures and tables for the northeast.** Paper 11. Asheville, NC: Southeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture; 1951. 28 p.

Lyon, L. Jack. **Vegetal development following prescribed burning of Douglas-fir in south-central Idaho.** Res. Paper INT-105. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1971. 30 p.

Lyon, L. Jack. **Vegetal development on the Sleeping Child Burn in western Montana, 1961 to 1973.** Res. Paper INT-184. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1976. 24 p.

Lyon, L. Jack; Stickney, Peter F. **Early vegetal succession following large northern Rocky Mountain wildfires.** Proc. Tall Timbers Fire Ecology Conf. 14:335-375; 1976.

Martin, Robert E. **Fire manipulation and effects in western juniper (*Juniperus occidentalis* Hook.).** In: Martin, R. E.; Dealy, J. E.; Caraher, D. L., eds. Proceedings of the Western Juniper Ecology and Management Workshop; Bend, OR. Gen. Tech. Rep. PNW-74. Portland, OR: Pacific Northwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1978: 121-136.

Marty, Robert J.; Barney, Richard J. **Fire costs, losses, and benefits: an economic valuation procedure.** Gen. Tech Rep. INT-108. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1981. 11 p.

Mills, Thomas J.; Bratten, Frederick W. **FEES: design of a Fire Economics Evaluation System.** Res. Paper PSW-65. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 26 p.

Mueggler, Walter F. **Range resources and management problems in northern Idaho and northeastern Washington.** Res. Paper INT-68. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1962. 31 p.

Mueggler, Walter F.; Blaisdell, James P. **Effects on associated species of burning, rotobeating, spraying, and railing sagebrush.** J. Range Manage. 11:61-66; 19 68.

Mueggler, W. F.; Stewart, W. L. **Grassland and shrubland habitat types of western Montana.** Gen. Tech. Rep. INT-66. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1980. 154 p.

Nelson, Thomas C. **Fire management policy in the National Forests—a new era.** J. For. 77:723-725; 1979.

Pase, Charles P. **Herbage production and composition under immature ponderosa pine stands in the Black Hills.** J. Range Manage. 11:238-243; 1958.

Paulsen, Harold A. **Range management in the central and southern Rocky Mountains: a summary of the status of our knowledge by range ecosystems.** Res. Paper RM-154. Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1975. 34 p.

Peterson, David L. **Estimating postfire timber damage with a simulation model.** In: Proceedings of the seventh conference on fire and forest meteorology; 1983 April 25-28; Fort Collins, CO. Boston, MA: Am. Meteorol. Soc.; 1983: 159-162.

Ritters, Kurt; Brodie, J. Douglas; Hann, David W. **Dynamic programming for optimization of timber production and grazing in ponderosa pine.** Forest Sci. 28:517-526; 1982.

Salazar, Lucy A.; Bradshaw, Larry S. **Techniques for display and interpretation of fire behavior probabilities.** [In preparation].

Schroeder, Mark J.; Glovinsky, Monte; Hendricks, Virgil F.; Hood, Frank C.; and others. **Synoptic weather types associated with critical fire weather.** Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1964. 492 p.

Schultz, Vern, Range Administration Specialist, Bureau of Land Management, U.S. Department of the Interior, Portland, OR. [Telephone conversation with David L. Peterson]. May 1982.

Schweitzer, Dennis L.; Andersen, Ernest V.; Mills, Thomas J. **Economic efficiency of fire management programs at six National Forests.** Res. Paper PSW-157. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 29 p.

Sneva, Forrest A. **Grazing return following sagebrush control in eastern Oregon.** J. Range Manage. 25:174-178; 1972.

Stickney, Peter F. **Database for postfire succession, first 6 to 9 years, in Montana larch-fir forests.** Gen. Tech. Rep. INT-62. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1980. 133 p.

Tueller, Paul T.; Beeson, C. Dwight; Tausch, Robin J.; West, Neil E.; Rea, Kenneth H. **Pinyon-juniper woodlands of the Great Basin: distribution, flora, vegetal cover.** Res. Paper INT-229. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1979. 22 p.

U.S. Department of Agriculture, Forest Service. **Guidelines for economic and social analysis of programs, resource plans, and projects; final policy.** Federal Register 47(80):17940-17954; 1982.

U.S. Department of Agriculture, Forest Service. **An assessment of the forest and range land situation in the United States.** Publication FS-345. Washington, DC: U.S. Department of Agriculture, Forest Service; 1980. 631 p.

U.S. Department of Agriculture, Forest Service. **Fire considerations in forest planning.** Washington, DC: [Fire in Land Management Planning Task Force]. U.S. Department of Agriculture, Forest Service; 1979. 50 p.

U.S. Department of Agriculture, Forest Service. **A model for the determination of wildland resource values.** Washington, DC: Cooperative Fire Protection. U.S. Department of Agriculture, Forest Service; 1971. 39 p.

U.S. Office of Management and Budget. Circular A-94. Washington, DC; 1972. 4 p.

Uresk, D. W.; Rickard, W. H.; Cline, J. F. **Perennial grasses and their response to a wildfire in south-central Washington.** J. Range Manage. 33:111-114; 1980.

Uresk, D. W.; Cline, J. F.; Rickard, W. H. **Impact of wildfire on three perennial grasses in south-central Washington.** J. Range Manage. 29:309-310; 1976

Van Wagner, C. E. **Height of crown scorch in forest fire.** Can. J. Forest Res. 3:373-378; 1973.

Willms, W.; Bailey, A. W.; McLean, A. **Effect of burning or clipping *Agropyron spicatum* in the autumn on the spring foraging behavior of mule deer and cattle.** J. Appl. Ecol. 17:69-84; 1980.

Wright, Henry A. [Letter to David L. Peterson]. February 1983. 3 leaves. Located at: Pacific Southwest Forest and Range Experiment Station, Riverside, CA.

Wright, Henry A.; Bailey, Arthur W. **Fire ecology and prescribed burning in the Great Plains: a research review.** Gen. Tech. Rep. INT-77. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1980. 60 p.

Wright, Henry A.; Bailey, Arthur W. **Fire ecology: United States and southern Canada.** New York: John Wiley and Sons; 1982. 501 p.

Wright, Henry A.; Neuenschwander, Leon F.; Britton, Carlton M. **The role and use of fire in sagebrush-grass and pinyon-juniper plant communities.** Gen. Tech. Rep. INT-58. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1979. 48 p.

Wulf, Norman W., Silviculturist, Northern Region (R-1), Forest Service, U.S. Department of Agriculture, Missoula, MT. [Telephone conversation with David L. Peterson]. October 1982.

Peterson, David L.; Flowers, Patrick J. **Estimating postfire changes in production and value of Northern Rocky Mountain-Intermountain rangelands.** Res. Paper PSW-173. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1984. 19 p.

A simulation model was developed to estimate postfire changes in the production and value of grazing lands in the Northern Rocky Mountain-Intermountain region. Ecological information and management decisions were used to simulate expected changes in production and value after wildfire in six major rangeland types: permanent forested range (ponderosa pine), transitory range (Douglas-fir, larch, lodgepole pine, western white pine), mountain grassland, sagebrush, pinyon-juniper, and western hardwoods. Changes varied widely in quantity and duration among the range types. The largest decrease in net value was calculated for mountain grassland ($7/acre for a 2-year period). The largest increase in net value was calculated for a ponderosa pine sawtimber stand with 100 percent basal area removal ($36/acre for a 150-year period). The estimates calculated in this study should be useful in land and fire management planning in the Northern Rocky Mountain-Intermountain area.

Retrieval Terms: fire economics, fire effects, net value change, range management, simulation model, transitory range

United States
Department of
Agriculture

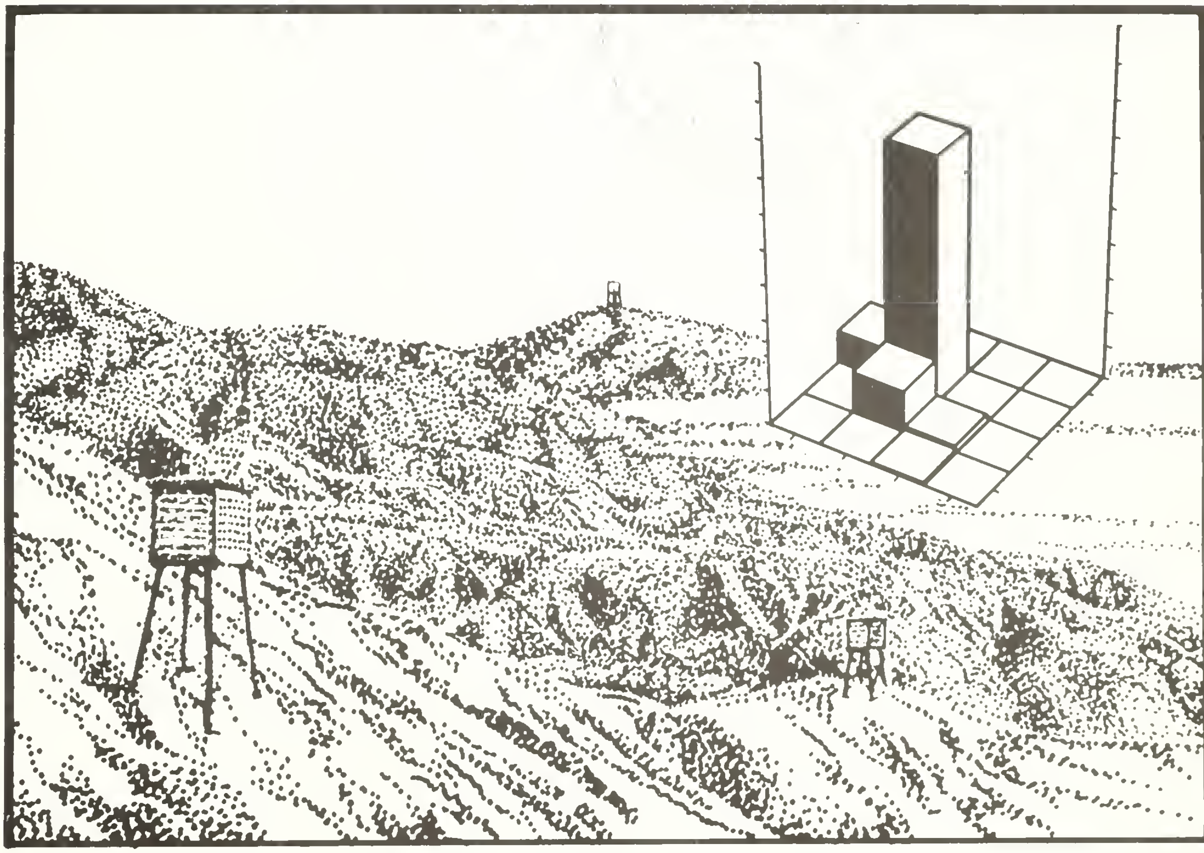
Forest Service

**Pacific Southwest
Forest and Range
Experiment Station**

Research Paper
PSW-174

Changes in Fire Weather Distributions: Effects on Predicted Fire Behavior

Lucy A. Salazar Larry S. Bradshaw



The Authors:

LUCY A. SALAZAR is a research forester assigned to the Station's Fire Management Planning and Economics Research Unit, headquartered at the Forest Fire Laboratory, Riverside, California. She earned a bachelor's degree in mathematics (1976) from the University of California, Irvine, and a master's degree in natural resources, with an emphasis in forestry (1980), at Humboldt State University, Arcata. She joined the Station staff in 1980. **LARRY S. BRADSHAW** is a research meteorologist with Systems for Environmental Management, Missoula, Montana. He received a bachelor's degree in meteorology (1975) from the University of Utah.

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

December 1984

Changes in Fire Weather Distributions: Effects on Predicted Fire Behavior

Lucy A. Salazar Larry S. Bradshaw

CONTENTS

IN BRIEF . . .

Salazar, Lucy A.; Bradshaw, Larry S. **Changes in fire weather distributions: effects on predicted fire behavior.** Res. Paper PSW-174. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1984. 11 p.

Retrieval Terms: fire weather, fire behavior, probabilistic fire modeling, wildfire

Average worst fire weather conditions used to predict daily fire danger are inadequate to simulate the range of possible events needed for long-term planning. We studied the effects that selected changes in weather databases have on computed fire behavior parameters in the northern Rocky Mountains. Cumulative and joint probability distributions of rate-of-spread and fireline intensity were computed from a base and four alternative weather files for eight test cases. Fire environment descriptors (fuel, slope, aspect, and time-of-year) varied among the test cases.

Weather files were stratified by two elevation and two time-of-year classes. The time-of-year classes were used to estimate live fuel moisture for fuel complexes with live fuels. Daily values of six fire weather elements were broken into subjective classes to facilitate computing unique combinations of the six elements. Each unique combination (weather day) was integrated with fire environment descriptors defined by the test case to compute a fire behavior value for that weather combination and test case. The output values were weighted by frequency of occurrence of a particular weather combination.

Changes in fire behavior distributions resulting from different weather files were analyzed for each case. One of the alternative weather files contained once-daily observations of weather elements; the others contained elements adjusted for diurnal and spatial variation in addition to the once-daily observations. Two of the alternative weather files contained data from fewer weather stations than did the base file. The fourth alternative weather file was from a higher elevation band.

The once-daily and the high-elevation alternatives resulted in more extreme fire behavior than did the base or the other two alternatives for all cases. Fire behavior distributions derived from the base and its alternatives differed less within each test case than between cases. Cases with more flammable fuel complexes varied more among the base and alternative weather files than did cases with less flammable fuel complexes.

In terms of probabilistic long-term planning needs within the study area, the source and amount of weather data were not critical factors in producing differences in fire behavior distributions of rate-of-spread and fireline intensity. The number of stations providing weather data was reduced substantially below the number available without a considerable change in the distributions of rate-of-spread and fireline intensity. Any of the four weather alternatives tested, including weather from only one station, were adequate for predicting the fire behavior of the test cases exhibiting low-intensity, slow-spreading fires. Depending on the resolution of the planning model, small weather subsets could also sufficiently represent higher intensity, faster spreading fires. Further analysis is necessary to determine this optimum subset of weather data, which would be based on output resolution requirements, fuel complexes, and geographical area. The techniques used in this study are appropriate for use in long-term fire management planning models.

The development of organized protection against wildfires has led to increasing effort to determine the most efficient placement and use of firefighters and equipment. The Fire Economics Evaluation System (FEES) is a long-term planning model being developed at the Pacific Southwest Forest and Range Experiment Station (Mills and Bratten 1982). It is designed to estimate the economic efficiency, fire-induced changes in resource outputs, and risk characteristics of a specified range of fire management program options. Fire behavior is one input to the economic evaluation process; modeling or computer simulation of suppression effectiveness and the resulting effect of fire is also part of that process.

To predict fire behavior, fire planners use fire behavior variables such as rate-of-spread (ROS) and fireline intensity (FLI). ROS describes the forward rate-of-spread of a fire, and FLI describes the difficulty of controlling it in terms of the heat it generates. These two variables are markedly affected by weather conditions, including windspeed, temperature, and relative humidity. They are also affected by slope, elevation, aspect, time-of-day, time-of-year, and type and amount of fuel. Therefore, site-specific and timely weather data are needed to determine real-time fire behavior for both fire suppression and prescribed burning.

An extensive spatial network of fire weather stations throughout the United States provides weather data once a day for the National Fire Danger Rating System (NFDRS) (Deeming and others 1977). When possible, fire weather is measured at the peak fire danger time (midafternoon), and at an open location, at midslope, on a southerly or westerly exposure. The NFDRS indexes the daily fire danger on the basis of 24-hour average-worst fire spread conditions for a particular area; however, the archived data are inadequate for simulating an entire fire season's probable range of events. Fires occurring on locations or at times not typified by average-worst conditions also need to be taken into account. For example, diurnal changes in weather may significantly affect fire behavior potential.

At lookout stations in Idaho, maximum temperatures were lower by 10° to 17° F (5.5 to 9.4° C) and minimum temperatures higher by about 4° F (2° C) than those at valley stations (Larsen 1922). The average daily wind velocity at mountain stations was about three times that at the valley stations. Day and night wind velocities at higher stations differed less than they did at valley stations. Relative humidity was lower at night and higher during the day at higher elevations.

The effect of differences in altitude, aspect and time of day on fire behavior in the Northern Rocky Mountain Region have been documented to determine where and when to measure fire danger under "average-bad" conditions (Hayes 1941, 1942, 1944). The studies used only median daily values for August and did not account for daily and seasonal variations. Findings included these:

- Three altitudinal zones differed in fire behavior characteristics: low zone, below 3,000 feet (915 m); thermal belt, 3,000-4,000 feet (915-1,220 m); high zone, above 4,000 feet (1,220 m).
- Four diurnal periods differed in fire behavior characteristics: night, 2200-0600 local standard time (l.s.t.); morning transition, 0600-1000 l.s.t.; day, 1000-1800 l.s.t.; and evening transition, 1800-2200 l.s.t.
- Single daily measurements made at a valley bottom station at 1200 or 1700 l.s.t. and at a 5,500-foot (1,677 m) south slope station at 1400 l.s.t. represented "average-bad" conditions for the Northern Rocky Mountain Region.
- Three daily measurements of weather improved the accuracy of "average-bad" fire danger ratings.
- Each of the three sets of data taken at different sites and hours of the day provided similar estimates of the fire danger at other places and hours.

The data used in those studies were later analyzed by the principal component and cluster techniques (Furman 1978). Fuel moisture attributes for seven locations on the mountain ridge spanning 3300 feet (1000 m) elevation on two aspects in northern Idaho were grouped in the analysis. The results showed grouping by valley bottom, midslope, and mountaintop.

For 23 weather stations in the Rocky Mountain forest of southern Alberta, Canada, minimum relative humidity in summertime did not vary significantly at elevations up to 1000 feet (305 m) above a valley bottom (MacHattie 1966). Above that, relative humidity appeared to increase. Nightly maximum humidity varied most near the valley bottom.

Various studies have evaluated the extrapolation of weather data to other sites (Campbell 1972), differences between weather data taken at fire weather stations as opposed to airport stations (Mitchem and Pigg 1970, Simard 1969), and methods to refine a network to an optimum number of fire weather stations (Fujioka and Fosberg 1981, Furman 1975, Innes 1969, King and Furman 1976, Knorr 1942, Morris 1940). Most of these studies evaluated weather data in terms of fire danger and average-worst conditions, which have different optimization criteria than does probabilistic fire behavior modeling. Also, because methods for deriving fire danger indexes have changed during the course of these studies, their results cannot be directly compared.

Frandsen and Andrews (1979) emphasized the importance of evaluating distributions of fire behavior parameters so that more realistic assessments of effects can be formulated. Fire environment descriptors of fuels, slope, aspect, and distributions of weather variables have been used to estimate cumulative and joint probability distributions of rate-of-spread (Albini 1976, Rothermel 1972) and fireline intensity (Byram 1959).

This paper reports a study of the effects that selected changes in weather databases have on computed fire behavior parameters for eight test cases within the northern Rocky Mountains. The simulation techniques used in this study are appropriate for use in long-term fire management planning models.

Figure 1—The Northern Rockies and Northern Intermountain region comprised the study area (Schroeder and others 1964).

METHODS

Selecting Weather Stations

The Northern Rockies and Northern Intermountain region (Schroeder and others 1964) *(fig. 1)* made up the study area. Within this area over 300 Forest Service weather stations have data archived in the National Fire Weather Data Library (NFWDL) (Furman and Brink 1975). Because of the enormous amount of weather data available and associated processing costs, the number of eligible stations was initially reduced by eliminating those no longer in service, those with abnormally small amounts of data due to sporadic collection over the years or short fire seasons, and those with less than 10 years of data *(fig. 2)*. The data from the remaining stations were considered to be adequate for use in long-term planning because of their seasonal completeness and long coverage.

Stations were grouped into four strata: 0-4500 feet (1372 m) elevation and above 4500 feet to approximate valley and mountaintop weather, and April to June and July to September to typify spring and summer fire seasons in the study area. The thermal belt was not accounted for because of the incapability of including inversion events in our modeling scheme.

Windspeed, temperature, relative humidity, daily temperature extremes, and precipitation amount "represented" a day of weather because of their reliable presence in the weather data library and their significant effects on fire behavior. Averages of each of these six parameters, across all days of weather for all stations within a stratum, were clustered by the CLUSTER routine within the Statistical Analysis System (SAS) (Helwig and Council 1979). Averages were used because of the great amount of data involved.

Cluster analysis is used when no *a priori* or theoretical classification information about the data is available. Clustering methods attempt to maximize the Euclidean distance between clusters in a step-by-step process. Each observation (in this study a set of six averaged weather parameters) is initially placed in its ow cluster. The two closest clusters are then combined into one; an the two closest of the new set are combined, and so on (Helwi and Council 1979). No satisfactory method exists for determinin the number of clusters for any type of cluster analysis (Everi 1979). In this analysis the criterion used for choosing the numbe of clusters was data processing cost, and the resulting number were different for each of the four strata.

Within each cluster, the station that had the most weather day was subjectively chosen as the representative station for that clus ter. In some cases this station may have had the most complet record because it was accessible rather than because it was typica of the surrounding area. Therefore, caution should be exercise when using this method in other analyses. A weather file for rep resentative weather stations was created for each of the four strata

Elevation (ft)	Time of year	Stations	Weather day
0-4,500 (1,372 m)	April-June	33	24,268
0-4,500	July-September	13	25,422
> 4,500	April-June	26	14,918
> 4,500	July-September	20	30,899

These base data files contained the entire archived record for a days of entry.

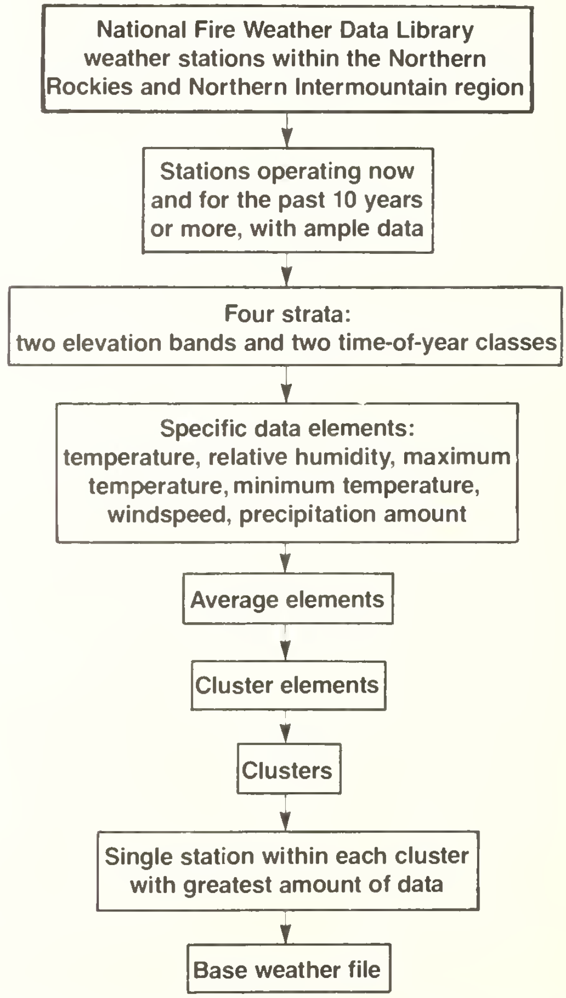


Figure 2—To reduce the large amount of data available, weather station were eliminated by a selection procedure.

Converting Weather Data to Probability Distributions

The base weather files were processed through the FIREWX computer program adapted from the National Fuels Appraisal Project (Radloff and others 1982) by Bradshaw (1982). FIREWX uses NFDRS fuel moisture subroutines (Deeming and others 1977), to derive unique combinations for selected ranges of the following parameters with their associated probabilities:

- 1-hour fuel moisture (percent)
- 10-hour fuel moisture (percent)
- 100-hour fuel moisture (percent)
- Herbaceous fuel moisture (percent)
- Woody (shrub) fuel moisture (percent)
- Windspeed (mi/h, 20-foot [6 m], 10-minute observed average)

To compute fuel moistures for situations other than those defined by the typical NFDRS weather station collection time and place, fuel moisture adjustment tables were used (Rothermel 1983). This fuel moisture adjustment required a reference temperature and relative humitidy, which were used to locate base fine (1- and 10-hour) fuel moisture in a table. The base fine fuel moisture was then adjusted as a function of time of year, time of day, slope, aspect, and a fuel-type shading factor (shaded versus exposed).

Reference temperatures at times other than the fire weather observation time were estimated by a diurnal temperature model (McCutchan 1979). The model uses the first two harmonics of a Fourier series to predict temperature at time "t" with the two independent variables being the day's temperature range and average temperature. Relative humidity at time "t" was then estimated by assuming a constant airmass and by conserving specific humidity from the observed relative humidity. If maximum and minimum temperatures were missing from a day's weather record, fine fuel moistures were derived directly from adjustments of the observation time fine fuel moistures.

Windspeed also fluctuates diurnally, but a diurnal windspeed model compatible with FIREWX was not available. Each day's observed windspeed was used for all time-of-day classes. Wind reduction factors specific to a fuel model (in terms of percentages of the observed windspeeds) were used to reduce the observed 20-foot (6 m) windspeed to midflame windspeed (Baughman and Albini 1980) required by the fire model. Windspeeds for NFDRS stations are recorded as 10-minute averages, and therefore, momentary gusts were not evaluated.

Analyzing Fire Behavior Distributions

Sensitivity analysis of computed fire behavior distributions was in terms of two weather data manipulations: varying the source and amount of weather data, and diurnally adjusting temperature and relative humidity. The four alternative data files were defined as follows:

Alternative file	Source of data
I	Five fire weather stations, Lolo National Forest, Montana
II	One fire weather station, Lolo National Forest
III	Observed weather only
IV	Higher elevation stations

The Lolo National Forest was subjectively chosen as a representative forest within the Northern Rockies and Northern Intermountain region. The breakdown of the subsets of weather stations was as follows:

Elevation (ft)	Time of year	Stations	Weather days
0-4,500 (1,372 m)	April-June	5	4,063
0-4,500	July-September	5	9,710
4,036 (1,230 m)	April-June	1	321
4,036	July-September	1	2,288

Fire weather distributions were not directly compared because only the notation of a change in the total number of unique weather combinations was possible. Individual unique weather combinations were not compared because they sometimes exceeded 3,000. The base and four alternative weather files were processed instead by a fire behavior computer program (Radloff and others 1982) adapted by Bradshaw (1982). It calculates joint probabilities and expected values of ROS and FLI from weather data, fuel model (Albini 1976), aspect, and slope class (0-39 pct, 40-79 pct, 80-100 pct). Midpoints of the slope classes were used in the fire behavior computations. The effect of different weather files on expected values and joint probabilities of ROS and FLI were then compared.

To facilitate the use of diurnally adjusted weather, daytime was approximated by the hours from 0500 to 2000 l.s.t. and divided into four subclasses: 0500-0759, 0800-1159, 1200-1559, and 1600-1959. Each subclass was weighted based on its frequency of occurrence at time of discovery on Forest Service Individual Fire Report forms (Form 5100-29) for the study area during 1970 to 1981. Subclasses were stratified by elevation band, time-of-year class, aspect, slope class, and fuel model derived from cover type. For modeling purposes, "cover type in vicinity of origin" on fire report forms was converted to fuel model. This conversion was based on the form entry of "fuel type in vicinity of origin," which is a relative ranking of ROS and resistance to control. Each fuel model was also assigned a ranking of these two parameters. A cross tabulation of cover type by these two rankings resulted in a distribution of fuel models for each cover type. Modeled fire behavior for these subclasses was weighted by their frequency percentages to delineate daytime fire behavior. This weighting scheme, therefore, emphasizes the situation-specific fire behavior occurring during those time-of-day classes when fires were discovered. The resulting weighted adjusted daytime fire behavior was compared with the unadjusted behavior derived solely from observed weather.

Table 1—*Slope, aspect, fuel model, and time-of-year class for eight test cases, 0-4500 ft (1372 m) elevation in the northern Rocky Mountains*

Case	Slope (pct)	Aspect	Fuel model[1] (percentage and description)	Time of year
1	0-39	N	2/9—2(40 pct)—open pine with grass understory and 9(60 pct)-long-needle pines	Apr.-June
2	40-79	N	8—healthy short-needle confier stand	Apr.-June
3	0-39	N	10/8—10(40 pct)-decadent short-needle conifer stand and 8(60 pct)-healthy short-needle conifer stand	Apr.-June
4	0-39	S	12/11—12(40 pct)-medium loading slash and 11(60 pct)-low loading slash	Apr.-June
5	0-39	N	2/9—2(40 pct)-open pine with grass understory and 9(60 pct)-long-needle pines	July-Sept.
6	40-79	N	8—healthy short-needle conifer stand	July-Sept.
7	0-39	N	10/8—10(40 pct) decadent short-needle conifer stand and 8(60 pct)-healthy short-needle conifer stand	July-Sept.
8	0-39	S	12/11—12(40 pct)-medium loading slash and 11(60 pct)-low loading slash	July-Sept.

[1] Albini (1976).

RESULTS AND DISCUSSION

Because of the many possible situations, results are presented for only eight cases that best represent a wide range of potential fire behavior *(table 1)*. Six of the eight cases involved the two-fuel model concept (Rothermel 1983) primarily because of the known heterogeneity of natural fuel beds. Fuel model percentages were subjectively determined to represent typical fuel bed arrays within the study area. The following standards apply when modeling fire behavior using the two-fuel model concept (Rothermel 1983). The wind reduction factor from the model with the greater percentage of areal coverage is used to compute ROS and FLI for both fuel models. If coverage is equal, the minimum reduction factor is used. ROS is predicted for each fuel model, then weighted by the areal percentage of the respective fuel model to produce one ROS value. FLI is not weighted; the maximum computed FLI for the two fuel models is used.

Cumulative Probabilities

When comparing the eight cases, note the differences in scale among some of the graphs in *figures 3* and *4*. ROS and FLI for cases 2 and 6 appear to differ substantially among alternatives, but the maximum values for ROS (3.0 ft/min [0.015 m/s]) and FLI (12 BTU/s/ft [41.5 kW/m]) are small. In all cases, alternative II had the lowest cumulative values for ROS *(fig. 3)* and FLI *(fig. 4)*. Alternative IV produced consistently higher values for both fire behavior parameters. These results substantitate earlier findings (Furman 1978; Hayes 1941, 1942, 1944; Larsen 1922) and show the effect that higher elevation patterns have on fire behavior. Overall the similarity among each base and its four alternatives was considerable. Fuel model was a notable cause of differences between cumulative probabilities of ROS and FLI. Lower severity fuel models (8 and 10/8) showed smaller differences (cases 2, 3, 6, and 7 in *figs. 3* and *4)*, whereas, higher severity fuel models (2/9 and 12/11) had greater differences (cases 1, 4, 5, and 8 in *figs. 3* and *4)*.

Percentile values of weather and fire behavior are frequently used in presuppression planning to rank the historical risk associated with certain fire management situations. A given fire behavior percentile value (90th, for example) indicates that 90 percent of the days in the sample exhibited behavior characteristics of the 90th percentile value or less. For ROS *(table 2)* and FLI *(table 3)*, these values indicate that, as above, smaller differences are found in the less severe fuel models (cases, 2, 3, 6, and 7) and larger differences in the higher severity fuel models (cases, 1, 4, 5, and 8) between alternatives. These differences in the 90th percentile values show the significance of fuel model selection in presuppression planning.

Joint Probabilities

To facilitate comparing joint probabilities of ROS and FLI, values were broken down subjectively into four classes to reflect relative ranking of fire behavior:

Rank:	ROS		FLI	
	ft/min	*(m/s)*	*BTU/s/ft*	*(kW/m)*
Low	0 - 2.5	(0.012)	0 - 100.0	(346)
Medium	2.51 - 12.5	(0.062)	100.1 - 500.0	(1,730)
High	12.51 - 25.0	(0.125)	500.1 - 1,000.0	(3,459)
Extreme	> 25.0		> 1,000.0	

Contingency tables were derived for the eight test cases from the base and four alternative data files and represented by three-dimensional histograms *(fig. 5)*. No major cell differences were shown by any of the eight base files and their alternatives, but—as would be expected—fire behavior differed substantially among the test cases. The majority of ROS and FLI values for cases 2, 3, 6, and 7 (fuel models 8 and 10/8) were consistently in the lowest ranks. Values for only fuel model 12/11 (cases 4 and 8) were in the higher categories.

Root mean square differences (RMSD's) among the base data and alternatives were also computed *(table 4)* as a convenient method of mathematically evaluating overall differences in joint probabilities. Because of their nonstatistical nature, RMSD's were only compared relatively. Certain differences and trends in RMSD's were evident. Both fuel models 8 (cases 2 and 6) and 10/8 (cases 3 and 7) showed low ROS and FLI, and different weather inputs did not substantially alter the fire behavior for these test cases. All RMSD's for fuel model 8 were less than 0.004 and for fuel model 10/8 were less than 0.014 *(table 4)*.

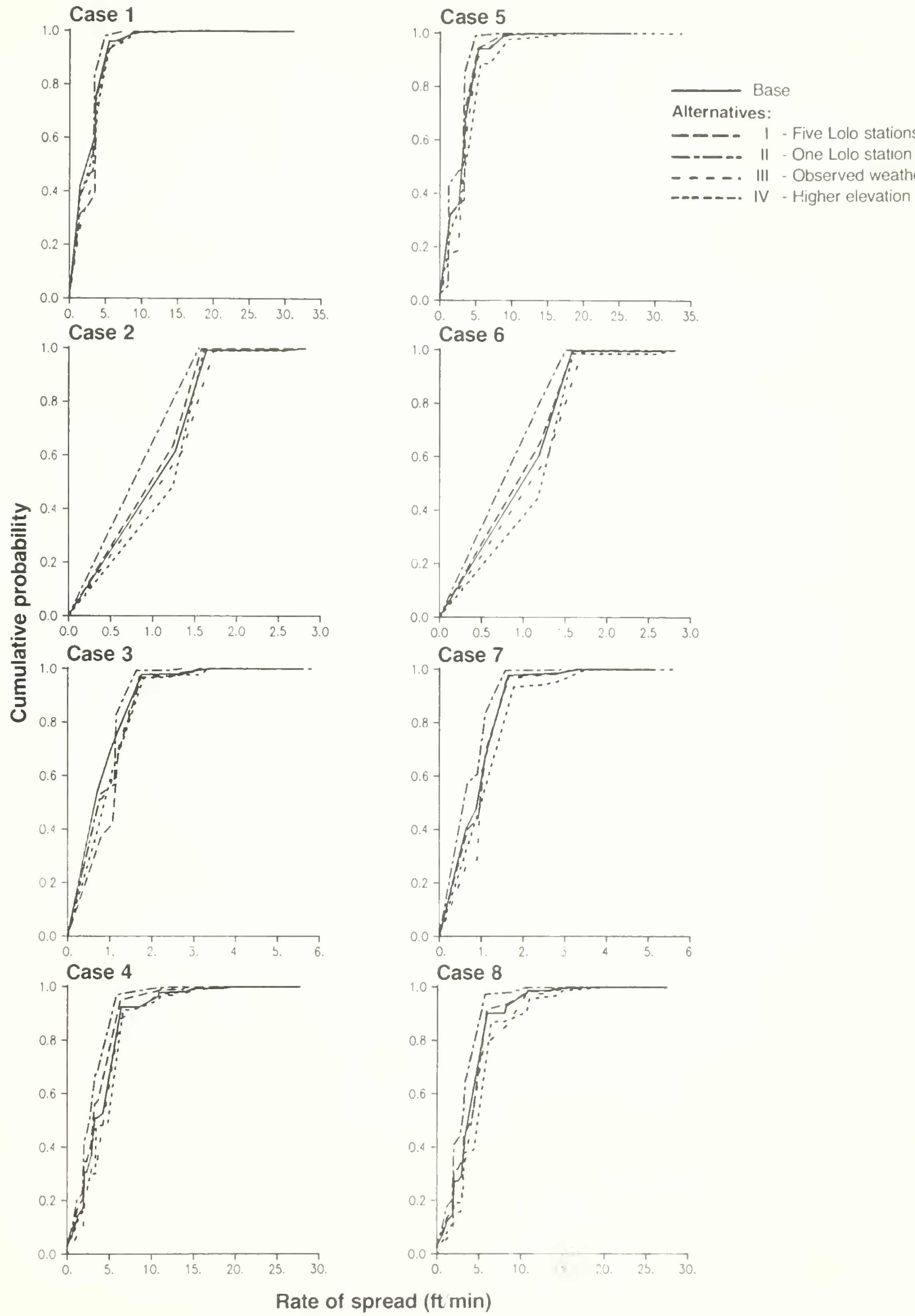


Figure 3—Cumulative probabilities of rate-of-spread were similar for each base weather file and four alternative files. Note the difference in scale among the graphs. (1 ft/min = 0.005 m/s)

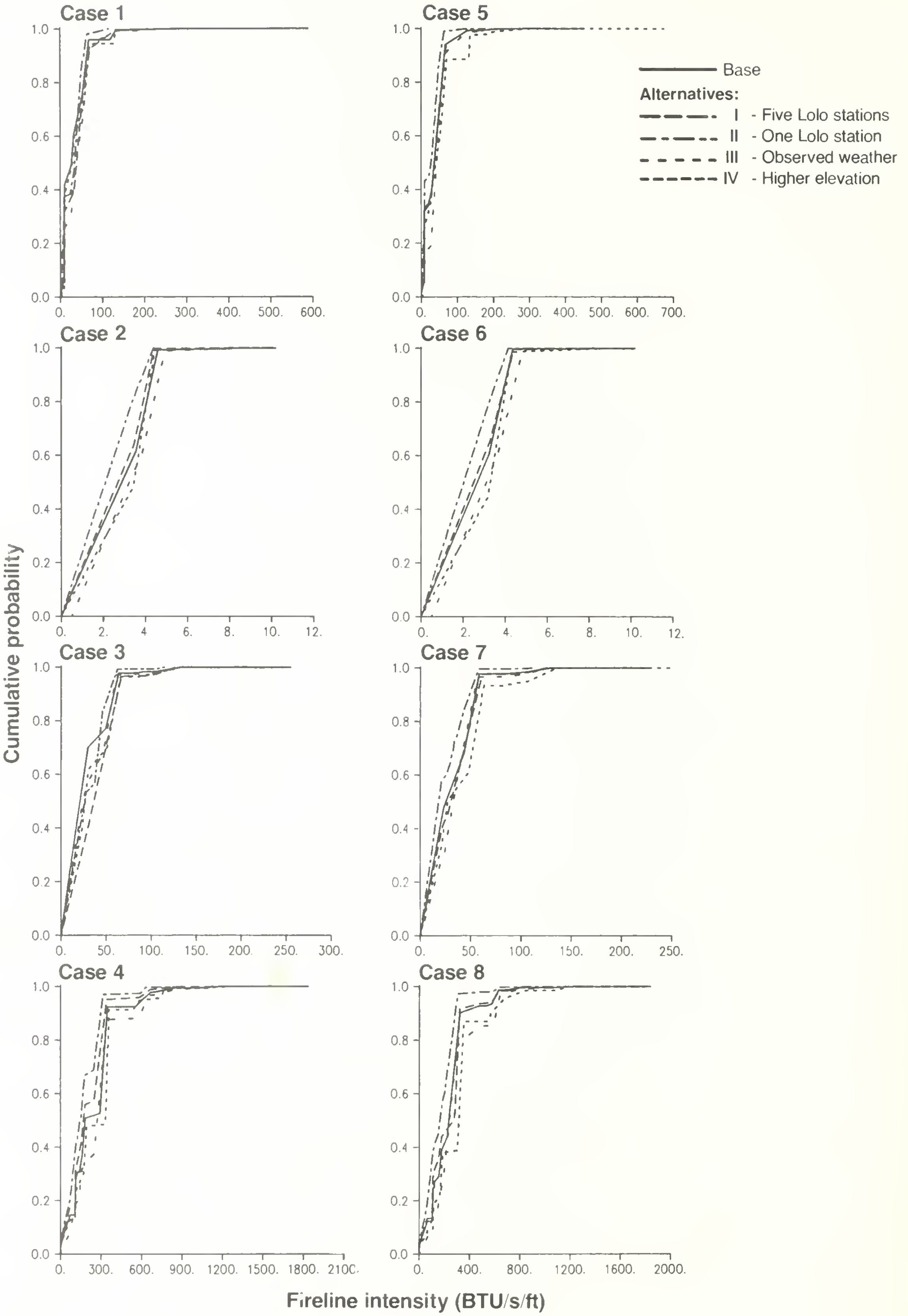


Figure 4—Cumulative probabilities of fireline intensity were similar for each base weather file and four alternative files. Note the difference in scale among the graphs. (1 BTU/s/ft = 3.4592 kW/m)

Table 2—*Ninetieth percentile rate-of-spread values (ft/min)*[1] *from base and four alternative weather files for eight test cases in the northern Rocky Mountains*

Weather file	Test cases							
	1	2	3	4	5	6	7	8
Base	4.94	1.55	1.55	6.27	5.07	1.48	1.50	5.97
Alternatives								
I Five Lolo stations	5.05	1.49	1.61	5.94	4.95	1.48	1.52	5.87
II One Lolo station	4.12	1.39	1.36	5.30	3.99	1.34	1.28	5.22
III Observed weather	5.17	1.64	1.58	7.40	5.20	1.60	1.49	9.16
IV Higher elevation	5.26	1.54	1.66	6.57	7.36	1.52	1.72	10.31

[1] Rate-of-spread of 1 ft/min = 0.005 m/s.

Table 3—*Ninetieth percentile fireline intensity values (BTU/s/ft)*[1] *from base and four alternative weather files for eight test cases in the northern Rocky Mountains*

Weather file	Test cases							
	1	2	3	4	5	6	7	8
Base	64.62	4.34	62.93	344.48	65.05	4.08	54.65	322.75
Alternatives								
I Five Lolo stations	68.84	4.15	62.67	329.30	66.54	4.09	56.65	319.48
II One Lolo station	56.67	3.88	61.09	298.05	53.91	3.69	48.84	286.63
III Observed weather	66.74	4.68	57.84	594.98	66.48	4.55	53.29	608.87
IV Higher elevation	68.38	4.26	62.47	358.84	133.66	4.13	61.66	570.14

[1] Fireline intensity of 1 BTU/s/ft = 3.4592 kW/m.

Fuel models 2/9 and 12/11 exhibited more varied fire behavior with higher RMSD's and more cells of the contingency table being filled. The range of RMSD's is 0.001 to 0.053 for fuel model 2/9 and 0.009 to 0.033 for fuel model 12/11 *(table 4)*.

No one alternative consistently had the smallest RMSD for all eight test cases. Alternative I had the smallest RMSD for four of the test cases, with values ranging from 0.001 to 0.032 *(table 4)*. Considering the small amount of data within Alternative II, it performed well with small RMSD's, ranging from 0.001 to 0.034 *(table 4)*. The greatest discrepancies again occurred for fuel models 2/9 and 12/11 (cases 1, 4, 5, and 8).

Alternative III had the highest overall RMSD's. The range was from 0.001 to 0.053 with four RMSD's greater than 0.025 *(table 4)*. These values are still small, but they do indicate that diurnal weather adjustments can affect fire behavior predictions, especially in the cases of faster spreading, higher intensity fuel models.

Alternative IV provided comparable results across all test cases with the best performance in the April-June stratum. This could be due to greater variations of weather patterns between elevation bands during the summer months.

The implications of these results go beyond long-term planning needs. Adjusting observed midafternoon temperature and relative humidity to other times of day and processing an entire day's weather gives managers a broader perspective than do average worst conditions. A diurnal windspeed adjustment would further enhance perspective, and a compatible diurnal windspeed model is being investigated. Ranges of fire behavior parameters allow for a better assessment of both wildfire and prescribed burning situations. Joint probabilities of ROS and FLI would improve the ability to evaluate long-range planning situations by allowing fire managers to consider suppression effectiveness and fire effects simultaneously.

The noncritical nature of the amount of weather inputs for long-term fire management planning indicated that real-time fire needs may be more important for placing weather stations or determining the number to maintain. For example, if long-term planning and suppression readiness needs were met by a small number of strategically placed stations recording diurnal weather (Furman 1982), mobile diurnal stations could be used for real-time fire behavior needs, such as prescribed burns and escaped fires. These mobile stations could also improve the forecasting of mesoscale phenomena, which are often the cause of extreme fire behavior that results in loss of life and resources (Chandler 1976).

Table 4—*Root mean square differences in rate-of-spread and fireline intensity contingency tables among four alternative data files when compared to the base data set for eight test cases in the northern Rocky Mountains*

Case	Alternatives			
	I Five Lolo stations	II One Lolo station	III Observed weather	IV Higher elevation band
1	0.032	0.020	0.053	0.013
2	.002	.003	.001	.001
3	.004	.005	.002	.004
4	.009	.025	.027	.013
5	.001	.034	.047	.019
6	.001	.001	.001	.004
7	.001	.006	.004	.014
8	.012	.033	.026	.016

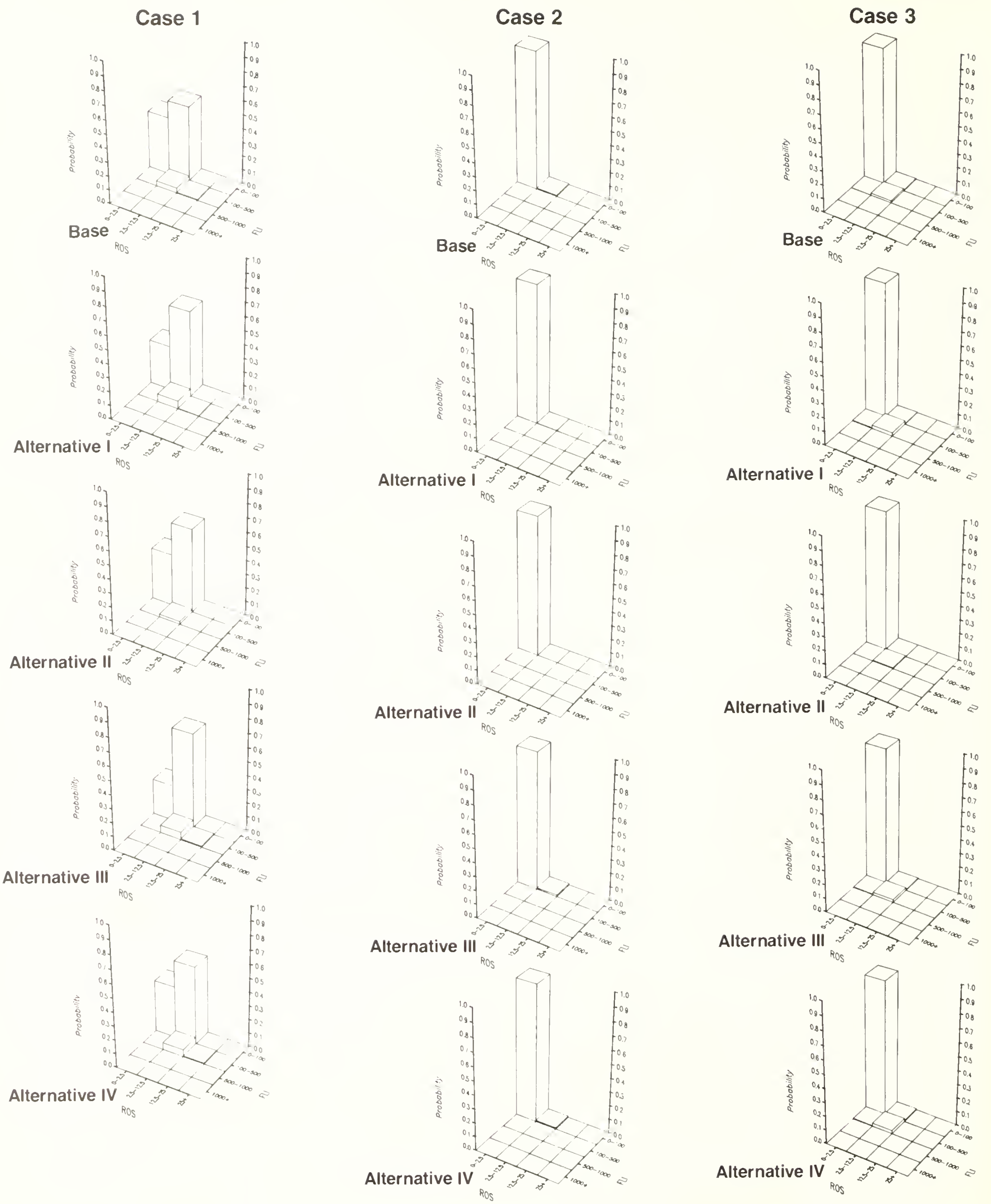
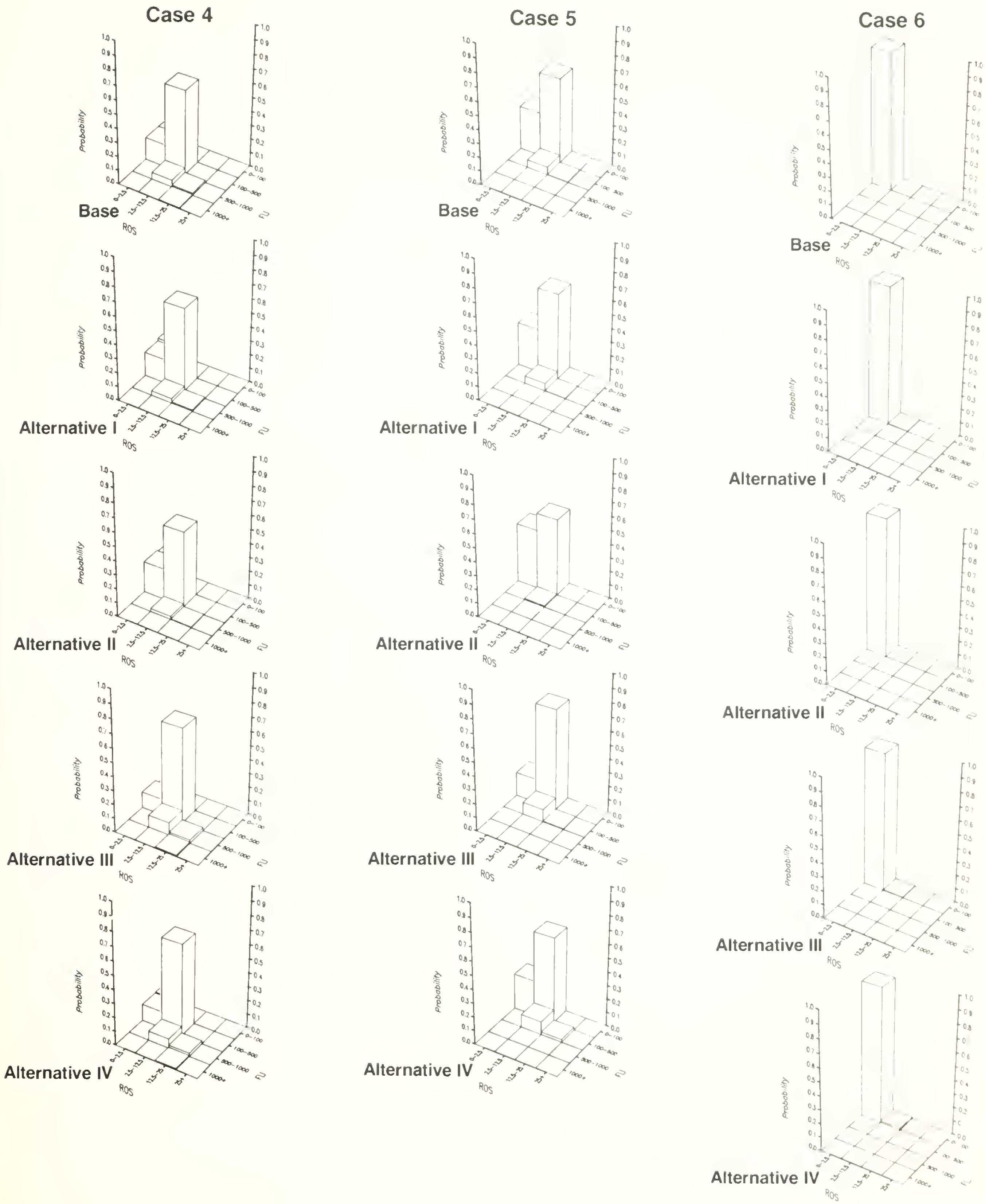
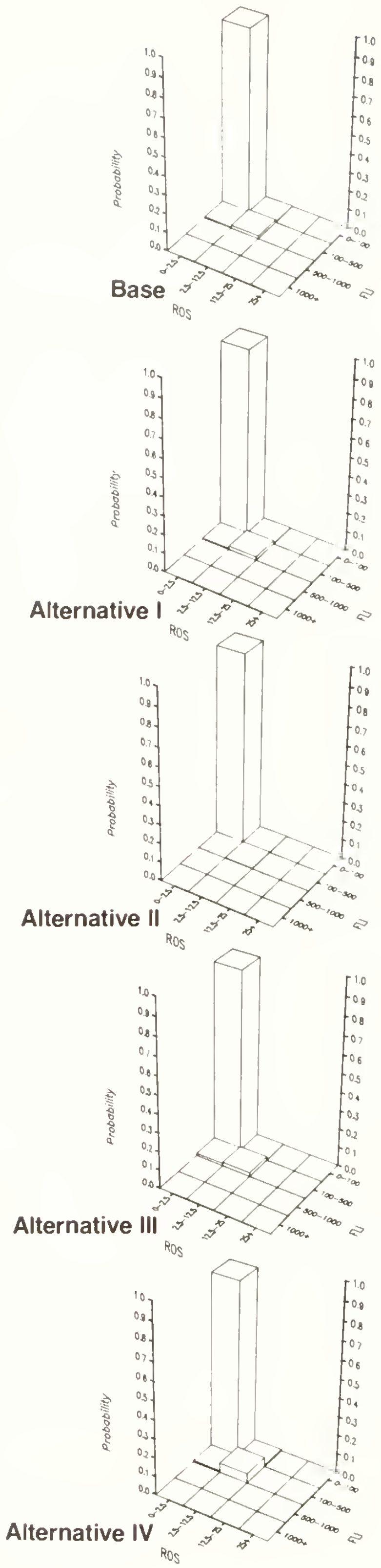


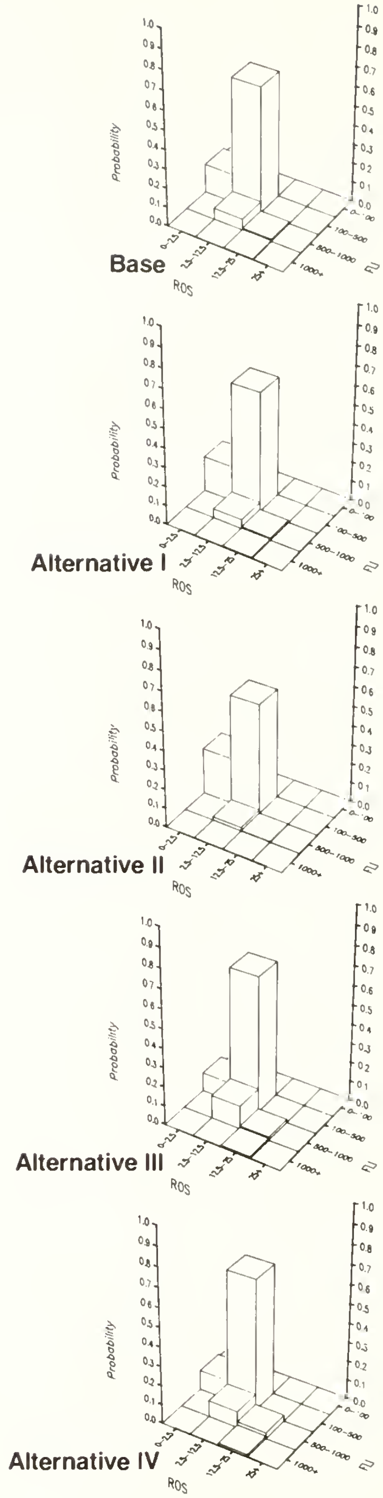
Figure 5—Three-dimensional histograms depict contingency tables for rate-of-spread (ROS) and fireline intensity (FLI) derived from base data files and four alternative files (Alternatives: I—five Lolo stations, II—one Lolo station, III—observed weather, IV—higher elevation stations).


Case 4
Case 5
Case 6
Base
Alternative I
Alternative II
Alternative III
Alternative IV
Probability
ROS
0–2.5
2.5–12.5
12.5–25
25+
0–100
100–500
500–1000
1000+

Case 7


Base
Alternative I
Alternative II
Alternative III
Alternative IV
Probability
ROS
FU

Case 8


Base
Alternative I
Alternative II
Alternative III
Alternative IV
Probability
ROS
FU

CONCLUSIONS

For probabilistic long-term planning needs, within the Northern Rockies and Northern Intermountain region, the source and amount of weather data were not critical factors in predicting distributions of rate-of-spread and fireline intensity. The number of weather stations can be substantially reduced below the maximum determined to be available, without a considerable change in the probabilistic distributions of the fire behavior parameters of rate-of-spread and fireline intensity. Suppression effectiveness and fire effects would have to be subsequently modeled to determine whether management decisions would change on the basis of the results. Any of the four alternative data files tested, including weather from only one station, would be adequate for predicting the fire behavior of the test cases showing lower intensity, slower spreading fires. Depending on the resolution of the planning model, smaller weather subsets could also sufficiently represent higher intensity, faster spreading fires. Further analysis is necessary to determine this optimum subset of weather data, which would be based on output resolution requirements, fuel models, and possibly geographic region.

REFERENCES

Albini, Frank A. **Estimating wildfire behavior and effects.** Gen. Tech. Rep. INT-30. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1976. 92 p.

Baughman, Robert G.; Albini, Frank A. **Estimating midflame windspeeds.** Proceedings, Sixth Conference on fire and forest meteorology; 1980 April 22-24; Seattle WA. Washington, DC: Society of American Foresters; 1980: 88-92.

Bradshaw, Larry S. **Probabilistic modeling of fire weather and fire behavior.** Cooperative Aid Agreement PSW-80-0024. Final report. Missoula, MT: Systems for Environmental Management; 1982. 60 p.

Byram, George M. **Combustion of forest fuels.** In: Davis, Kenneth P., ed. Forest fire control and use. New York: McGraw-Hill Book Co.; 1959. 61-89.

Campbell, Ralph E. **Prediction of air temperature at a remote site from official weather station records.** Res. Note RM-223. Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1972. 4 p.

Chandler, Craig C. **Meteorological needs of fire danger and fire behavior.** In: Baker, Douglas H., Fosberg, Michael A., tech. coord. Proceedings, Fourth national conference on fire and forest meteorology; 1976 November 16-28; St. Louis, MO. Gen. Tech. Rep. RM-32. Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1976: 38-41.

Deeming, John E.; Burgan, Robert E.; Cohen, Jack D. **The National Fire Danger Rating System—1978.** Gen. Tech. Rep. INT-39. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1977. 63 p.

Everitt, B. S. **Unresolved problems in cluster analysis.** Biometrics 35:169-181; 1979.

Frandsen, William H.; Andrews, Patricia L. **Fire behavior in nonuniform fuels.** Res. Paper INT-232. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1979. 34 p.

Fujioka, Francis M.; Fosberg, Michael A. **Design of a weather station network for natural resource management.** In: Weiss, A., ed. Proceedings, Computer techniques and meteorological data applied to agriculture and forestry: a workshop; 1981 March 30-31; Anaheim, CA. Lincoln, NE: University of Nebraska; 1981. 28-40.

Furman, R. William. **An aid to streamlining fire-weather station networks.** Gen. Tech. Rep. RM-17. Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1975. 4 p.

Furman, R. William. **Wildfire zones on a mountain ridge.** Assoc. Am. Geogr. 68(1):90-94; 1978.

Furman, R. William. **Archiving remote automatic weather station data.** Fire Manage. Notes. 43(3):3-5; 1982 Summer.

Furman, R. William; Brink, Glen E. **The National Fire Weather Data Library: What it is and how to use it.** Gen. Tech. Rep. RM-19. Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1975. 8 p.

Hayes, G. Lloyd. **Influence of altitude and aspect on daily variations in factors of forest fire danger.** Circ. 591. Washington, DC: U.S. Department of Agriculture; 1941. 39 p.

Hayes, G. Lloyd. **Differences in fire danger with altitude, aspect, and time of day.** J. For. 40(4):318-323; 1942.

Hayes, G. Lloyd. **Where and when to measure forest-fire danger.** J. For. 42(10):744-751; 1944.

Helwing, Jane T.; Council, Kathryn A., ed. **SAS user's guide.** 1979 ed. Cary, NC: SAS Institute Inc.; 1979. 157-161.

Innes, Williams. **A test for continuous monitoring of fire danger.** Calif. Fire Control Notes 20:1-8; 1969.

King, Rudy M.; Furman, R. William. **Fire danger rating network density.** Res. Paper RM-177. Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1976. 4 p.

Knorr, Philip. **Variations in fire danger factors on a ranger district in the longleaf pine region.** J. For. 40(9):689-692; 1942.

Larsen, J. A. **Weather records at lookout stations in northern Idaho.** Mon. Weath. Rev. 49(1):13-14; 1922.

MacHattie, L. B. **Relative humidity in Rocky Mountain forests of southern Alberta in summer.** Information Rep. FF-X-1. Ottawa, Canada: Forest Fire Research Institute, Department of Forestry; 1966. 54 p.

McCutchan, Morris H. **Determining the diurnal variation of surface temperature in mountainous terrain.** J. Appl. Meteorol. 18(9):1224-1229; 1979.

Mills, Thomas J.; Bratten, Frederick W. **FEES: design of a Fire Economics Evaluation System.** Gen. Tech. Rep. PSW-65. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 26 p.

Mitchem, Richard A.; Pigg, Charles A. **Can airport weather stations compute fire danger spead index ratings?** Fire Control Notes 31(13):12-14; 1970.

Morris, William C. **Statistical analysis of fire weather station distribution.** J. For. 38(4):318-321; 1940.

Radloff, David L.; Yancik, Richard F.; Walters, Kenneth G. **User's guide to the National Fuel Appraisal Process.** Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 41 p.

Rothermel, Richard C. **A mathematical model for predicting fire spead in wildland fuels.** Res. Paper INT-115. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1972. 40 p.

Rothermel, Richard C. **How to predict the spread and intensity of forest and range fires.** Gen. Tech. Rep. INT-143. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983. 161 p.

Schroeder, Mark J.; Glovinsky, M.; Hendricks, V.; and others. **Synoptic weather types associated with critical fire weather.** Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1964. 492 p.

Simard, A. J. **Variability in windspeed measurement and its effect on fire danger rating.** Information Rep. FF-X-19. Ottawa, Canada: Forest Fire Research Institute, Department of Forestry; 1969. 39 p.

Salazar, Lucy A.; Bradshaw, Larry S. **Changes in fire weather distributions: effects on predicted fire behavior.** Res. Paper PSW-174. Berkeley, CA. Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1984. 11 p.

Data that represent average worst fire weather for a particular area are used to index daily fire danger; however, they do not account for different locations or diurnal weather changes that significantly affect fire behavior potential. To study the effects that selected changes in weather databases have on computed fire behavior parameters, weather data for the northern Rocky Mountains were treated as probability distributions, then used in computer simulation to estimate distributions of rate-of-spread (ROS) and fireline intensity (FLI). Sensitivity of ROS and FLI to weather input changes was analyzed by varying the source and amount of weather data, and diurnally adjusting temperature and relative humidity. In eight representative cases, a minimum amount of data produced the lowest cumulative probabilities of ROS and FLI, and data from a higher elevation produced the highest values. For long-term planning, within the region studied, a small subset of weather data distributions was adequate for estimating probabilistic distributions of ROS and FLI. Joint probabilities of ROS and FLI differed substantially among test cases. Fire behavior values obtained with observed data were higher than those obtained with diurnally adjusted data. The simulation techniques used are appropriate for use in long-term fire management planning models.

Retrieval Terms: fire weather, fire behavior, probabilistic fire modeling, wildfire

United States
Department of
Agriculture

Forest Service

**Pacific Southwest
Forest and Range
Experiment Station**

Research Paper
PSW-175

Mixed Plantations of *Eucalyptus* and Leguminous Trees Enhance Biomass Production

Dean S. DeBell   Craig D. Whitesell   Thomas H. Schubert

The Authors:

did the research reported herein under cooperative agreements among the Pacific Northwest Forest and Range Experiment Station, Pacific Southwest Forest and Range Experiment Station, and BioEnergy Development Corporation. **DEAN S. DeBELL** is in charge of the Pacific Northwest Station's research on the biology and silviculture of forests of the Douglas-fir region, with headquarters in Olympia, Washington. He earned a bachelor of science degree (1963) in biology from Juniata College and master of forestry (1964) and doctoral degrees (1970) in forestry at Duke University. **CRAIG D. WHITESELL** heads up the Pacific Southwest Station's forestry research in the American Pacific Islands, and is stationed in Honolulu, Hawaii. He earned a bachelor of science degree (1951) in forestry at West Virginia University, and a master of forestry degree (1954) at Duke University. **THOMAS H. SCHUBERT** is a research silviculturist with the BioEnergy Development Corporation, Hilo, Hawaii. He earned a bachelor of science degree (1953) in forestry at New York State University College of Forestry, Syracuse, and a master of forestry degree (1955) and doctoral degree (1959) in biology at Harvard University.

Acknowledgments:

The research reported herein was supported in part by funds of the U.S. Department of Energy's Short Rotation Woody Crops Program provided under contract to BioEnergy Development Corporation. We thank the staff of the Corporation and of the Forest Service's Institute of Pacific Islands Forestry, Honolulu, Hawaii, and the Forestry Sciences Laboratory, Olympia, Washington, for assistance in field work, planning, and data analysis; the C. Brewer Analytical Laboratory for soil analyses; and the University of Hawaii Applied Research Laboratory for foliar analyses.

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

July 1985

Mixed Plantations of *Eucalyptus* and Leguminous Trees Enhance Biomass Production

Dean S. DeBell   Craig D. Whitesell   Thomas H. Schubert

CONTENTS

IN BRIEF

DeBell, Dean S.; Whitesell, Craig D.; Schubert, Thomas H. **Mixed plantations of *Eucalyptus* and leguminous trees enhance biomass production.** Res. Paper PSW-175. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, 1985. 6 p.

Retrieval Terms: Eucalyptus, Eucalyptus saligna, Eucalyptus grandis, Acacia melanoxylon, Albizia falcataria, legumes, species trials, plantations, Hawaii

Because of their quick growth and high yields, two *Eucalyptus* species are especially favored for wood, fiber, and fuel production in Hawaii. But the growth of *E. saligna* Sm. and *E. grandis* Hill ex Maid. is limited on many sites by low levels of available soil nitrogen. Supplemental nitrogen needed for sustained production of the species can be provided by application of synthetic nitrogen fertilizer or through use of N_2 -fixing plants—such as legumes—or both.

To test the effects of planting leguminous trees, two species—(*Acacia melanoxylon* R. Br. or *Albizia falcataria* (L.) Fosberg)—were added in 1:1 mixtures with *Eucalyptus* in managed biomass plantations along the Hamakua coast, island of Hawaii.

The experimental design consisted of three treatments: (1) pure *Eucalyptus*, (2) *Eucalyptus* mixed with *Acacia*, and (3) *Eucalyptus* mixed with *Albizia*. The trees were planted at 2-m by 2-m spacing in August 1979, and treatments were replicated three times on plots of 0.4 ha each. Height and diameter were measured at 6-month intervals. Foliar samples of *Eucalyptus* were collected at 14 months after planting and analyzed for N, P, K, S, Ca, and Mg. Soil samples were obtained at 65 months and analyzed for pH, N, P, K, Ca, and Mg.

At 25 months, *Eucalyptus* trees grown in mixture with legumes were larger than *Eucalyptus* trees grown in pure plantings. At 65 months, *Eucalyptus* grown in pure stands were 10.3 m tall and 8.5 cm in diameter. *Eucalyptus* grown with *Acacia* were 25 percent taller and 28 percent larger in diameter; and *Eucalyptus* grown with *Albizia* were 63 percent taller and 55 percent larger in diameter than *Eucalyptus* grown in pure plantings. Despite increased mortality of *Eucalyptus* trees in the mixed species treatments, differences in biomass yields per ha were even greater than differences in average tree size. Crop yields averaged 38 tonnes per ha in pure *Eucalyptus*, 52 in *Eucalyptus* with *Acacia*, and 95 in *Eucalyptus* with *Albizia*.

Foliar concentrations of N and some of the other macronutrients were increased in *Eucalyptus* in the mixed plantations—especially those including *Albizia*. Soil nutrients, with the exception of K in the surface soil, did not vary significantly among treatments.

This study demonstrates the potential for using leguminous trees in mixture with *Eucalyptus* for increased production in biomass plantations in Hawaii.

INTRODUCTION

Two *Eucalyptus* species are particularly favored for wood, fiber, and fuel production in Hawaii and other tropical and subtropical areas because they grow rapidly and produce high yields on short rotations (Walters 1980, Whitesell 1975). Production of *E. saligna* and *E. grandis*, however, is limited on many sites by low levels of available soil nitrogen. Responses to N fertilizer have been substantial (Miyasaka 1984), and supplemental N will undoubtedly be needed for sustained production from repeated croppings.

The availability and cost of N fertilizer depend heavily on the supply and price of fossil fuel. Fertilization is, therefore, a costly practice in Hawaii, and is not feasible in many developing countries. Nitrogen can also be added through symbiotic fixation, and the general presence of N_2-fixing plants is one of the most striking characteristics of many natural tropical rainforests (Cole and Johnson 1980).

We, therefore, conducted a test to evaluate effects of including N_2-fixing trees in managed *Eucalyptus* plantations. The trees tested were *Acacia melanoxylon* R. Br. and *Albizia falcataria* (L.) Fosberg; both are legumes and are known to grow well on the site selected for the study.

This paper reports results of tests after 65 months in which leguminous tree species were planted in mixture with *Eucalyptus* in managed biomass plantations on the island of Hawaii.

STUDY AREA

The test was established near Onomea on an area typical of much marginal and abandoned sugarcane land along the Hamakua coast (19° 30′ N, 155° 15′ W). Elevation of the planting site is about 420 m, and annual rainfall is 5080 mm, distributed fairly evenly throughout the year. Slopes are gentle, ranging from 0 to 10 percent. The soil series is Akaka silty clay loam (thixotropic isomesic typic Hydrandept) and is acidic (pH 4.8-5.0). Nitrogen concentration is similar to that of most soils of the Hamakua coast, averaging about 0.6 percent in the 0- to 20-cm surface layer and 0.4 percent at the 40- to 80-cm depth. Sugarcane was produced on the land for more than 50 years, but was abandoned in 1978 because of low yields. Immediately before the study was started, the area was occupied by residual sugarcane that was heavily infested with California grass (*Brachiaria mutica* [Forsk.] Stapf.). The site was prepared for planting by using a Rome cut-away harrow, which flattened and cut up the sugarcane and grass to form a mulch. Developing vegetation was sprayed with glyphosate[1] prior to planting in 1979.

METHODS

The experimental design was a complete block with three treatments replicated in three blocks. Treatments were: (1) pure *Eucalyptus*, (2) *Eucalyptus* mixed with *Acacia melanoxylon*, and (3) *Eucalpytus* mixed with *Albizia falcataria*. The *Eucalyptus* seedlings consisted of *E. saligna* and *E. grandis*; one block contained *E. saligna* only, one block contained *E. grandis* only, and the third block contained a mixture of *E. grandis* and *E. saligna*. Differences associated with "block" in all analyses of tree size were not significant, however; thus, *E. saligna*, *E. grandis*, and the mixture thereof are treated and referred to as *Eucalpytus* in the rest of this paper.

In the *Eucalyptus*-legume mixture plots, *Eucalyptus* and either *Acacia* or *Albizia* were planted in alternate rows, thus providing a 50:50 mix. Three-month-old container seedlings were planted at 2 m by 2 m spacing (2500 trees per ha) in August 1979. Individual seedlings were fertilized with 115 g of N-P-K (14-14-14) at planting and 6 months later; each application was equal to about 40 kg N, P, and K per ha. In addition, *Eucalyptus* trees in pure plantings received 115 g of urea fertilizer (46 percent N) at 15 months—an application equal to about 130 kg N per ha. Thus, the test is to some degree a comparison of alternative methods of adding to N supply (synthetic fertilizer vs. N_2-fixing plants); unfortunately, subsequent performance of this plantation and other plantations in the area have indicated that this level of N fertilization is much below the optimum.

Plots were about 0.4 ha each, and growth measurements were collected on 50 interior trees of each genus (*Eucalyptus*, *Acacia*, and *Albizia*) present in each plot at approximately

[1]This publication does not contain recommendations for pesticide uses reported, nor does it imply that they have been registered by the appropriate government agencies.

6-month intervals. Heights were measured to the nearest 0.1 m with a telescoping pole and diameters were recorded to the nearest 0.1 cm by diameter tape. Stocking (trees per ha) was estimated at 65 months by tallying all live stems in five rows of 10 planting spots for trees of each genus in the center of each plot.

Foliage samples were collected from the upper crown of 10 to 15 interior *Eucalyptus* trees in each plot at 14 months. Dried foliage was analyzed for nutrient elements at the University of Hawaii as follows: total N by standard Kjeldahl procedure; P, total S, Ca, Mg, and K by X-ray fluorescence.

Soil samples were collected at 65 months from the 0- to 20-cm and 60- to 80-cm layers at 4 randomly selected points in the interior of each plot and composited by layer. Samples were air dried at room temperature in the C. Brewer Analytical Laboratory. Live roots and gravel were removed and discarded. Soil aggregates were crushed with a rolling pin, and the soil was passed through a 2-mm sieve. The 2-mm soil was weighed, and subsamples were taken for subsequent analyses. One subsample of soil from each plot was dried to constant weight at 100°C to determine moisture content. Soil pH was determined on soil-water pastes by glass electrode. Total N was estimated by the semimicro-Kjeldahl method (Bremner 1965). Minerals determined and analytical methods used were as follows: extractable P (extracted with Truog solution (Truog 1930) by the molybdenum blue technique (Chapman and Pratt 1961); exchangeable K, Ca, and Mg (extracted with neutral 1N NH_4OAC) by standard atomic absorption spectrophotometric methods.

Tree measurement (height and diameter) data were averaged for each plot and genus, and differences among treatments at each measurement date were evaluated by standard analyses of variance. When treatments were significantly different, the means were separated by Duncan's Multiple Range Test. Similar statistical procedures were applied to data from foliar and soil analyses. Patterns of stand development were compared by plotting average height against age for *Eucalyptus* in the three treatments and for each species in the *Eucalyptus*-legume mixtures.

Biomass at 65 months was estimated for *Eucalyptus* trees of mean basal area in each treatment with the equation: $\log_e$ Dry Weight = -3.8604 + 0.9644 $\log_e$ (Diameter^2 x Height). This equation was developed from trees of comparable age and size (n = 93, R^2 = 0.99, RMSE = 0.11).[2] The equation was also used to estimate dry weight of *Acacia* and *Albizia*, based on the following assumptions and modifications: (1) height-diameter relationships were approximately the same as for *Eucalyptus* in this trial; (2) wood density, moisture content, and branching patterns of *Acacia* were also similar to *Eucalyptus;* and (3) wood density of *Albizia* was about one-half that of *Eucalyptus*. We therefore used the equation without modification for *Acacia*. For *Albizia*, we multiplied the dry weight estimated with the equation by 0.50 and consider this to be a conservative estimate because multiple stems occurred on most trees. Mean tree weights were then multiplied by number of surviving trees per ha to provide estimates of dry biomass per ha.

Table 1—*Average sizes and survival of trees at 65 months in pure* Eucalyptus *and mixed* Eucalyptus-*legume plantings, Hawaii*[1]

Treatment and species	Mean dbh	Mean height	Stems per hectare	Sample size
	cm	*m*		
Pure:				
Eucalyptus	8.5 a	10.3 a	2200	3
Mixed:				
Eucalyptus	10.9 ab	12.8 ab	1012	3
Acacia	8.4	9.1	1012	3
Total			2024	
Mixed:				
Eucalyptus	13.2 b	16.8 b	838	3
Albizia	13.6	16.5	1225	3
Total			2063	
Root mean square error[2]	1.3	2.1		

[1]Means followed by the same letter do not differ significantly at the 5 percent level of probability.

[2]For comparing height and diameter values for *Eucalyptus*.

RESULTS AND DISCUSSION

Substantial differences existed among treatments at 65 months in size and number of remaining *Eucalyptus*, *Acacia* and *Albizia* trees *(table 1)*. Heights averaged 13.3 m for *Eucalyptus*, 9.1 m for *Acacia*, and 16.5 m for *Albizia;* diameters were 10.9 cm, 8.4 cm, and 13.6 cm, respectively. Height and diameter of *Eucalyptus* trees in the mixed plantings were greater than in the pure plantings even though the latter received additional N fertilizer. *Eucalyptus* grown with *Acacia* were 25 percent taller and 28 percent larger in diameter than those grown in pure plantings. *Eucalyptus* trees grown with *Albizia* were significantly larger (63 percent taller and 55 percent larger in diameter) than *Eucalyptus* in pure plantings.

Such differences in average size of *Eucalyptus* trees in the mixed species treatments were associated with increased competition-related mortality. About 2200 trees per ha remained in the pure *Eucalyptus* planting *(table 1);* thus survival was 88 percent. The mixture of *Eucalyptus* and *Acacia* had somewhat lower overall survival (81 percent) and the two species had equal survival. Average survival in the *Eucalyptus-Albizia* treatments was similar (83 percent) to that of the *Eucalyptus-Acacia* mixture, but the two species differed markedly. Only two-thirds of the *Eucalyptus* trees remained after 65 months whereas 98 percent of the *Albizia* survived.

Differences among treatments in size of *Eucalyptus* trees developed during the second growing season *(fig. 1)*. Heights and diameters did not vary significantly among treatments at 12 months, but the difference between *Eucalyptus* grown in

[2]This value for root mean square error is in terms of the natural logarithm of biomass.

pure plantings and those grown with *Albizia* became significant at 25 months and remained so throughout the study. At 30 months, *Eucalyptus* grown with *Acacia* averaged about 2 m taller than *Eucalyptus* grown in pure plantings, and this difference in height remained nearly constant to 65 months. Increase in the height difference for *Eucalyptus* grown with *Albizia* was gradual, however; from 30 to 65 months, the difference between *Eucalyptus* mixed with *Albizia* and those in pure plantings increased from 4 m to more than 6 m.

Average heights of *Acacia* and *Eucalyptus* were similar for 25 months after which *Eucalyptus* overtopped *Acacia* and more or less continued its early growth rate of nearly 3 m per year *(fig. 2)*. Growth rate of Acacia diminished from 25 to 65 months. Heights of *Albizia* and *Eucalyptus* also were about

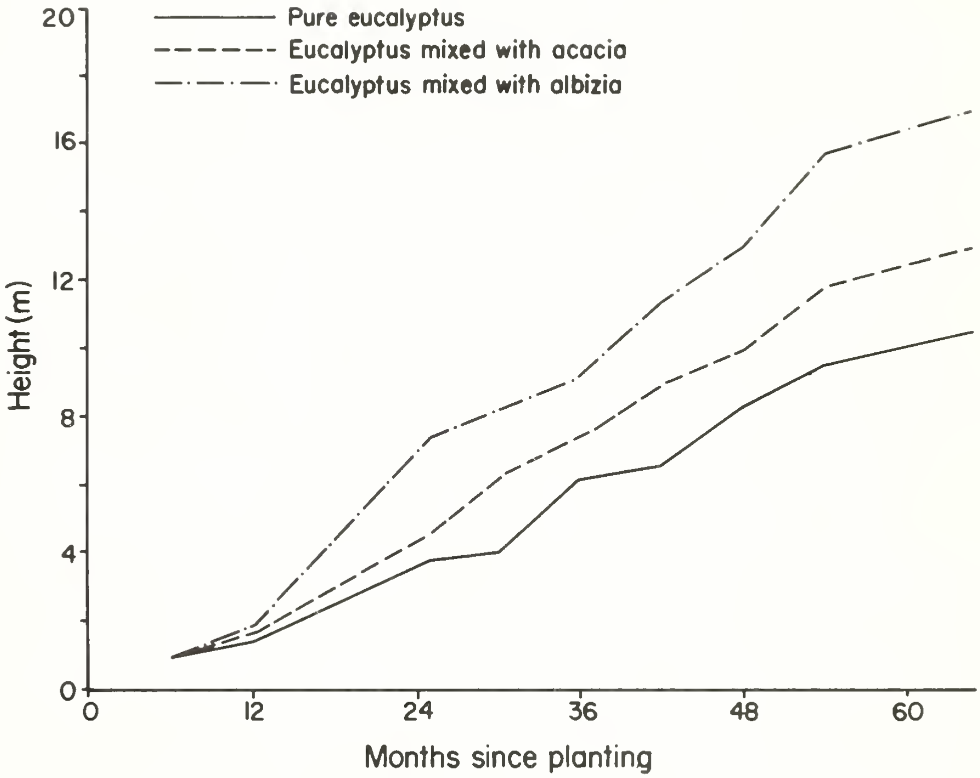


Figure 1—Average height of *Eucalyptus* trees grown in pure and mixed stands.

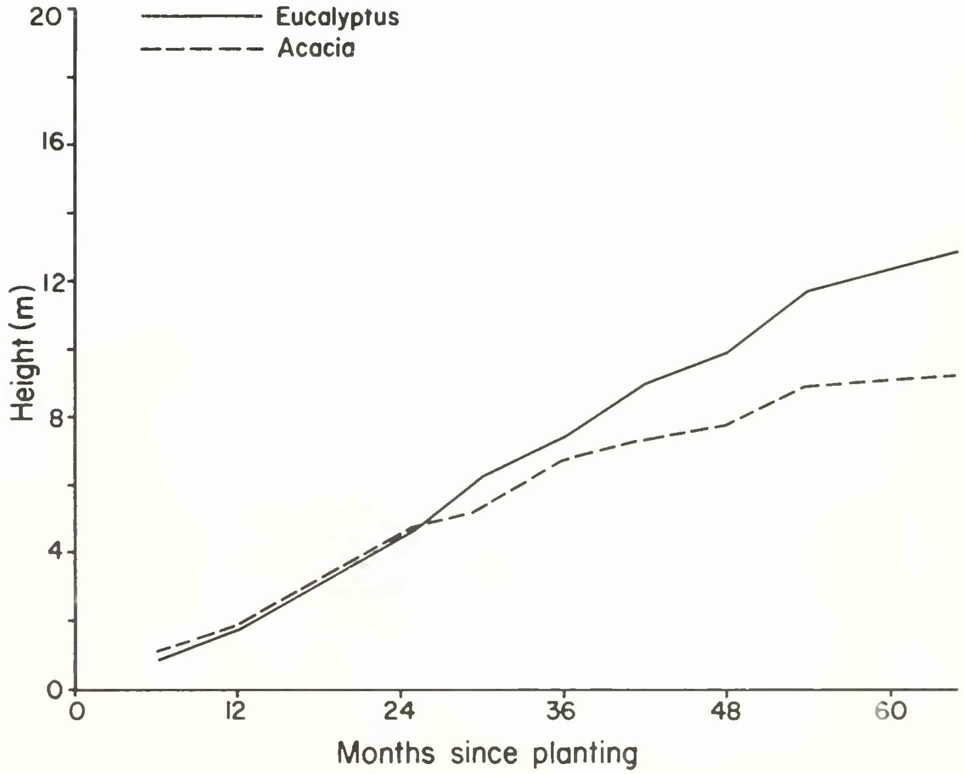


Figure 2—Average height of *Eucalyptus* and *Acacia* grown in mixture.

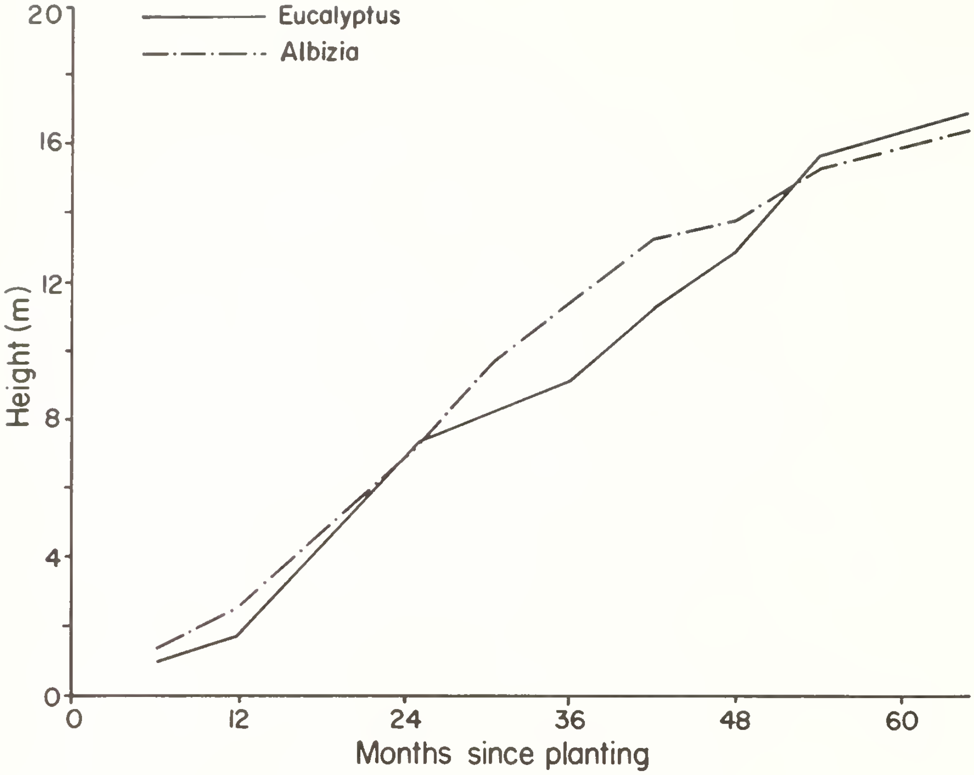


Figure 3—Average height of *Eucalyptus* and *Albizia* grown in mixture.

the same for the first 25 months, but *Albizia* overtopped *Eucalyptus* from 25 to nearly 54 months *(fig. 3)*. Despite its subordinate position in the mixed plantings for more than 2 years, *Eucalyptus* mixed with *Albizia* were taller than *Eucalyptus* in the other treatments throughout this period. This result is counter to our expectation concerning mixtures of nitrogen-fixing and other principal crop trees. We would expect growth of the latter to be depressed when they are overtopped by N_2-fixing trees and little apparent benefit until the principal crop trees attained a superior crown position. The *Eucalyptus* species in this experiment may be tolerant of the shade cast by the open, spreading canopy and feathery foliage of *Albizia;* possibly such light shade is even favorable. *Albizia falcataria* is used extensively in agroforestry in Java, and several agricultural and horticultural crops (annual and perennial) are grown beneath it (National Academy of Sciences 1979).

The enhanced height and diameter of *Eucalyptus* in mixed plantings were associated with greater gains in dry biomass yields *(table 2)*. Estimated dry weight of average *Eucalyptus* trees in pure plantings was about 17 kg; weights were 104 percent and 306 percent greater for *Eucalyptus* grown with *Acacia* and *Albizia*, respectively. Increased growth in the mixtures was accompanied by greater mortality, but yields per hectare were substantially higher than yields in pure *Eucalyptus* plantings. Despite the presence of less than one-half as many *Eucalyptus* trees in the mixtures, dry weight of *Eucalyptus* alone in the mixture with *Acacia* was nearly equal to that in pure plantings; weight of *Eucalyptus* in the mixture with *Albizia* was 55 percent greater than that in pure plantings. When estimated weights of the leguminous trees were included, total dry yield of the *Eucalyptus-Acacia* planting was 37 percent greater than yield in pure *Eucalyptus* planting, and yield of *Eucalyptus-Albizia* plantings was about 2.5 times that of the pure planting. Such yields represent mean annual production rates (tonnes per ha) of 6.9 for pure *Eucalyptus*, 9.5 for *Eucalyptus-Acacia*, and 17.6 for *Eucalyptus-Albizia* plantings.

Data on foliar concentrations of macronutrients *(table 3)* suggest that increased nitrogen is responsible, at least in part, for the subsequent enhanced growth of *Eucalyptus* in the mixed plantings. At 14 months, N concentration averaged 9

Table 2—*Sizes of mean trees and estimated yields of dry biomass at 65 months for pure* Eucalyptus *and mixed* Eucalyptus-*legume plantings, Hawaii*

Treatment and species	Tree of mean basal area		Dry weight per mean tree	Dry weight per hectare
	Dbh	Height		
	cm	*m*	*kg*	*tonnes*
Pure:				
Eucalyptus	9.5	11.6	17.1	37.6
Mixed:				
Eucalyptus	12.1	14.9	34.9	35.3
Acacia	9.3	11.3	16.0	16.2
Total				51.5
Mixed:				
Eucalyptus	15.3	19.0	69.4	58.2
Albizia	14.6	18.1	30.3	37.1
Total				95.3

percent and 32 percent higher in foliage of *Eucalyptus* mixed with *Acacia* and *Albizia*, respectively, than in foliage of pure *Eucalyptus* plantings. Even the highest foliar N concentrations attained in this study were quite low for *Eucalyptus*. Thus, it is quite probable that N remained a major factor limiting production in all treatments. Some of the other macronutrients also tended to be higher in the mixed plantings, especially those plantings including *Albizia*. Such increases in concentrations of non-nitrogenous macronutrients may be related to enhanced root growth (hence, increased exploitation of soil) or to increased rates of nutrient cycling (hence, greater availability) associated with additions of nitrogen-rich litter to the soil in the mixed plantings, or to both conditions.

Analyses of macronutrients and pH in soils collected at 65 months in the various treatments *(table 4)* do not shed light on factors responsible for superior growth performance of the mixed plantings or present clearcut evidence of treatment effects on the soils. Only extractable K in the 0- to 20-cm soil layer differed significantly among treatments. Some trends, however, are noteworthy. Concentrations of total N, extractable P, and extractable K were slightly lower in the mixed species treatments, and appeared to vary inversely with growth and yield of the treatments. Presumably the lower amounts of these nutrients reflect greater uptake by the vegetation in the mixed plantings. The higher concentrations of Ca and Mg and slightly higher pH in the surface soil layer of the *Eucalyptus-Albizia* plantings were surprising, and are at variance to recent findings as to soil changes beneath a major nitrogen-fixing tree (*Alnus rubra* Bong.) in the temperate zone (DeBell et al. 1983; DeBell and Radwan 1984). With alder and some agricultural legumes, nitrification rates increase as N accumulates in the soil leading to a decrease in pH; concomitantly, Ca and Mg are leached to lower levels of the soil profile. Nitrogen did not increase in soil beneath the treatments containing N_2-fixing legumes in the present study, and this may partially account for such contrasting results. Moreover, we know little about uptake and cycling of calcium and magnesium in *Acacia* and *Albizia* stands.

Table 3—*Concentrations of nutrients in* Eucalyptus *foliage collected at 14 months, Hawaii*[1]

Treatment	N	P	K	Ca	Mg	S	Sample size
				Percent			
Pure	.88a	.11a	.67a	.71a	.37a	.11a	3
Mixed:							
with *Acacia*	.96b	.12a	.87b	.73a	.37a	.12a	3
with *Albizia*	1.16c	.13b	.91b	.91b	.36a	.14b	3
Root mean square error[2]	.019	.003	.050	.071	.050	.003	

[1]Means followed by the same letter do not differ significantly at the 5 percent level of probability.

[2]For comparing nutrient values among treatments.

Table 4—*Concentrations of macronutrients and pH in soils beneath pure* Eucalyptus *and mixed* Eucalyptus-*legume plantings at 65 months*

Treatment	Soil depth	N	P	K	Ca	Mg	pH
	cm	*Percent*			*ppm*		
Pure *Eucalyptus*	0-20	0.62	16	29	32	33	5.2
	60-80	.45	10	16	55	33	5.4
Mixed:							
with *Acacia*	0-20	.57	13	26	27	21	5.2
	60-80	.42	8	16	21	9	5.4
with *Albizia*	0-20	.55	12	14	78	54	5.4
	60-80	.41	6	9	52	24	5.5
Root mean square	0-20	.07	6	7	11	31	0.4
error[1]	60-80	.09	6	7	10	24	0.3

[1]For comparing macronutrient concentrations and pH in soils among treatments at each soil depth.

CONCLUSIONS

Eucalyptus growth can be increased substantially by planting the species in mixture with leguminous trees. *Eucalyptus* trees in mixed plantings were larger than those in pure plantings even though the latter received an additional fertilizer amendment equivalent to about 130 kg N per ha. Total biomass production was also much greater in the mixed species plantations.

Albizia appears especially promising for inclusion in such mixtures. It led to the best *Eucalyptus* growth (per tree and per hectare) despite the fact that it overtopped *Eucalyptus* for a considerable length of time and *Eucalyptus* survival was lowest when mixed with *Albizia*. Based on other studies, however, we know that relative growth patterns of *Eucalyptus* and *Albizia* vary greatly with site conditions and therefore effects of *Albizia* on *Eucalyptus* growth and on total biomass production may differ on other sites.

Information on foliar nutrient concentrations obtained in this experiment confirms a close relationship between nitrogen status and growth of *Eucalyptus*. The possibility that admixtures of legumes may enhance availability and cycling of mineral macronutrients as well as nitrogen merits further study. We also need to confirm and understand the factors responsible for the differences or lack thereof in soil properties in the various treatments: Why did N concentrations not increase in the soil beneath the mixed plantings containing N_2-fixing trees? Why did Ca, Mg, and pH values tend to be higher beneath *Albizia*-containing treatments? Although the individual tree growth and total crop yield advantages of the mixed species plantings are obvious, additional information on nutrients is needed to appraise the long-term economic and ecological costs and benefits of using legumes in mixture or in rotation with *Eucalyptus*.

REFERENCES

Bremner, J. M. Total nitrogen. In: Black, C. A., ed. **Methods of soil analysis.** Part 2. Agronomy. 1965:1149-1178.

Chapman, Homer D.; Pratt, Parker F. **Methods of analysis for soils, plants and waters.** Berkeley: University of California Division of Agricultural Sciences; 1961. 309 p.

Cole, D. W.; Johnson, D. W. **Mineral cycling in tropical forests.** In: C. T. Youngberg, ed. Forest soils and land use: proceedings of the fifth North American forest soils conference; 1978 August. Ft. Collins, CO: Colorado State University, Department of Forest and Wood Sciences; 1980; 341-356.

DeBell, D. S.; Radwan, M. A.; Kraft, J. M. **Influence of red alder on chemical properties of a clay loam soil in western Washington.** Res. Paper PNW-313. Portland, OR: Pacific Northwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983. 7 p.

DeBell, D. S.; Radwan, M. A. **Repeated coppicing of cottonwood and alder affects soil properties.** Agronomy Abstracts 1984: 258.

Miyasaka, S. C. **Comparison of quick- and slow-release fertilizers in young plantings of *Eucalyptus* species.** Tree Planters' Notes 35(2):20-24, Spring 1984.

National Academy of Sciences. **Tropical legumes: Resources for the future.** Washington, DC; 1979. 331 p.

Truog, Emil. **The determination of the readily available phosphorus of soils.** J. Am. Soc. Agron. 22: 874-882; 1930.

Walters, Gerald A. **Saligna eucalyptus growth in a 15-year-old spacing study in Hawaii.** Res. Pap. PSW-151. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1980. 6 p.

Whitesell, Craig D. **Growth of young saligna eucalyptus in Hawaii 6 years after thinning.** Res. Note PSW-299. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1975. 3 p.

The Forest Service, U.S. Department of Agriculture, is responsible for Federal leadership in forestry. It carries out this role through four main activities:

- Protection and management of resources on 191 million acres of National Forest System lands.
- Cooperation with State and local governments, forest industries, and private landowners to help protect and manage non-Federal forest and associated range and watershed lands.
- Participation with other agencies in human resource and community assistance programs to improve living conditions in rural areas.
- Research on all aspects of forestry, rangeland management, and forest resources utilization.

The Pacific Southwest Forest and Range Experiment Station

- Represents the research branch of the Forest Service in California, Hawaii, and the western Pacific.

DeBell, Dean S.; Whitesell, Craig D.; Schubert, Thomas H. **Mixed plantations of *Eucalyptus* and leguminous trees enhance biomass production.** Res. Paper PSW-175. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1985. 6 p.

Two *Eucalyptus* species—*E. saligna* Sm. and *E. grandis* Hill—are especially favored in Hawaii for wood, fiber, and fuel production because of their quick growth and high yields. Their growth is limited, however, on many sites by low levels of available nitrogen. Supplemental nitrogen can be provided by nitrogen-fixing plants, such as legumes. A test was conducted to determine whether planting two leguminous species—*Acacia melanoxylon* R. Br. and *Albizia falcataria* (L.) Fosberg—could increase biomass production. Results after 65 months suggest that *Eucalyptus* growth can be increased substantially by planting the species in mixture with leguminous trees. Total biomass production was much greater in the mixed species plantations than in the pure *Eucalyptus* plantation.

Retrieval Terms: Eucalyptus, Eucalyptus saligna, Eucalyptus grandis, Acacia melanoxylon, Albizia falcataria, legumes, species trials, plantations, Hawaii

Research Paper PSW-176
in shelved separately in
an envelope to the right
of this volume.

United States
Department of
Agriculture

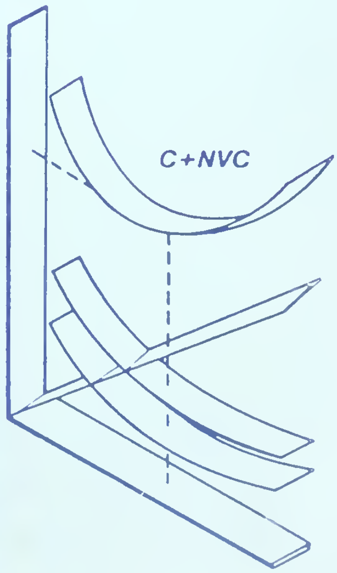
Forest Service

**Pacific Southwest
Forest and Range
Experiment Station**

Research Paper
PSW-177

Watershed Modeling for Fire Management Planning in the Northern Rocky Mountains

Donald F. Potts David L. Peterson Hans R. Zuuring



The Authors:

DONALD F. POTTS is an associate professor of watershed management at the University of Montana, School of Forestry. He earned a bachelor of arts degree in chemistry (1972) at the State University of New York at Buffalo, and a master of science degree in forestry (1976) and a doctorate in forest meteorology (1979) at the State University of New York, College of Environmental Science and Forestry, Syracuse. **DAVID L. PETERSON** is a research ecologist with the Station's research unit studying fire management planning and economics headquartered in Riverside, California. He earned a bachelor of science degree in zoology (1976), master of science degree in botany (1977), and a doctorate in ecology (1980) from the University of Illinois, Urbana-Champaign. He served on the faculty of the Department of Forestry at the University of Illinois before joining the Station's research staff in 1981. **HANS R. ZUURING** is an associate professor of biometrics at the University of Montana, School of Forestry, and a station biometrician at the Montana Forest and Conservation Experiment Station. He earned a forestry degree (1966) at the University of Toronto, Ontario, Canada, and a doctorate in forest biometry (1975) at Iowa State University, Ames, Iowa.

Acknowledgments:

We thank Thomas Brown, Richard Cline, and Owen Williams for reviewing the manuscript; Patrick Flowers for assisting with the economic analysis; and Richard Dyrland for providing information on water valuation.

Publisher:

Pacific Southwest Forest and Range Experiment Station
1960 Addison Street, Berkeley, California 94704

October 1985

Watershed Modeling for Fire Management Planning in the Northern Rocky Mountains

Donald F. Potts David L. Peterson Hans R. Zuuring

CONTENTS

IN BRIEF...

Potts, Donald F.; Peterson, David L.; Zuuring, Hans R. **Watershed modeling for fire management planning in the northern Rocky Mountains.** Res. Paper PSW-177. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1985. 11 p.

Retrieval Terms: fire effects, net value change, sediment, water yield, watershed models

Water yield and sediment production almost always increase after wildfire has destroyed vegetative cover. The value of water generally is not as much appreciated in the water-rich northern Rocky Mountains as it is elsewhere. Increased water yield becomes economically beneficial, however, when its potential for consumptive and nonconsumptive uses is realized. Whether the effects of increased sedimentation are esthetic, biological, physical, or economic, they are usually detrimental.

Fire management programs for the National Forests are required to be an integral part of land management planning. Managers must be able to estimate postfire changes in resource outputs and values within the context of a particular fire management program. The quantity of additional water and sediment produced is a function of fire characteristics and site-specific factors: vegetation, climate, and physical characteristics. Planning, however, requires a broad resolution analysis system. Therefore, site-specific water and sediment yield models were adapted to meet broad resolution planning objectives.

In a study of fire-induced changes in watersheds in the northern Rocky Mountains, two simulation models were applied. Procedures from Water Resources Evaluation of Nonpoint Silvicultural Sources (WRENSS) estimated water yield, and a closely related model estimated four major components of sediment yield—natural sediment, sediment from management-induced mass erosion, sediment from management-induced surface erosion, and sediment delivery. Computerized versions of the models were used to estimate postfire water yield for 18 possible management cases and postfire sediment yield for 81 cases. Net value change of water resources was calculated with investment analysis.

Water yield was most affected by basal area loss; the greater the loss, the greater the relative increase in water yield. Water yield increased over natural yield, however, only if fire or salvage logging or both removed greater than 50 percent of stand basal area.

Fire had a relatively small effect on sediment production in most cases. Increases were relatively large only for fires with large areas. Natural sediment yield increased more than did management-induced sediment yield. Postfire sediment increases were severe only on sites with steep slopes and large fires.

Increased water yields resulted in a beneficial net value change for all cases. Benefits were substantial (up to \$33.42 per acre or \$80.21 per hectare) in some cases and were less than \$5 per acre (\$12 per hectare) only in some cases with 50 percent basal area loss. Net value change was increasingly negative as basal area loss increased. Net value change for sediment yield was detrimental for all cases, but was always less than \$.01 per acre (\$.02 per hectare).

INTRODUCTION

Wildfire on forested watersheds in the northern Rocky Mountains increases both water yield and sediment production. Increased water yield is beneficial, but increased sedimentation is detrimental. Fire management programs for National Forest lands are required to be an integral part of land management plans and to be cost-effective (Nelson 1979; U.S. Dep. Agric., Forest Serv. 1979). In selecting a particular fire management program, a manager must be able to estimate accurately long-term changes in water resource outputs and values caused by wildfire.

Site-specific information about effects of fire is available for some ecosystems in the northern Rocky Mountains (Tiedemann and others 1979). For land management, however, the planning system must go beyond procedures based on site-specific information—it must be a broad resolution analysis system capable of estimating and analyzing changes caused by fire (Mills and Bratten 1982).

Fire produces both onsite and downstream effects on water resources. These different effects are impossible to separate, making broad resolution modeling difficult. However, some responses of water resources to fire are common or nonsite-specific (Tiedemann and others 1979, p. 23):

1. Fire exerts pronounced effects on basic hydrologic processes leading to increased sensitivity of the landscape to eroding forces and to reduced land stability. This is manifested primarily as increased overland flow, and greater peak and total discharge. These provide the transport force for sediment from the landscape.
2. Erosion responses to burning are a function of several factors including: degree of elimination of protective cover; steepness of slopes; degree of soil nonwettability; climatic characteristics; and rapidity of vegetation recovery.
3. Sedimentation, increased turbidity levels, and mass erosion appear to be the most serious threats to water resources after fire (especially wildfire). Elimination of protective streambank cover has been shown to cause temperature increases that might pose a threat to aquatic life.
4. Despite the lack of documentation of fire size and intensity, large fires of high intensity appear to have the greatest potential for causing damage to water resources.

Many hydrologic models exist, each with unique features associated with the objectives for which it was developed. Available methodologies have many limitations in meeting the objectives of fire management planning. Sediment and water yield models that are used most often are deterministic and site-specific. Probabilistic water yield modeling is limited by dependence on historical records for generating probability distributions. Stochastic models assume time-invariance of hydrologic systems. Probabilistic sediment yield models for large areas are nonexistent.

Because no combination of existing watershed models provides exactly what is required for fire management planning, we adapted the Water Resources Evaluation of Nonpoint Silvicultural Sources (WRENSS) water yield model (U.S. Dep. Agric., Forest Serv. 1980) and a closely related sediment yield model (Cline and others 1981). These models are usually applied to site-specific situations, but are easily simplified and generalized. The modified models produce realistic estimates of changes in resource outputs at the level of resolution required for fire management planning. An investment analysis procedure is used to calculate the net value change of water resource outputs. These estimates may also be useful for quantifying change in production and value of resources for postfire impact assessment and escaped fire situation analyses.

This paper describes the use of site-specific water and sediment yield models to produce broad resolution estimates of expected changes in the northern Rocky Mountains due to fire. It describes model inputs and expected changes in resource outputs in terms of analysis units that represent various classes of watersheds, fire characteristics, and management options.

METHODS

Analysis Units

Numerous specific data are needed to estimate changes in postfire water yield and sediment production. Some of these inputs are general and others specific. Because estimates will be used in a planning context, a list of descriptors is needed that identifies nonsite-specific management situations at a broad level of resolution, and is compatible with the data. Therefore, we proposed a list of parameters that describe possible management

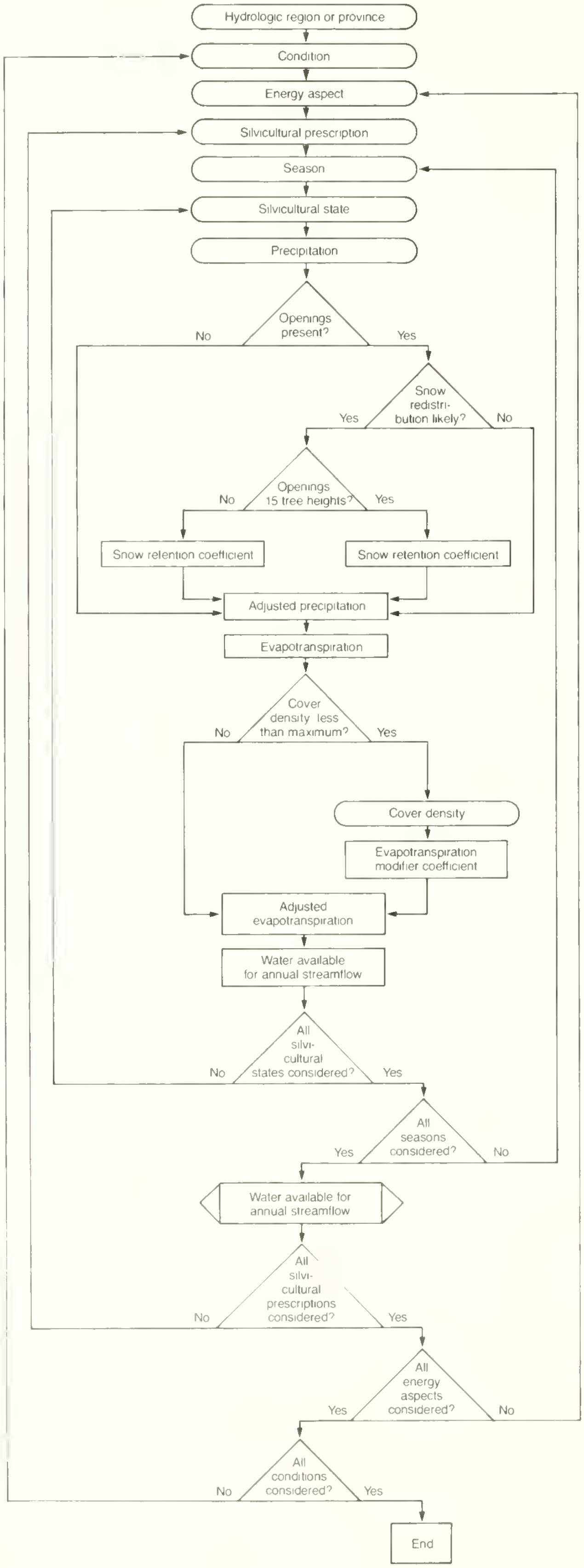


Figure 1—WATBAL is a complex model that simulates water available for streamflow in snow-dominated hydrologic regimes. Snow retention coefficients are from WRENSS documentation (U.S. Dep. Agric., Forest Serv. 1980).

cases or *analysis units* in terms of watershed characteristics, fire damage, and management decisions:

<u>Parameter</u>	<u>Class</u>
Slope, percent	20
	60
	90
Aspect	North
	South
	East, west
Cover type	Douglas-fir
	Ponderosa pine
	Western white pine
	Fir-spruce
	Hemlock-Sitka spruce
	Larch
	Lodgepole pine
Cover type age class	Sawtimber
	Pole
	Seedling/sapling
Annual precipitation, inches (cm)	15 (38)
	30 (76)
	45 (114)
Fire size, acres (ha)	30 (12)
	380 (154)
	2800 (1133)
Basal area loss, percent	20
	50
	90
	100
Roads	Present
	Absent
Salvage logging	Yes
	No

Three slope classes describe gentle, moderate, and steep slopes, because the models require a specific value for each class. Three aspect classes are used: north aspects have low evapotranspiration rates, south aspects have high rates, and east and west aspects are combined because they have similar intermediate rates. The seven major timber cover types identified in the northern Rocky Mountains are used in the model (Garrison and others 1977; U.S. Dep. Agric., Forest Serv. 1967). The cover type age class system is that used by the Forest Service. Precipitation is an input parameter because of its importance in determining water yield. Annual precipitation varies considerably by elevation and latitude in the northern Rocky Mountains, and can be correlated with these two factors in the context of land management planning. Values chosen for classes of annual precipitation generally are representative of precipitation received at 3000, 4500, and 6000 feet (910, 1360, and 1820 m) elevation in the northern Rocky Mountains. The values that represent three fire size classes are means within the fire size classes 0–99, 100–999, and 1000+ acres (0–41, 42–416, and 417+ ha) for the northern Rocky Mountains during 1970 to 1981 (Bratten 1983). Roads and salvage logging can affect the quantity of postfire sediment production; assumptions related to the effect of road density and salvage logging are discussed in the section on sediment yield. The many other assumptions and decision rules required in the watershed models are discussed in the following sections on the water yield and sediment yield models.

Water Yield Model

WRENSS (U.S Dep. Agric., Forest Serv. 1980) procedures use two different computer models: PROSPER in rain-dominated hydrologic regimes (below 4000 feet in the northern Rocky Mountains) (Goldstein and others 1974); and WATBAL in snow-dominated regimes (Leaf and Brink 1973a, 1973b). Because PROSPER has not been used extensively or validated in the northern Rocky Mountains, we used procedures from WATBAL only.

WATBAL was intended to be a site-specific model, but geographic regional coefficients and modifiers "will yield reasonable results which are applicable in the respective regions" (U.S. Dep. Agric., Forest Serv. 1980, p. III. 26). The following conventions and definitions were assumed for WATBAL (*fig. 1*):

Condition and silvicultural state—The model first estimates existing water yield from the burned area. All analysis units are assumed to be previously undisturbed and exhibit complete hydrologic utilization.

Energy aspect—Primary aspects considered are north, south, and east-west. While evapotranspiration rates are usually higher on west aspects than on east aspects because of greater afternoon vapor pressure deficits, the potential shortwave radiation loads are the same. These primary aspects are the same as the analysis unit classes listed on page 2.

Silvicultural prescription—Each fire size is assumed to represent a uniform subwatershed. Changes in water yield are determined for only the disturbed area. Analysis unit basal area loss and salvage decision rules define the silvicultural prescription.

Season—Three predisturbance and postdisturbance hydrologic seasons are used to estimate seasonal evapotranspiration and runoff: winter (October 1–February 28), spring (March 1–June 30), and summer-fall (July 1–September 30).

Precipitation—Only two of the analysis unit precipitation classes are used in the water yield analysis (30 and 45 inches). A generalized monthly distribution of total annual precipitation in the northern Rockies was used to form the seasons described above. With this distribution, even total vegetation removal would not produce significant surplus water for runoff unless annual precipitation was greater than about 20 inches (508 mm). WATBAL assumes that large openings are absent in undisturbed stands, and that snow received in the northern Rockies—particularly west of the Continental Divide—is unlikely to undergo significant redistribution when disturbance creates openings in a stand. Precipitation is not adjusted in either case.

Evapotranspiration—Seasonal evapotranspiration is determined from seasonal precipitation using the regional relationships provided in WRENSS.

Cover density and evapotranspiration modifier coefficients—Cover density is defined by an index that references the capability of the stand to use energy input for evapotranspiration. This capability varies as a function of crown closure, vertical foliage distribution, species, and stocking. WATBAL assumes that existing cover density in the undisturbed state is maximum cover density, and that hydrologic utilization is complete. Basal area loss in each analysis unit is related to residual cover density using regional relationships provided in WRENSS. The ratio of residual cover density to maximum cover density by season, elevation, and aspect determines the evapotranspiration modifier coefficient using regional relationships provided in WRENSS. Adjusted seasonal evapotranspiration is subtracted from seasonal precipitation to determine the seasonal water available for streamflow. Seasonal increases or decreases are summed to provide the estimate of net water yield change from the disturbed area after fire. WATBAL assumes that hydrologic recovery, that is, return to complete hydrologic utilization, occurs exponentially with time over a 25-year period.

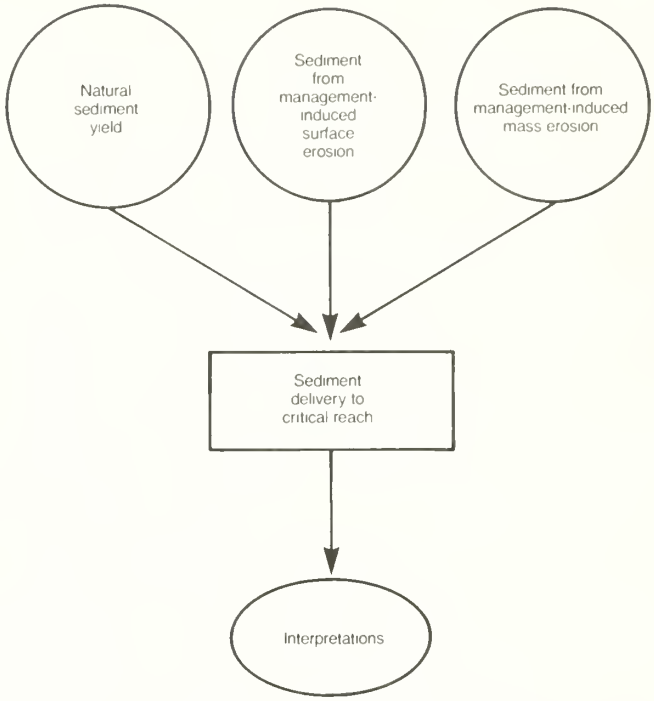


Figure 2—Sediment yield at a critical reach of a stream has several components.

Sediment Yield Model

The sediment yield model used in Forest Service's Northern (R-1) and Intermountain (R-4) Regions (Cline and others 1981, p. 1) is a "conceptual framework which outlines a process and is designed to be supplemented by local data . . . . " Its limitations and assumptions are clearly documented. At its current state of validation, the model can be used as a planning tool to compare land management alternatives.

The sediment yield model estimates four major components: (1) natural sediment yield, (2) sediment from management-induced mass erosion, (3) sediment from management-induced surface erosion, and (4) sediment delivery (*fig. 2*).

Natural Sediment Yield

The sediment yield model allows the user to supply estimates of natural sediment yield, if available. An alternative procedure empirically relates natural sediment yield to a calculated Mass Erosion Hazard Rating (MEHR) (U.S. Dep. Agric., Forest Serv.

1980, ch. 5). The procedure assumes that the predominant mass erosion hazard in the northern Rocky Mountains is from debris avalanche and debris flow failures.

Seven weighting factors, each with three classes, are used to determine the MEHR for each analysis unit. In order of decreasing importance, the factors are these: slope; precipitation; and—all least important—soil depth, subsurface drainage, soil texture, bedding structure, and slope configuration. MEHR slope weighting factor classes are the same as the analysis unit slope classes, and MEHR precipitation weighting factor classes are the same as the analysis unit precipitation classes. The least important MEHR weighting factors tend to require the most site-specific information. Because the analysis units do not provide this information, all were given medium class weights. Therefore, a total of nine MEHRs was required to characterize natural sediment yield in the given analysis units (three slope classes by three precipitation classes).

Sediment From Management-Induced Mass Erosion

WRENSS also provides a Management Induced Mass Erosion Hazard Rating (MIMEHR) system (U.S. Dep. Agric., Forest Serv. 1980, ch. 5). The sediment produced from management-induced mass erosion is difficult to quantify. As an approximation, we simply added the numerical MIMEHR and MEHR values, and determined the incremental sediment increase predicted from the empirical MEHR-natural sediment yield relationship given in the sediment yield model (Cline and others 1981).

Three weighting factors, each with three classes, are used to determine the management-induced hazard of debris avalanche and debris flow failures. In order of importance, these factors are (1) roads and skidways, (2) vegetative cover removal, and (3) harvest systems. The weight of each of these factors is influenced by slope, specific management practices, and the roading-salvage decisions made for each analysis unit. For example, slope greatly influences impacts of high density roading in disturbed areas. Vegetative cover removal is determined by fire intensity and salvage decisions for a given analysis unit. Slope limits specific harvest systems if salvage logging takes place. System assumptions concerning road density, fire intensity, and salvage logging methods are discussed in the next section.

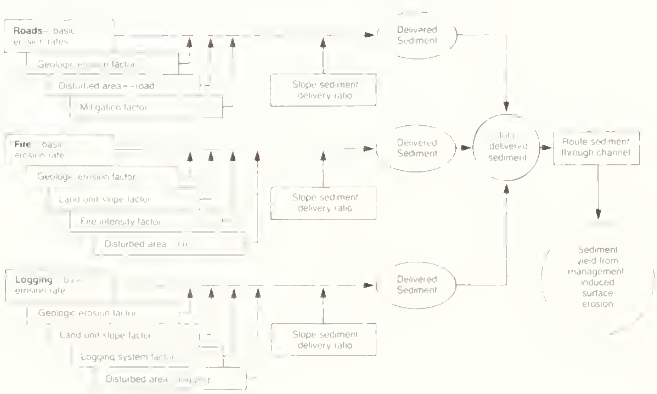


Figure 3—Management-induced surface erosion is a function of erosion caused by roads, fire, and logging.

Table 1—*Basic erosion rates (tons/mi²/yr) for three management practices over time, Idaho Batholith*

Practice	Year						
	1	2	3	4	5	6	>6
Roads[1]	67,500	18,000	5,000	5,000	5,000	5,000	5,000
Fire[2]	550	120	25	5	[3]0	0	0
Logging[4]	340	180	140	90	40	20	0

[1]Roads include horizontal distance from toe of fill to top of cut. Standard 16-foot road is assumed to have sustained 5–7 percent grade, balanced construction, inslope with ditch, native surface, and cross drains at 500-foot spacing. Standard road is constructed in granitic materials on a 50 percent side slope and is maintained annually.

[2]Standard fire is assumed to have burned at high intensity and consumed at least 40 percent of standing vegetation. Side slope is assumed to be approximately 45 percent.

[3]A zero indicates that erosion is not increased by a management practice at the given point in time.

[4]Standard logging system is clearcut with tractor yarding. Temporary roads and skid trails are assumed to be cross ditched and seeded as part of standard logging practice.

Sediment From Management-Induced Surface Erosion

The sediment yield model considers surface erosion and sediment production resulting from roads, fire, and logging *(fig. 3)* (Cline and others 1981). The surface erosion component was designed primarily from research conducted on granitic soils on the Idaho Batholith. Basic erosion rates are associated with standard management practices *(table 1)*.

Basic erosion rates were modified with a geologic erosion factor for miscellaneous hard metamorphic rocks (Cline and others 1981). This linear multiplier is about 0.4. In other words, we assumed that basic erosion rates are 40 percent of the rates on granitic soil. Conversely, our sediment yield estimates can be modified for granitic soils with a multiplication factor of 2.5.

Additional assumptions of the sediment production model are these *(fig. 3)*:

Disturbed area, road—Road density is 1 mi/mi² (0.6 km/km²) in areas undisturbed by fire. In disturbed areas, road density is 2 mi/mi² (1.2 km/km²). Analysis unit watersheds are 4.5 mi² (11.7 km²); this assumption is discussed in the section on sediment delivery. The analysis unit fire size class determines the total length of road in a disturbed area; the remaining undisturbed area provides the additional road length. The total road disturbance width (toe of fill to top of cut) is 50 ft (15 m).

Mitigation factor, road—A number of vegetative and physical mitigation measures for road construction have erosion reduction percentages associated with them (Cline and others 1981). The maximum allowable reduction of the basic road erosion rates is 80 percent. We assume 80 percent reduction through a combination of seed and fertilizer application, and partial road closure (no maintenance).

Land unit slope factor, fire and logging—After fire or logging, erosion rates increase more on steeper slopes than they do on gentler slopes. Standard side slope is 45 percent. The land unit slope factor increases or decreases the basic erosion rates proportionally by the amount they deviate from the 45 percent slope.

The analysis unit slope classes produce adjustment factors of 0.6 (20 pct slope), 1.5 (60 pct) and 2.6 (90 pct).

Fire intensity factor—All fires burn with medium intensity: soil surface litter and humus are destroyed on up to 40 percent of the area, and the A horizon is heated intensely (Cline and others 1981). The fire intensity factor is 0.5, in other words, the basic erosion rate for the standard fire is reduced by one half.

Disturbed area, fire and logging—The analysis unit fire size classes determine the area disturbed by fire. If the salvage decision is made, then the same area is disturbed by logging.

Logging system factor—If timber is salvaged on an analysis unit, the disturbed area is clearcut. For the 20 percent slope class, the standard tractor logging system is used (factor = 1.0). For the two steeper slope classes (60 and 90 pct), a cable logging system is used (factor = 0.62).

Sediment Delivery

Not all material detached during surface erosion is transported to stream channels. The amount that reaches the stream channel divided by the amount that was originally detached is called the sediment delivery ratio. Sediment delivery is a complex process and the sediment yield model uses the WRENSS systematic technique for estimating delivery efficiency (U.S. Dep. Agric., Forest Serv. 1980, ch. 4).

The estimation procedure determines the relative area of a polygon formed as a function of eight land characteristics and applies this proportion to a conversion curve to determine sediment delivery for a slope class (*fig. 4*). The land characteristics are all site-specific, but the model assumptions place all analysis units into one of three sediment delivery classes on the basis of original analysis unit slope classes.

Not all material delivered to a stream channel is transported out of a watershed. Efficiency of channel delivery is a function of the drainage area (Cline and others 1981). The model assumes that the analysis unit watersheds (4.5 mi^2 or 11.7 km^2) have a routing coefficient of about 0.75.

Economic Analysis

The value of water resources after fire was determined by subtracting present net value of the resource with fire from present net value without fire:

$$NVC = PNV_{w/o} - PNV_{w} \qquad (1)$$

where

NVC = net value change per acre burned

$PNV_{w/o}$ = present net value of all future revenues in the "without-fire" situation

PNV_{w} = present net value of all future revenues in the "with-fire" situation

The general form of equation 1 can be expanded to its computational form:

$$NVC = \sum_{n=0}^{y} \frac{PQ_{w/o,n}}{(1+i)^n} - \sum_{n=0}^{y} \frac{PQ_{w,n}}{(1+i)^n} \qquad (2)$$

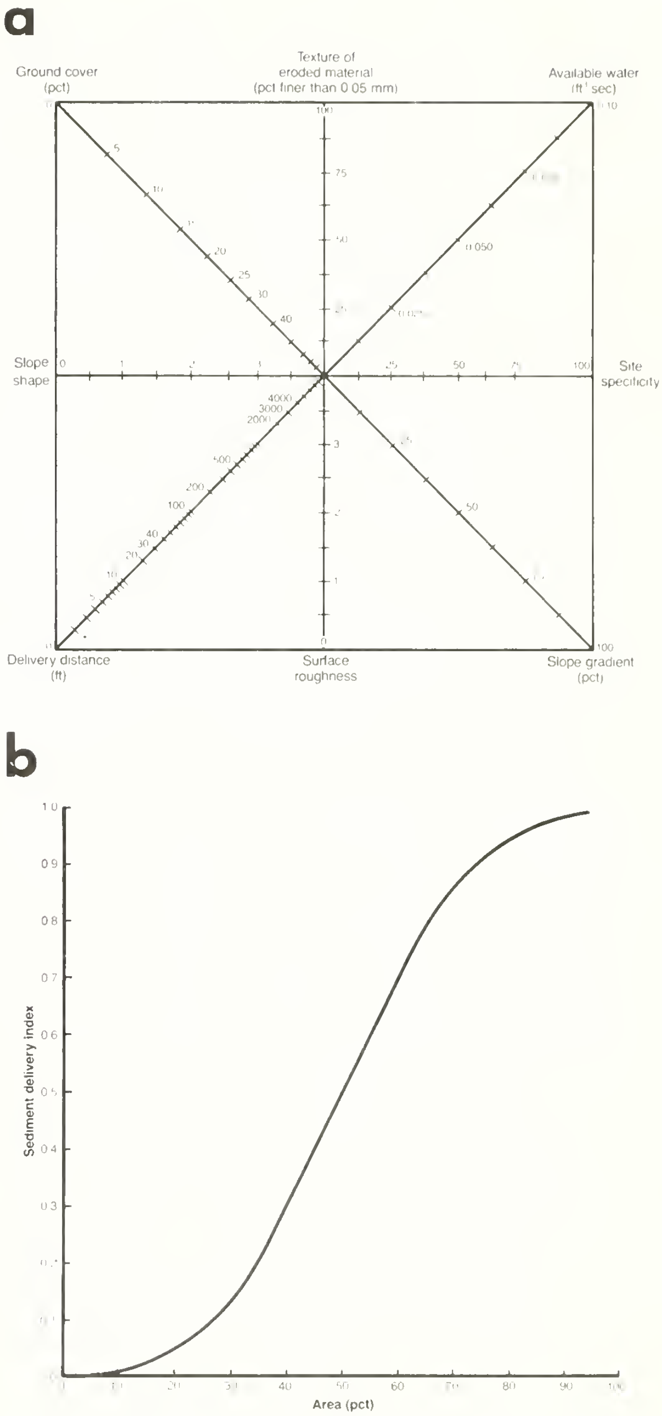


Figure 4—Relative areas of eight land characteristics that make up a polygon (a) are applied to a conversion curve (b) to determine the sediment delivery index. This index is used to calculate the quantity of detached material that reaches a stream channel. Slope shape is a dimensionless variable where 0 = concave, 4 = convex. Surface roughness is a dimensionless variable where 0 = smooth, 4 = rough. Site specificity is a dimensionless variable that expresses relative site specificity of a given analysis unit. Variables are discussed in greater detail in the WRENSS documentation (U.S. Dep. Agric., Forest Serv. 1980).

where

P = per unit value (of water or sediment), measured in 1982 dollars

$Q_{w/o,n}$ = yield (of water or sediment) per acre without fire in year n

$Q_{w,n}$ = yield (of water or sediment) per acre with fire in year n

i = discount rate

n = year of transaction

y = number of years in postfire time stream.

We assumed that differences in management costs between with-fire and without-fire regimes are negligible, and that all physical effects of fire are negligible beyond 25 years for water yield and 5 years for sediment yield. Discount rates of 4 and 10 percent were used in this analysis. The USDA Forest Service currently uses a 4 percent rate in land management planning, and the federal Office of Management and Budget (1972) recommends a 10 percent rate. Net value change was calculated with SASSY, an investment analysis computer package (Goforth and Mills 1975). SASSY performs the calculation in equation 2, given the following inputs: the timing or investment year of with-fire and without-fire water or sediment yields, the yield amount (acre-ft/acre for water, tons/mi^2 for sediment), price per unit, and discount rate.

The per-unit value of water was based on the value calculated for Forest Service Region 1 in the 1985 draft Resources Planning Act (RPA) Program, $13.50 (1982 dollars) per acre-foot of added water yield. The value of water is assumed to be equal to the marginal utility of the last increment of water in the lowest value consumptive use, which is irrigation. Water is used for irrigation only after higher value needs are met. Water benefit values are those used in RPA (Frank and Beattie 1979). The marginal product of the water input was calculated from estimated agricultural production functions, but estimated value of return flow and reuse were not included (Frank and Beattie 1979). The use of RPA values for the valuation of water yield is currently mandated for land management planning on all National Forests.

Water values can be determined by using criteria other than the lowest value consumptive use, such as the value of added water for the production of electricity (Vaux and Pour-Sanaie 1983). Water yield values for nine National Forests in the Columbia River Basin were weighted by forest acreage to produce an average value for the basin. Values ranged from $8.58 to $53.68 per acre-ft, with a weighted average value of $31.84 (1980 dollars). Use of this average value obviously would produce much higher estimates of economic change in water yield than would the marginal value.

Water value can also be calculated as the sum of the values for multiple uses. For example, the same increment of water can be used for irrigation, hydroelectric power generation, and municipal consumption. In addition, the use of water for agriculture depends on whether water can be made available for irrigation at times when it is needed. Although water surpluses are normally greatest in spring, demand for irrigation is usually greatest in late summer. Availability throughout the year often depends on storage capacity in reservoirs. The value of water is closely related to the actual demand for its use; this demand may vary.

Several methods can be used to calculate water value. Although we used RPA water values, the net value changes can be adjusted with an appropriate multiplier if a different water yield value is used.

The best per-unit values available for sediment production are estimates from the 1985 draft RPA Program. Sediment effects were tied to the direct impact on other resources or facilities (e.g., reservoirs) through damages and opportunity costs. Several studies and reports from different areas in the northern Rocky Mountains were categorized and weighted by kinds of impacts and land area involved.

The RPA value of $7 per thousand tons for Forest Service Region 1 was used to calculate NVC in equation 2; only the increase in sediment caused by fire was included. An increase in sediment production after a postfire salvage logging operation was attributed to fire, but sediment production due to an existing road system was not.

RESULTS AND DISCUSSION

Estimates of Postfire Water Yield

We estimated postfire water yield for 18 analysis units (*table 2*) using the computerized version of WRENSS, WSDU*WATER.WET. Complete model documentation and sensitivity analysis are available (Williams and Daddow 1984).

Results are given for a Douglas-fir cover type. With the exception of lodgepole pine, all cover types yield similar evapotranspiration modifier coefficients for the three basal area loss classes; therefore, postfire water yield increases will be similar. If estimates for a lodgepole pine cover type are desired, reduce the water yield increases *(table 2)* by about 20 percent.

The general seasonal distribution of annual precipitation used in this analysis was 40 percent winter, 40 percent spring, and 20 percent summer-fall. Winter precipitation contributed most to total water yield (Williams and Daddow 1984). The assumed distribution should provide valid results for most of the northern Rocky Mountains.

Basal area loss was the most important analysis unit parameter that affected water yield because it determines postfire evapotranspiration of a forest stand. The greater the basal area loss, the greater was the relative increase in water yield *(table 2)*. Water yield increased over natural yield only if fire or salvage logging or both removed greater than 50 percent of stand basal area. Increasing basal area loss from 90 to 100 percent produced an incremental increase in water yield almost as large as the difference between water yield for 50 and 90 percent losses.

Table 2—*Estimated natural water yield, and total increases in water yield 1 and 25 years after fire, by analysis unit, northern Rocky Mountains*

Analysis unit	Analysis unit parameters			Water yield			
	Annual precipitation	Aspect	Basal area loss	Natural	1-year increase postfire		Total 25-year increase in water yield
	inches		*pct*	*acre-ft/acre*		*pct*	*acre-ft/acre*
1	30	North	50	1.420	0.015	1	0.126
2			90	1.420	0.140	10	1.250
3			100	1.420	0.267	19	2.241
4		East-west	50	1.218	0.047	4	0.393
5			90	1.218	0.143	12	1.204
6			100	1.218	0.247	20	2.073
7		South	50	0.986	0.087	9	0.729
8			90	0.986	0.187	19	1.365
9			100	0.986	0.287	29	2.409
10	45	North	50	2.497	0.045	2	0.378
11			90	2.497	0.212	8	1.781
12			100	2.497	0.372	15	3.075
13		East-west	50	2.296	0.053	2	0.450
14			90	2.296	0.170	7	1.428
15			100	2.296	0.292	13	2.456
16		South	50	2.104	0.097	5	0.821
17			90	2.104	0.217	10	1.822
18			100	2.104	0.327	16	2.746

The largest increase in water yield was calculated for analysis unit 12, a site with high precipitation, north aspect, and 100 percent of basal area removed *(table 2)*. Analysis units with high precipitation had higher water yields than did their low precipitation counterparts. Analysis units with north aspects had higher water yields than did units on south and east-west aspects for a given precipitation class and basal area loss.

Possible Adjustments

Annual precipitation in the northern Rocky Mountains varies with latitude and elevation. The water yield estimates (*table 2*) are generally representative of mid-elevation and higher elevation timber harvest zones. However, water yield estimates may be needed for other precipitation levels. The model estimates water yield increases that are nearly linear with precipitation increases above a minimum level of precipitation (Williams and Daddow 1984). Therefore, natural water yield estimates *(table 2)* may be adjusted by approximately 0.4 acre-ft per 5-inch precipitation increment.

Adjusting postfire increases in water yield to a different precipitation class is difficult due to nonlinear functions used in the model. However, increases in first-year postfire percentage are reasonably consistent in given aspect and basal area loss classes. Water yield increases for a different precipitation class can be approximated by simply multiplying an *adjusted* natural water yield by the appropriate (basal area loss and aspect class) percentage increase *(table 2)*.

Total 25-year water yield increases are determined by integrating an exponential function over a 25-year recovery period. A simple algorithm multiplies the first-year postfire increase by 8.0. *Adjusted* total 25-year water yield may be determined in a similar manner by multiplying *adjusted* first-year postfire increase by 8.0.

Total Yield Increases

The water yield estimates *(table 2)* are independent of fire size class. To estimate total water yield increases, multiply the water yields *(table 2)* by the fire size. We did *not* use the model to predict changes in peak discharge or the timing of peak discharge.

Estimates of Postfire Sediment Yield

We estimated sediment yield 1 year after fire for 81 analysis units (3 precipitation classes by 3 slope classes by 3 fire-size classes by 3 road-salvage decisions) with WATSIM, a computerized version of the sediment yield model (Zuuring and Potts, 1985) *(table 3)*.

Fire had a relatively small effect on sediment production in most analysis units. Only those analysis units with the largest fire size class had relatively large increases in sediment. Salvage logging had its greatest effect on the largest fire size class as well, but produced relatively small increases for all analysis units. Natural sediment yield was greater than management-induced sediment yield (fire plus roads plus logging) in 60 of the 81 analysis units *(table 3)*.

The largest absolute increase in sediment production was calculated for analysis unit 81, a roaded site with high precipitation, 90 percent slope, a 2800-acre fire, and salvage logging. The estimated sediment yield of 181.2 tons/mi^2/yr is still relatively small and decreases rapidly over time. The largest relative in-

Table 3—*Estimated sediment yield 1 year after fire by analysis unit, showing separate contributions from fire, roads, and salvage logging, northern Rocky Mountains*

Analysis unit	Analysis unit parameters					Sediment yield[1]						
	(1) Annual precipitation	(2) Slope	(3) Fire size	(4) Roads	(5) Salvage logging	(6) Natural	(7) Fire	(8) Roads	(9) Logging	(10) Management induced	(11) Total	(12) Increase over natural
	inches	*pct*	*acres*			*tons/mi²/yr*						*pct*
1	15	20	30	No	No	10.2	--	0	0	--	10.2	0
2				Yes	No	10.2	--	8.3	0	8.3	18.5	81
3				Yes	Yes	10.2	--	8.3	--	8.3	18.5	81
4			380	No	No	10.2	.6	0	0	.6	10.8	6
5				Yes	No	10.2	.6	8.3	0	8.9	19.1	87
6				Yes	Yes	10.2	.6	8.3	.6	9.5	19.7	93
7			2800	No	No	10.2	8.3	0	0	8.3	18.5	81
8				Yes	No	10.2	8.3	8.3	0	16.6	26.8	163
9				Yes	Yes	10.2	8.3	8.3	5.1	21.7	31.9	213
10		60	30	No	No	19.2	.6	0	0	.6	19.8	3
11				Yes	No	19.2	.6	12.8	0	13.4	32.6	70
12				Yes	Yes	19.2	.6	12.8	--	13.4	32.6	70
13			380	No	No	19.2	3.2	0	0	3.2	22.4	17
14				Yes	No	19.2	3.2	12.8	0	16.0	35.2	83
15				Yes	Yes	19.2	3.2	12.8	1.3	17.3	36.5	90
16			2800	No	No	19.2	30.7	0	0	30.7	49.9	160
17				Yes	No	19.2	30.7	12.8	0	43.5	62.7	227
18				Yes	Yes	19.2	30.7	12.8	11.5	55.0	74.2	286
19		90	30	No	No	48.6	.6	0	0	.6	49.2	1
20				Yes	No	48.6	.6	17.3	0	17.9	66.5	37
21				Yes	Yes	48.6	6	17.3	--	17.9	66.5	37
22			380	No	No	48.6	8.3	0	0	8.3	56.9	17
23				Yes	No	48.6	8.3	17.3	0	25.6	74.2	53
24				Yes	Yes	48.6	8.3	17.3	1.3	26.9	75.5	55
25			2800	No	No	48.6	73.0	0	0	73.0	121.6	150
26				Yes	No	48.6	73.0	17.3	0	90.3	138.9	186
27				Yes	Yes	48.6	73.0	17.3	14.7	105.0	153.6	216
28	30	20	30	No	No	11.5	--	0	0	--	11.5	0
29				Yes	No	11.5	--	8.3	0	8.3	19.8	72
30				Yes	Yes	11.5	--	8.3	--	8.3	19.8	72
31			380	No	No	11.5	.6	0	0	.6	12.1	5
32				Yes	No	11.5	.6	8.3	0	8.9	20.4	77
33				Yes	Yes	11.5	.6	8.3	.6	9.5	21.0	83
34			2800	No	No	11.5	8.3	0	0	8.3	19.8	72
35				Yes	No	11.5	8.3	8.3	0	16.6	28.1	144
36				Yes	Yes	11.5	8.3	8.3	5.1	21.7	33.2	187
37		60	30	No	No	22.4	.6	0	0	.6	23.0	3
38				Yes	No	22.4	.6	12.8	0	13.4	35.8	60
39				Yes	Yes	22.4	.6	12.8	--	13.4	35.8	60
40			380	No	No	22.4	3.2	0	0	3.2	25.6	14

crease in sediment production over natural yield was calculated for analysis unit 18, a roaded site with low precipitation, 60 percent slope, a 2800-acre fire, and salvage logging.

Postfire sediment increases were severe only on sites with steep slopes and large fires. Resource managers and planners concerned with sediment production should be aware of this general trend. Management decisions can be based on absolute increases in sediment production, relative increases, or both. The criterion used may depend on which resources are emphasized within a watershed and the projected reliability of the absolute values.

Possible Adjustments

Changing one of the assumptions can significantly change some postfire sediment yield estimates *(table 3)*. However, the analysis unit watersheds are "simple" scenarios: each represents a single land-type unit, an area homogeneous in physical and vegetative characteristics. With the exception of standard road-erosion mitigation practices, assumptions like minimum delivery distances ensure high sediment yield estimates.

We assumed a miscellaneous metamorphic rock type for this analysis. This type is representative of one of four basic groups of rock types and the geologic erosion factors associated with

Table 3—*Estimated sediment yield 1 year after fire by analysis unit, showing separate contributions from fire, roads, and salvage logging, northern Rocky Mountains— continued*

Analysis unit	Analysis unit parameters					Sediment yield[1]						
	(1) Annual precipitation	(2) Slope	(3) Fire size	(4) Roads	(5) Salvage logging	(6) Natural	(7) Fire	(8) Roads	(9) Logging	(10) Management induced	(11) Total	(12) Increase over natural
	inches	*pct*	*acres*			*tons/mi²/yr*						*pct*
41				Yes	No	22.4	3.2	12.8	0	16.0	38.4	71
42				Yes	Yes	22.4	3.2	12.8	1.3	17.3	39.7	77
43			2800	No	No	22.4	30.7	0	0	30.7	53.1	137
44				Yes	No	22.4	30.7	12.8	0	43.5	65.9	194
45				Yes	Yes	22.4	30.7	12.8	11.5	55.0	77.4	246
46		90	30	No	No	53.8	.6	0	0	.6	54.4	1
47				Yes	No	53.8	.6	17.3	0	17.9	71.7	33
48				Yes	Yes	53.8	.6	17.3	--	17.9	71.7	33
49			380	No	No	53.8	8.3	0	0	8.3	62.1	15
50				Yes	No	53.8	8.3	17.3	0	25.6	79.4	48
51				Yes	Yes	53.8	8.3	17.3	1.3	26.9	80.7	50
52			2800	No	No	53.8	73.0	0	0	73.0	126.8	136
53				Yes	No	53.8	73.0	17.3	0	90.3	144.1	168
54				Yes	Yes	53.8	73.0	17.3	14.7	105.0	158.8	195
55	45	20	30	No	No	17.9	--	0	0	--	17.9	0
56				Yes	No	17.9	--	8.3	0	8.3	26.2	46
57				Yes	Yes	17.9	--	8.3	--	8.3	26.2	46
58			380	No	No	17.9	.6	0	0	.6	18.5	3
59				Yes	No	17.9	.6	8.3	0	8.9	26.8	50
60				Yes	Yes	17.9	.6	8.3	.6	9.5	27.4	53
61			2800	No	No	17.9	8.3	0	0	8.3	26.2	46
62				Yes	No	17.9	8.3	8.3	0	16.6	34.5	93
63				Yes	Yes	17.9	8.3	8.3	5.1	21.7	39.6	121
64		60	30	No	No	35.6	.6	0	0	.6	36.2	2
65				Yes	No	35.6	.6	12.8	0	13.4	49.0	38
66				Yes	Yes	35.6	.6	12.8	--	13.4	49.0	38
67			380	No	No	35.6	3.2	0	0	3.2	38.8	9
68				Yes	No	35.6	3.2	12.8	0	16.0	51.6	45
69				Yes	Yes	35.6	3.2	12.8	1.3	17.3	52.9	49
70			2800	No	No	35.6	30.7	0	0	30.7	66.3	86
71				Yes	No	35.6	30.7	12.8	0	43.5	79.1	122
72				Yes	Yes	35.6	30.7	12.8	11.5	55.0	90.6	154
73		90	30	No	No	76.2	.6	0	0	.6	76.8	1
74				Yes	No	76.2	.6	17.3	0	17.9	94.1	23
75				Yes	Yes	76.2	.6	17.3	--	17.9	94.1	23
76			380	No	No	76.2	8.3	0	0	8.3	84.5	11
77				Yes	No	76.2	8.3	17.3	0	25.6	101.8	33
78				Yes	Yes	76.2	8.3	17.3	1.3	26.9	103.1	35
79			2800	No	No	76.2	73.0	0	0	73.0	149.2	96
80				Yes	No	76.2	73.0	17.3	0	90.3	166.5	119
81				Yes	Yes	76.2	73.0	17.3	14.7	105.0	181.2	138

[1]-- = negligible.

them (Cline 1982). Simple multiplication can be used to adjust the management-induced sediment *(table 3)* for other rock types. To adjust the prediction to hard sedimentary rocks, multiply by 1.25; to soft sedimentary rock or schist, multiply by 1.75; to granitics, multiply by 2.5.

Total Yield Increases

Adding the *adjusted* management induced sediment to the natural sediment (column 10 plus column 6, *table 3*) provides an *adjusted* total (column 11) that would then provide an *adjusted* increase over natural sediment yield (column 12).

Net Value Change of Water Resources

Increased water yields resulted in a beneficial (negative) net value change for all analysis units *(table 4)*. Net value change was proportional to the physical change in water yield *(table 2)*. Benefits were substantial in some cases, and were less than $5 per acre only in some analysis units with 50 percent basal area loss. The largest increase in value was $33.42 per acre (at a 4 percent discount rate) for an analysis unit with high rainfall, north aspect, and 100 percent basal area loss. The most important trend was that net value change was increasingly negative as basal area

Table 4—*Net value change of postfire water yield by analysis unit, northern Rocky Mountains*

Analysis unit	Analysis unit parameters			Net value change[1]	
	Annual precipitation	Aspect	Basal area loss	4 pct rate	10 pct rate
	inches		*pct*	*1982 dollars*	
1	30	North	50	−1.37	−1.05
2			90	−13.34	−10.27
3			100	−23.98	−18.49
4		East-west	50	−10.14	−4.84
5			90	−12.79	−9.88
6			100	−22.12	−17.06
7		South	50	−7.89	−6.07
8			90	−16.84	−12.97
9			100	−25.86	−19.93
10	45	North	50	−4.04	−3.12
11			90	−19.04	−14.68
12			100	−33.42	−25.76
13		East-west	50	−4.79	−3.70
14			90	−15.21	−11.74
15			100	−26.25	−20.23
16		South	50	−8.71	−6.71
17			90	−19.43	−14.99
18			100	−29.34	−22.62

[1]Negative net value change indicates an increase (benefit) in postfire water value.

loss increased *(table 4)*. The magnitude of the change in NVC between 50 and 90 percent basal area loss for a given precipitation class and aspect was similar to that between 90 and 100 percent basal area loss. Net value increased more than $20 per acre (at a 4 percent discount rate) for all analysis units with 100 percent basal area loss.

Net value change for sediment production was detrimental (positive) for all analysis units but was always less than $.01 per acre, because the per-unit value of sediment is so low ($7 per thousand tons). Net value changes for fire-caused sediment production are not included because of these extremely small value changes.

The economic impact of increased sediment production after fire is small, even if the fire is large and severe and includes salvage logging. Net value change caused by increased sediment is insignificant compared with that caused by increased water yield. Small increases in postfire sediment production may have some local impacts, such as temporary damage to fish habitat. Although this kind of damage is poorly quantified and difficult to assess with an economic analysis, minimization of damage to fish habitat by sediment may have a greater influence on management decisions in some cases than do economic criteria. Relative increases in sediment production *(table 3)* may be used to assist in these management decisions.

Fires that are severe enough to kill at least half of the basal area in a stand can cause substantial increases in water yield *(table 2)* and some relatively large beneficial net value changes *(table 4)*. A postfire management decision to remove additional timber in a salvage logging operation results in an even greater net value change. Increased water yield in areas used for commercial timber production can offset possible losses in the value of timber due to fire. Increased water yield in unroaded or wilderness areas can result in substantial economic benefits because no commercial timber is lost.

CONCLUSIONS

An analytical system can be used to estimate nonsite-specific postfire changes in water resource outputs at a broad level of resolution appropriate for planning. We used well-documented, state-of-the-art procedures to estimate these changes rather than develop a new untested system. Greater confidence in estimates can be obtained only with a case-by-case analysis. We have also indicated possible adjustments to our estimates that would permit a greater level of site specificity. The water and sediment yield models are both readily available and can be used directly if greater resolution is necessary.

Water yield increases after fire are affected greatly by the amount of basal area killed by fire and removed by salvage logging. This increase is greatest in the year immediately after fire and decreases exponentially during a 25-year postfire period. This increase can be up to 0.4 acre-ft/acre in the first year after fire and 3.1 acre-ft/acre for the 25-year period *(table 2)*.

Fire had a relatively small effect on sediment production, even if there was a postfire timber harvest. The increase in sediment was greatest in the year after the fire and decreased during a 5-year postfire period. Maximum sediment production in absolute terms was only 181 tons/mi^2/yr (428 tonnes/km^2/yr), although increase over natural yield was as high as 284 percent. The greatest increases in sediment yield were calculated for analysis units with steep slopes and large fires.

The economic benefits of increased water yield are directly proportional to the quantity of water produced. Although water is not valued as highly in the northern Rocky Mountains as it is in other regions of the country, estimated postfire net value change was as high as $33 per acre. This benefit of fire should be considered with benefits and losses for other resources in calculating total net value change for various fire management situations. Increased sediment production is detrimental but the predicted loss of net value is small. The net value change estimates in this paper allow resource managers to make decisions on the basis of economic criteria. Environmental impacts such as damage to fish habitat from sediment may outweigh economic considerations in some cases. Estimates of sediment production reported here can be used to make decisions based on physical output changes.

We recommend using estimates reported in this paper for planning and other broad resolution applications only. The estimates may have some value for postfire impact assessment and escaped fire situation analyses, but should be used cautiously for such site-specific purposes. Users should be aware of the basic structure and assumptions of the water and sediment yield models before applying these estimates to any management situation.

REFERENCES

Bratten, Frederick W., Operations Research Analyst, Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Riverside, CA [Conversation with David L. Peterson]. September 1983.

Cline, Richard G. **Rock type characteristics used for extrapolation of coefficients in a sediment yield model**. Soil, Air and Water Notes 82–1. Missoula, MT: Northern Region, Forest Service, U.S. Department of Agriculture; 1982. 8 p.

Cline, Richard G.; Cole, Gene; Megahan, Walter F.; Patten, Rick; Potyondy, John. **Guide for predicting sediment yields from forested watersheds**. Missoula, MT: Northern Region, Forest Service, U.S. Department of Agriculture; 1981. 48 p.

Frank, Michael D.; Beattie, Bruce R. **The economic value of irrigation water in the western United States: an application of ridge regression**. Tech. Rep. 99. College Station, TX: Texas A&M University. 1979.

Garrison, George A.; Bjugstad, Ardell J.; Duncan, Don A.; Lewis, Mont E.; Smith, Dixie R. **Vegetation and environmental features of forest and range ecosystems**. Agric. Handb. 475. Washington, DC: U.S. Department of Agriculture, Forest Service; 1977. 68 p.

Goforth, Mark H.; Mills, Thomas J. **A financial return program for forestry investments, including sensitivity of results to data errors**. Agric. Handb. 488. Washington, DC: U.S. Department of Agriculture; 1975. 18 p.

Goldstein, R.A.; Mankin, J.B.; Luxmore, Robert J. **Documentation of PROSPER: a model of the atmosphere-soil-plant water flow**. Environ. Sci. Div. Publ. 579. Oak Ridge, TN: Oak Ridge National Laboratory; 1974. 75 p.

Leaf, Charles F.; Brink, Glen E. **Computer simulation of snowmelt within a Colorado subalpine watershed**. Res. Paper RM-99. Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1973a. 22 p.

Leaf, Charles F.; Brink, Glen E. **Hydrologic simulation model of Colorado subalpine forest**. Res. Paper RM-107. Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1973b. 23 p.

Mills, Thomas J.; Bratten, Frederick W. **FEES: Design of a Fire Economics Evaluation System**. Gen. Tech. Rep. PSW-65. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 26 p.

Nelson, Thomas C. **Fire management policy in the National Forests—a new era**. J. For. 77: 723–725; 1979.

Office of Management and Budget. Circular A-94. Washington, DC; 1972. 4 p.

Tiedemann, Arthur R.; Conrad, Carol E.; Dieterich, John H.; and others. **Effects of fire on water: a state-of-knowledge review**. Gen. Tech. Rep. WO-10. Washington, DC: Forest Service, U.S. Department of Agriculture; 1979. 28 p.

U.S. Department of Agriculture, Forest Service. **Forest Survey Handbook 4813.1 Section 74: geographic forest types**. Washington, DC; 1967: 74 to 74.2–3.

U.S. Department of Agriculture, Forest Service. **Fire considerations in forest planning**. [Fire in Land Management Planning Task Force]. Washington, DC; 1979. 50 p.

U.S. Department of Agriculture, Forest Service. **An approach to Water Resources Evaluation of Nonpoint Silvicultural Sources (Procedural Handbook)**. EPA-600/8-80-012. Washington, DC: Environmental Protection Agency; 1980. 772 p.

Vaux, Henry J.; Pour-Sanaie, Mahmood. **Valuation of fire-induced water and sediment yields in the Columbia Basin**. 1983. Unpublished draft supplied by author.

Williams, Owen R.; Daddow, Richard L. **WSDU*WATER.WET: the computerized version of chapter III—Hydrology—of the WRENSS handbook**. Rep. WSDG-AD-00007. Fort Collins, CO: Watershed Systems Development Group, Forest Service, U.S. Department of Agriculture; 1984. 45 p.

Zuuring, Hans R.; Potts, Donald F. **WATSIM—a user's guide: computer simulation of sediment yields using the Regions 1 & 4 sediment yield prediction procedure**. Montana Forest and Conservation Experiment Station Misc. Publ. 43. Missoula, MT: School of Forestry, University of Montana; 1985. 24 p.

Potts, Donald F.; Peterson, David L.; Zuuring, Hans R. **Watershed modeling for fire management planning in the northern Rocky Mountains.** Res. Paper PSW-177. Berkeley, CA; Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1985. 11 p.

Two simulation models were adapted to estimate postfire changes in water yield and sediment production in northern Rocky Mountain watersheds. Data on topography, vegetation, and climate were used to simulate expected changes in resource production and value after wildfire. Management decisions were incorporated into the simulation approach. The results suggest that water yield increases were most affected by the amount of basal area killed by fire and removed by salvage logging, that estimated postfire benefits due to increased water yield were substantial, and that losses due to increased sedimentation were negligible. This simulation approach can be useful to managers who need to estimate long-term changes in water yield and value caused by wildfire.

Retrieval Terms: fire effects, net value change, sediment, water yield, watershed models

United States
Department of
Agriculture

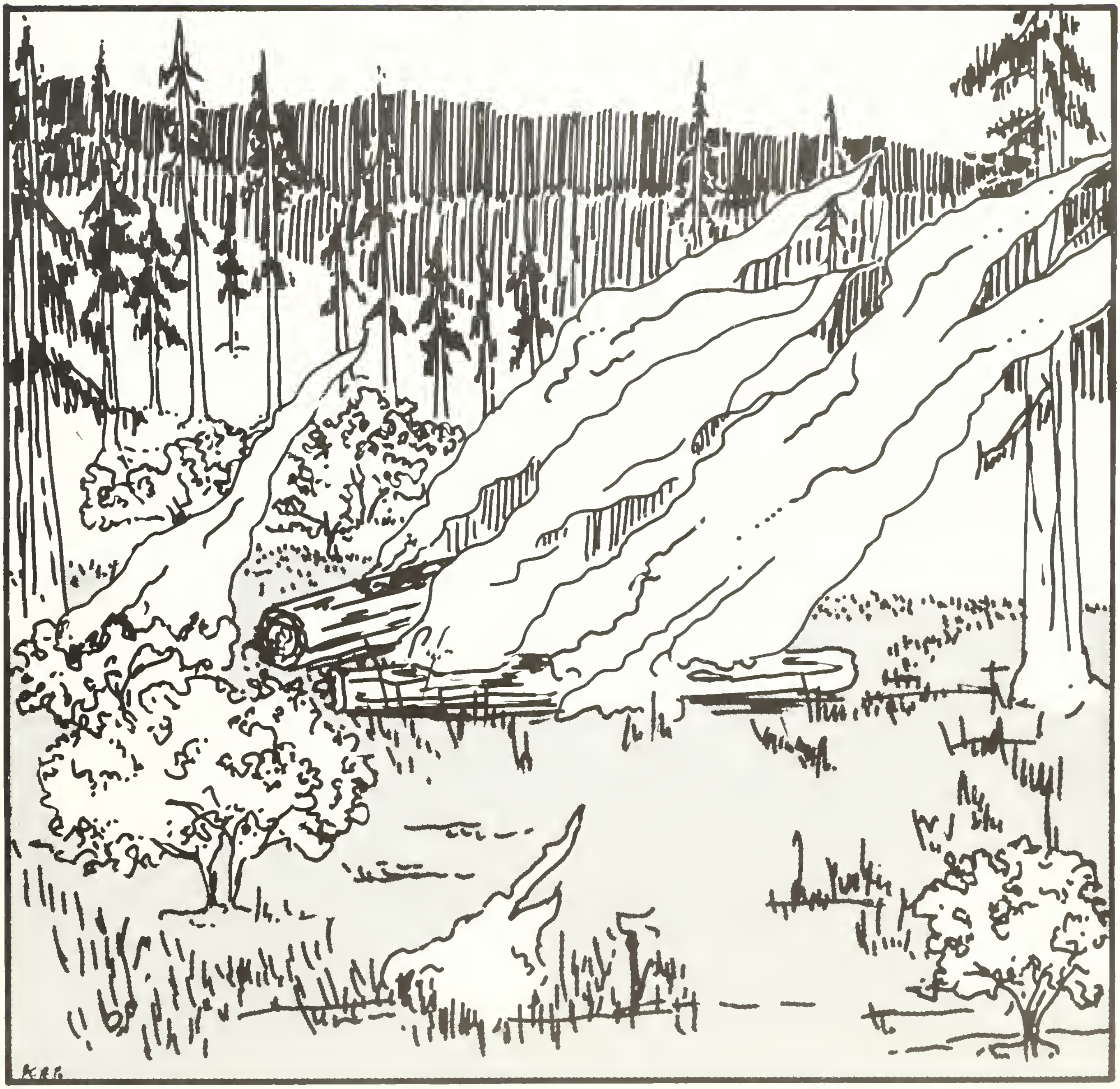
Forest Service

Pacific Southwest
Forest and Range
Experiment Station

Research Paper
PSW-178

Sensitivity of Fire Behavior Simulations to Fuel Model Variations

Lucy A. Salazar



The Author:

LUCY A. SALAZAR is a research forester assigned to the Station's Fire Management Planning and Economics Research Unit, headquartered at the Forest Fire Laboratory, Riverside, California. She earned a bachelor's degree in mathematics (1976) from the University of California, Irvine, and a master's degree in natural resources, with an emphasis in forestry (1980), at Humboldt State University, Arcata. She joined the Station staff in 1980.

Publisher:

Pacific Southwest Forest and Range Experiment Station
1960 Addison Street, Berkeley, California 94704

October 1985

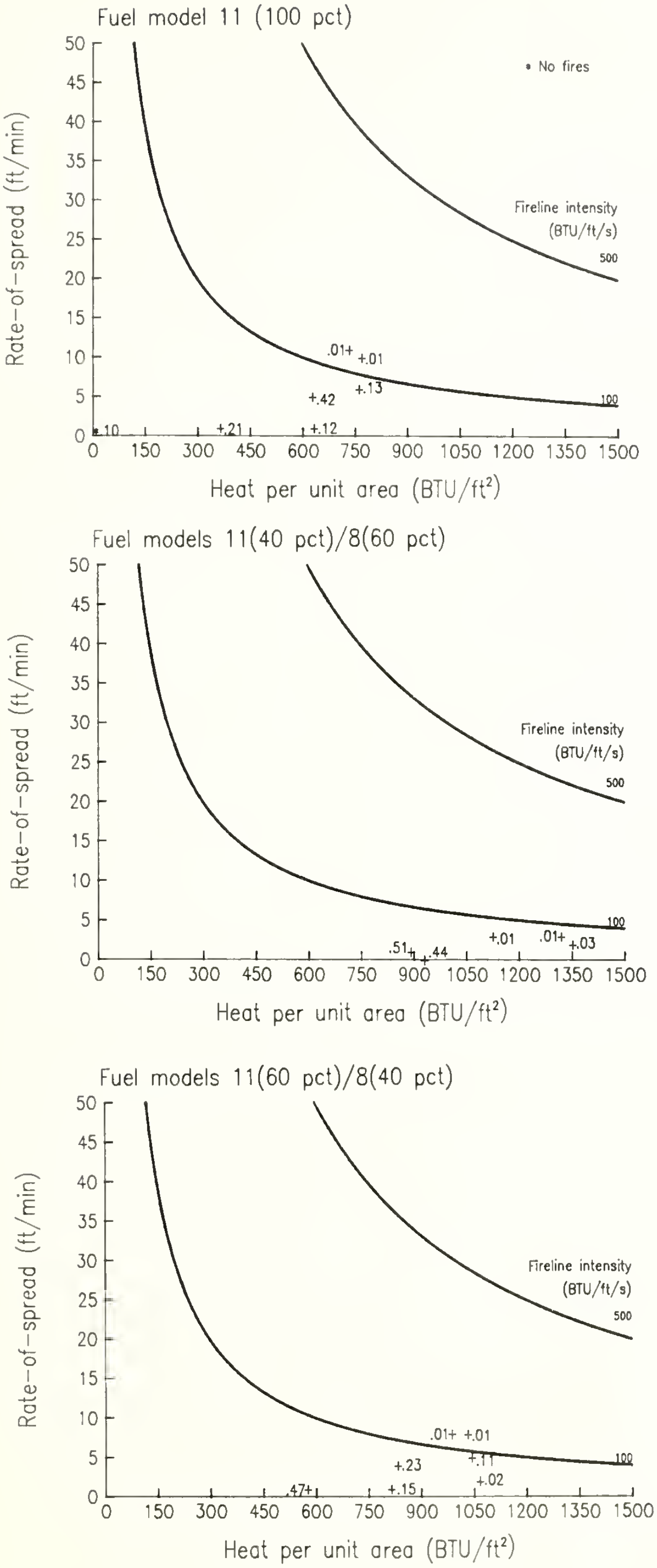


Figure 11

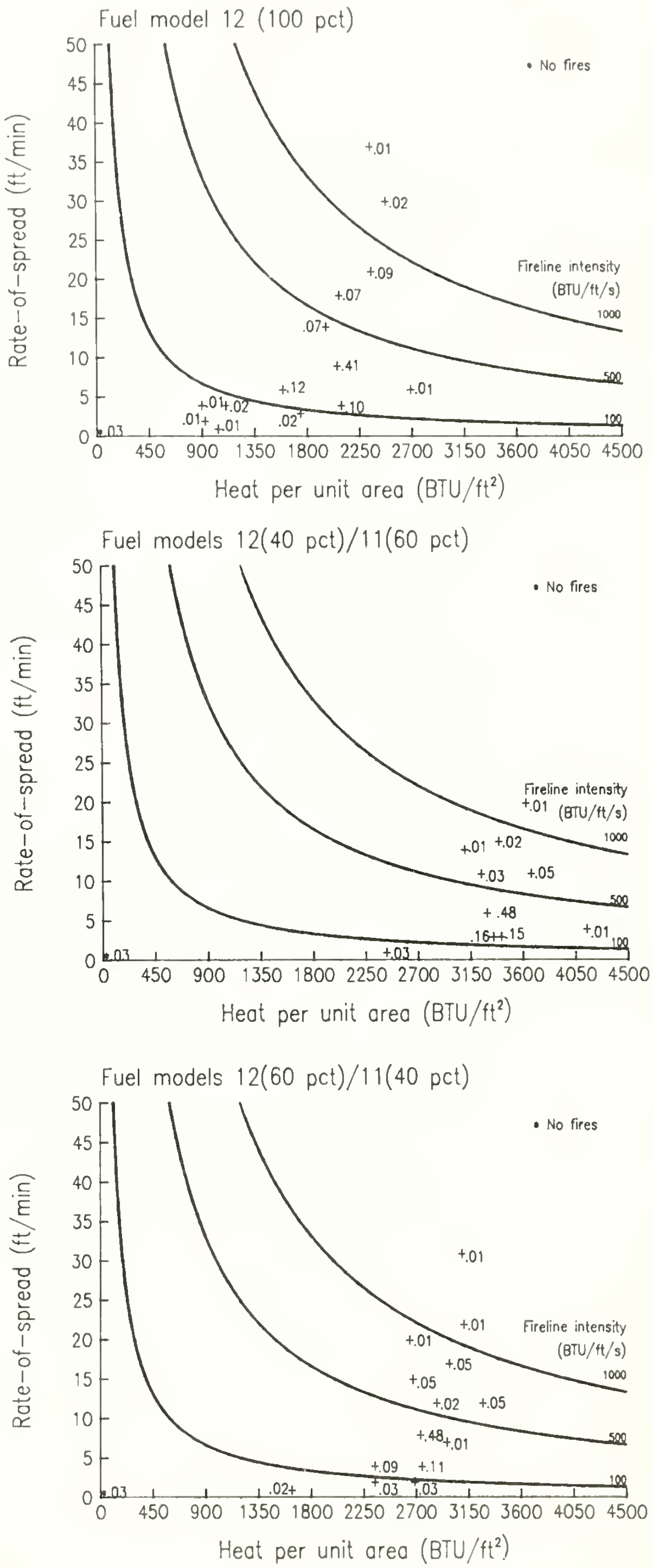


Figure 12

THIS IS A CORRECTED PAGE FOR:
Salazar, Lucy A. Sensitivity of fire behavior simulations to fuel model variations. Res. Paper PSW-178. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1985. 11 p.

Sensitivity of Fire Behavior Simulations to Fuel Model Variations

Lucy A. Salazar

CONTENTS

IN BRIEF...

Salazar, Lucy A. **Sensitivity of fire behavior simulations to fuel model variations.** Res. Paper PSW-178. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1985. 11 p.

Retrieval Terms: fire behavior, fuel models, probabilistic fire modeling, wildfire

Stylized fuel models, or numerical descriptions of fuel arrays, are used as inputs to fire behavior simulation models. These fuel models are often chosen on the basis of generalized fuel descriptions, which are related to field observations. Site-specific observations of fuels or fire behavior in the field are not readily available or necessary for most fire management planning situations. Fuels are thought of in general terms and a single fuel model is often assigned to represent large areas of land. Variations in weather, which can substantially affect fire behavior, are not reflected in the available aids for selecting fuel models. The sensitivity of simulated fire behavior variables to the 13 fire behavior fuel models and two-fuel-model alternatives was analyzed. The two-fuel-model concept demonstrated the effect of combining fuel models on simulated fire behavior results.

Weather data from 20 fire weather stations within the Northern Rockies and Intermountain Zone were processed by a computer program that produced joint distributions of live and dead fuel moistures and windspeeds. These joint weather-related distributions, along with definitions of fuel model, slope, aspect, time of year, and time of day were used as inputs to a fire behavior simulation model. Model output was joint distributions of rate-of-spread and fireline intensity. The fire behavior distributions for the set of 13 fuel models and their two-fuel-model alternatives were displayed on the fire behavior characteristics chart, which allows comparisons of ranges and frequencies of occurrence.

The results showed the sensitivity of the simulated fire behavior to the 13 fuel models at 100 percent area coverage, and the wide range of outcomes that this set of fuel models represents. The two-fuel-model simulations also showed a broad range of results, indicating that this alternative use of fuel models could add substantially to a fire manager's planning capabilities. Interpretations of the fire behavior characteristics chart indicated how often certain fuel conditions could present suppression problems, and that variations of the area coverages in the two-fuel-model alternatives could dramatically affect initial attack effectiveness. Other factors, including arrival times, production rates, and multiple fire events would also have to be evaluated in an actual situation.

The set of 13 fire behavior fuel models may not be adequate for simulations in some site-specific, high resolution wildland situations. Alternative methods, such as creating custom fuel models, may be more appropriate.

INTRODUCTION

Fire managers must be aware of the effect that selection of a fuel model will have on predictions of fire behavior and suppression effectiveness. A set of 13 stylized fuel models used extensively in fire behavior modeling was developed on the assumption that fuel array parameters are inherent to a model (Albini 1976). That is, once characteristics such as fuel loading, moisture of extinction, and surface-area-to-volume ratios are defined, they need not be remeasured. A commonly used wildfire spread model, which uses fuel models as inputs, assumes that fire progresses in a quasi-steady state through continuous fuel beds that are contiguous to the ground (Rothermel 1972). For fire management planning purposes, fuels are thought of in general terms, and a single fuel model is often assigned to represent large areas of land.

A fuel model must be assigned not only on the basis of the generalized physical description of the fuel bed, but also on the fire behavior characteristics it is known to produce (Rothermel 1983). Site-specific observations of fuels or fire behavior in the field are not readily available or necessary for most fire management planning situations. Therefore, visual and descriptional aids to the selection of the appropriate fuel models based on field observations have been developed (Anderson 1982, Main and Haines 1983). Adjustment procedures have also been developed to match a fuel model to observed fire behavior once a fuel model has been selected (Rothermel and Rinehart 1983). A guide to fuel model selection included a description of the expected fire behavior and a single rate-of-spread and flame length value for each of the 13 fire behavior fuel models, calculated with one windspeed and fuel moisture value input (Anderson 1982). However, variations in weather and topographic conditions will produce different fire behavior results from these calculated values.

An alternative procedure available to fire managers is applying the two-fuel-model concept (Rothermel 1983). Two fuel models are used in the fire spread model to represent fuel arrays that are not uniform enough to be described with a single fuel model. In this procedure, rates-of-spread are weighted by the proportional area coverage assigned to each of the two selected fuel models.

This paper documents the sensitivity of distributions of selected fire behavior variables (rate-of-spread, fireline intensity, and heat per unit area) to the 13 fuel models and to changes in the percent area coverage assigned to the two-fuel-model combinations. These results are discussed in a fire management planning context, but implications for real-time fire modeling are also apparent.

METHODS

Data from National Fire Weather Data Library weather stations were processed, by a computer program that produced joint distributions of fuel moistures and windspeeds. These weather-related inputs, in addition to fuel model, slope, aspect, time-of-day, and time-of-year, were used to produce joint probabilities of rate-of-spread and fireline intensity (Salazar and Bradshaw in preparation).

The 20 weather stations that provided the information were all located above 4500 ft (1372 m) in the Northern Rockies and Intermountain Zone, which encompasses eastern Oregon and Washington, Idaho, western Montana, and southwestern Wyoming (Schroeder and others 1964). All recorded weather data from July to September 1954 to 1981 were processed, representing a total of 30,899 days of weather (Salazar and Bradshaw 1984). This elevation band and time-of-year class were chosen because the majority of fires in the northern Rocky Mountains occur in those situations.

Only fires starting during the day were simulated. To allow for diurnal adjustments of temperature and relative humidity, which affect fuel moistures, daytime was split into four time periods: 0500 to 0759, 0800 to 1159, 1200 to 1559, and 1600 to 1959 local standard time. The midpoints of each of these periods were used in the computation of diurnal temperatures and relative humidities (Salazar and Bradshaw 1984). The National Fire Danger Rating System curing routines were used to represent seasonal changes in fuel moisture (Bradshaw and others 1984). The standard recorded 20-ft (6-m) windspeed was used for all time-of-day classes and was reduced to midflame windspeed (Baughman and Albini 1980).

Fire behavior was calculated for each time-of-day class, and the resulting set of four joint frequency distributions aggregated into one by the use of weighting factors. Weights for each time-of-day class were derived from the frequency that detection times

Table 1—*Inherent characteristics of 13 fire behavior fuel models*

Fuel model description	Fuel loading[1] 1 hr	10 hr	100 hr	Live	Fuel bed depth[2]	Moisture of extinction dead fuels	Wind reduction factor
	tons/acre				*ft*	*percent*	
1 Short grass (1 ft)	0.74	0.00	0.00	0.00	1.0	12	36
2 Timber (grass and understory)	2.00	1.00	.50	.50	1.0	15	25
3 Tall grass (2.5 ft)	3.01	.00	.00	.00	2.5	25	44
4 Chaparral (6 ft)	5.01	4.01	2.00	5.01	6.0	20	55
5 Shrubs (2 ft)	1.00	.50	.00	2.00	2.0	20	42
6 Dormant shrubs, hardwood slash	1.50	2.50	2.00	.00	2.5	25	44
7 Southern rough	1.13	1.87	1.50	.37	2.5	40	25
8 Closed timber litter	1.50	1.00	2.50	.00	.2	30	17
9 Long needle pine, hardwood litter	2.92	.41	.15	.00	.2	25	17
10 Timber (litter and understory)	3.01	2.00	5.01	2.00	1.0	25	12
11 Light logging slash	1.50	4.51	5.51	.00	1.0	15	36
12 Medium logging slash	4.01	14.03	16.53	.00	2.3	20	43
13 Heavy logging slash	7.01	23.04	28.05	.00	3.0	25	46

Source: Anderson (1982), Baughman and Albini (1980)

[1] tons/acre × .2241 = kg/m^2

[2] ft × .3048 = m

on Forest Service fire reports (Form FSH 5100.29) appeared in each class (Salazar and Bradshaw in preparation). This weighting procedure emphasized the weather conditions at the times fires were detected. Fires were assumed to be in a steady state at the time of detection.

The large number of joint occurrences of rate-of-spread and fireline intensity precluded the storage and use of each unique combination that was generated. The outputs for these two fire behavior parameters were instead split into four classes, with the class boundaries subjectively chosen to represent low, medium, high, and extreme severity:

Class	Fire severity	Rate-of-spread	Fireline intensity
		ft/min (m/min)	*BTU/ft/s (kW/m)*
1	Low	0 – 2.5 (0.762)	0 – 100 (346)
2	Medium	2.51 – 12.5 (3.810)	100.1 – 500 (1730)
3	High	12.51 – 25.0 (7.620)	500.1 – 1000 (3459)
4	Extreme	25.01 +	1000.1 +

Frequencies and expected values were generated for each unique combination of these fire classes and were graphically displayed. The fire behavior computer processor also produces two other fire behavior variables—length-to-width ratio and scorch height (Salazar and Bradshaw in preparation). The results for each of these variables were also separated into four classes. Even though these two extra variables were not used in this study, the unique combinations that they produced were kept intact. Therefore, a unique combination of rate-of-spread and fireline intensity sometimes had several expected values.

Each of the 13 fire behavior fuel models (*table 1*) was input to the fire behavior processor. Other necessary inputs and their designated standards for this study were 20 percent slope and south aspect. Again, these inputs where chosen because a large number of fires in the northern Rocky Mountains occur under these circumstances.

The two-fuel-model weighting procedure was applied by combining each of the 13 fuel models with another one of the set under two different area coverage percentages (*table 2*). The second fuel model was subjectively chosen to represent a feasible combination. The processor calculated fire behavior for both fuel models. The rate-of-spread values were weighted together by the proportion of area coverage assigned to each fuel model. In the examples, the area proportions were subjectively chosen at either 40 or 60 percent to get an indication of the effect that the dominating fuel model (i.e., the one with the greatest area coverage) had on the weighted results. The wind reduction factors (Baughman and Albini 1980), which affect rate-of-spread and fireline intensity calculations, were those of the fuel model with the higher proportion. The computed fireline intensities were not weighted together. The largest calculated fireline intensity of the two fuel models was stored as the output because it was assumed to be the most useful for planning situations.

The fire behavior-characteristics chart incorporates the fire behavior variables of rate-of-spread, fireline intensity, and heat per unit area into one graph. It has been known to be useful in many fire management situations (Andrews and Rothermel 1982, Main and Haines 1983, Rothermel 1983). This chart was used to display the fire behavior distributions of the 13 fuel models and their two-fuel-model alternatives. Because only rate-of-spread and fireline intensity were calculated by the processor, the following formula was used to calculate heat per unit area from the expected values of rate-of-spread and fireline intensity:

$$\text{Heat per unit area (BTU/ft}^2\text{)} = \frac{\text{fireline intensity (BTU/ft/s)} \times 60 \text{ (s/min)}}{\text{rate-of-spread (ft/min)}}$$

Suppression capabilities can also be predicted directly from interpretations of the fireline intensity bands, which were also graphed on the chart (Andrews and Rothermel 1982):

Fireline intensity, BTU/ft/s (kW/m)	Interpretation
<100 (346)	Fire generally can be attacked at the head or flanks by persons using hand tools. Handline should hold the fire.
100–500 (1730)	Fires are too intense for direct attack at the head by persons using hand tools. Handline cannot be relied on to hold fire. Equipment such as plows, bulldozers, pumpers, and retardant aircraft can be effective.
500–1000 (3459)	Fires may present serious control problems—torching out, crowning, and spotting. Control efforts at the fire head will probably be ineffective.
>1000	Crowning, spotting, and major fire runs are probable. Control efforts at head of fire are ineffective.

RESULTS OF SENSITIVITY ANALYSIS

Equilibrium, steady-state burning conditions were assumed for this analysis (Rothermel 1972). Therefore, the results do not account for situations that include:

• Smoldering fires in tightly packed litter, duff, snags, or rotten wood

• Extreme fire behavior exhibited by crowning, spotting, or fire whirls

• More fuel nonuniformity than that assumed for the two-fuel-model procedure.

The potential for severe fire behavior, however, is indicated by the interpretations of fireline intensity above (Andrews and Rothermel 1982). For example, fires with fireline intensities greater than 1000 BTU/ft/s (3459 kW/m) will probably result in crowning and spotting conditions, making direct attack at the fire head virtually ineffective.

The differences in fire behavior potential of the 13 fuel models and their selected two-fuel-model alternatives are displayed by their frequency distributions on fire behavior characteristics charts (*figs. 1-13 in appendix*). The maximum expected values

Table 2—*Two-fuel-model alternatives for each of the 13 fire behavior fuel models*

Fuel model	Fuel models (percent area coverage)	
	Alternative 1	Alternative 2
1	1(40)/9(60)	1(60)/9(40)
2	2(40)/9(60)	2(60)/9(40)
3	3(40)/2(60)	3(60)/2(40)
4	4(40)/7(60)	4(60)/7(40)
5	5(40)/8(60)	5(60)/8(40)
6	6(40)/9(60)	6(60)/9(40)
7	7(40)/8(60)	7(60)/8(40)
8	8(40)/10(60)	8(60)/10(40)
9	9(40)/8(60)	9(60)/8(40)
10	10(40)/8(60)	10(60)/8(40)
11	11(40)/8(60)	11(60)/8(40)
12	12(40)/11(60)	12(60)/11(40)
13	13(40)/11(60)	13(60)/11(40)

varied substantially between fuel models. Therefore, the scales may differ between fuel models, but the scales are the same among the three alternatives for each fuel model. A weighted average of the fire behavior variables was displayed for points that were too close to be legible. Some frequency distributions do not add up to 1.0 due to rounding.

Often the recorded weather was such that a simulated fire could not spread. These "nonfire" events and their frequency of occurrence are also displayed for comparison purposes in the position for zero rate-of-spread and zero heat per unit area. The variability in the occurrence frequency of these nonfire events is mainly due to differences in the fuel-model-specific moisture of extinction (i.e., the fuel moisture content above which the fire will not spread) of the dead fuels (*table 1*).

The fire behavior characteristics charts show (1) the sensitivity of the fire behavior outputs to the 13 fuel models, at 100 percent area coverage, and (2) the wide range of outcomes that this set of fuel models represents. Two of the fuel models dominated by short grass (*figs. 1 and 2*) exhibited some potential for high rates-of-spread, with predominantly low to moderate intensity levels. A fire in the tall grass fuel model (*fig. 3*) would almost always be difficult to suppress if it occurred under the weather conditions modeled here. A fire in the chaparral fuel model (*fig. 4*) would present suppression difficulties to hand crews approximately 93 percent of the time, but nonfire days occurred 3 percent of the time. The other three shrub fuel models (*figs. 5–7*) exhibited much less severe fire behavior potential. Fires in the timber-dominated fuel models (*figs. 8–10*) would rarely present suppression problems except in situations where they exceeded the surface fire conditions assumed in this study. The slash fuel models (*figs. 11–13*) varied dramatically in their fire behavior potential, due to inherent differences in loading, moistures of extinction, wind reduction factors, and fuel depths. Fuel models of different general categories often showed similar fire behavior results. For example, simulation results for fuel models 2 and 7 (*figs. 2 and 7*) overlapped in the 400 to 500 BTU/ft^2 (4540–5674 kJ/m^2) heat per unit area and the 0 to 10 ft/min (3.048 m/min) rate-of-spread bands. This overlap could prompt a fire manager to select a fuel model typically used for southern rough to describe an open pine modeling situation.

In some cases the second fuel model substantially affected the resulting fire behavior distributions and in other cases a second fuel model had little effect on the resulting fire behavior. For example, the rate-of-spread values representing the combination of 40 percent fuel model 1 and 60 percent fuel model 9 are lower than those for 100 percent fuel model 1 (*fig. 1*). But at the same time, heat per unit area increased substantially. Conversely, the two alternative combinations for fuel models 8, 9, and 10 (*figs. 8–10*) had little rate-of-spread variation, but the heat per unit area was more markedly affected.

DISCUSSION AND CONCLUSIONS

The use of fire behavior class boundaries and expected values within these classes aggregated the resulting data, making it much more manageable for planning purposes. At the same time, by generalizing the data into discrete points, some of the actual data, which might be necessary for high resolution applications, were eliminated. The consequences of this elimination would have to be evaluated case by case.

The fire behavior characteristics chart provided a useful and easily interpretable medium for displaying the fire behavior potential for the 13 fuel models used in this study. The results showed that fire behavior simulations that use the fire behavior fuel models usually produced a wide range of possible outcomes. An awareness of this range would be especially useful in real-time wildfire and prescribed fire situations. Also, in actual fire situations some fuel models evidently could be used interchangeably under specific weather and fuel conditions.

The use of the two-fuel-model concept keeps the integrity of the fire behavior simulations and simultaneously accounts for some of the spatial heterogeneity of forest fuel beds. The two-fuel-model concept offers virtually innumerable combinations for fire behavior simulations. Both the fuel model selection and the percent area coverage are potential options available to the fire manager in evaluating the effect of changes in fuel profiles on fire behavior. For example, windthrow within a closed timber stand could be represented by a combination of fuel models 10 and 13. The encroachment of pines on open grasslands could be displayed by a combination of fuel models 1 and 2. For site-specific, high resolution modeling the set of 13 fuel models may not be adequate under some situations. Alternative methods, such as those used in creating custom fuel models for the BEHAVE computer fire modeling system (Burgan and Rothermel 1984), might be more appropriate.

Interpretations of the fire behavior characteristics chart indicate how often certain fuel conditions could present suppression problems. Other factors that affect suppression effectiveness would also have to be considered, including arrival times, production rates, and multiple fire events. From these simulated results and the generalized interpretations of the fire behavior characteristics chart, variations in fuel model area coverages apparently could dramatically affect initial attack effectiveness. Further research is necessary to determine if this effect is as substantial in actual wildfire situations.

APPENDIX

Fire behavior characteristics charts for 13 fuel models each with two two-fuel-model alternatives (*figs. 1-13*) show differences in their fire behavior potential by frequency distributions. The fuel model percentages correspond to those in *table 2*. (ft/min × .3048 = m/min, BTU/ft/s × 3.4592 = kW/m, BTU/ft² × 11.349 = kJ/m²)

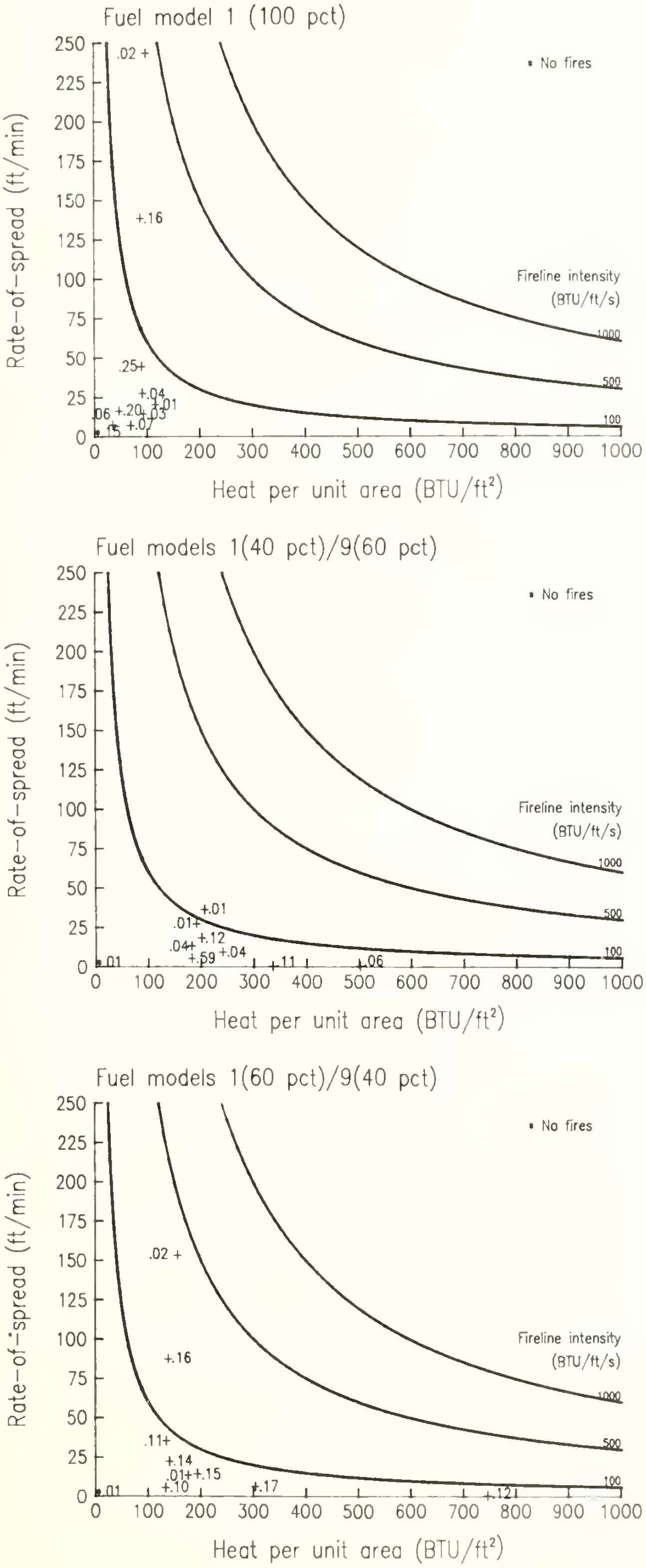


Figure 1

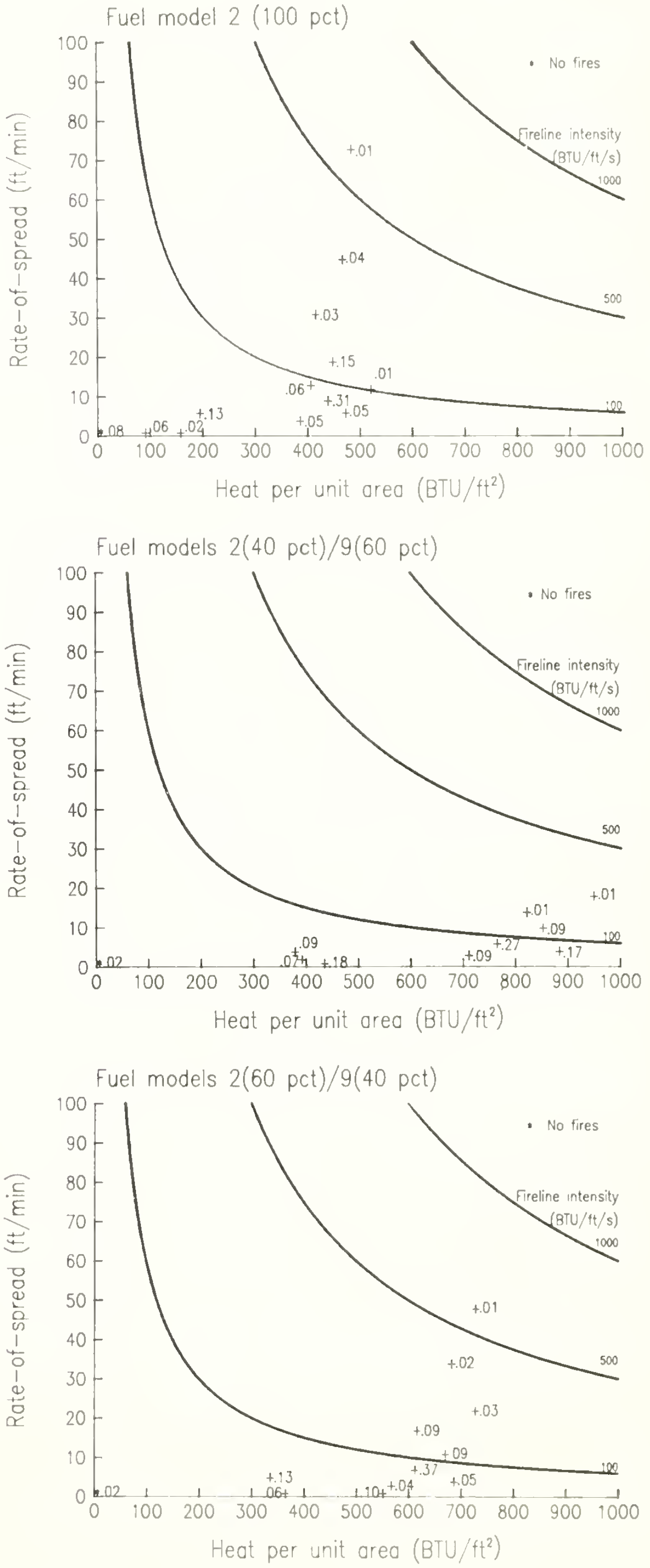


Figure 2

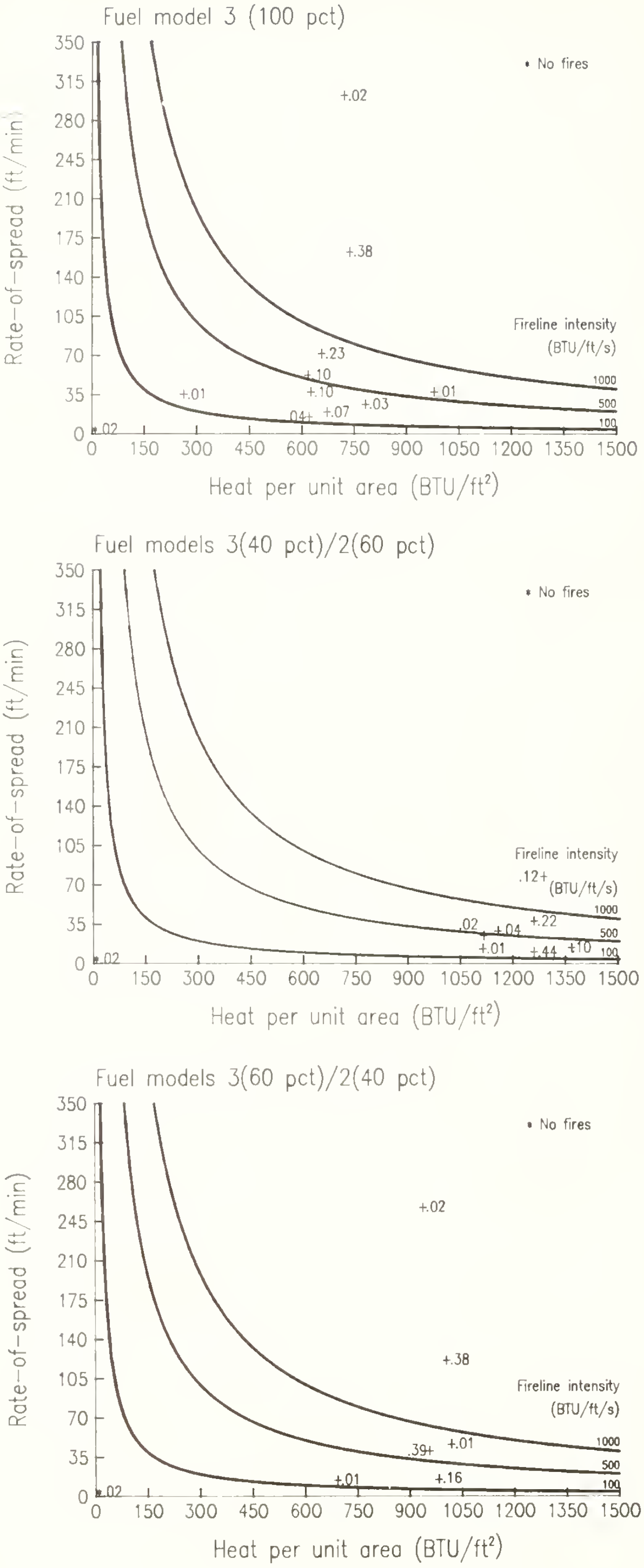


Figure 3

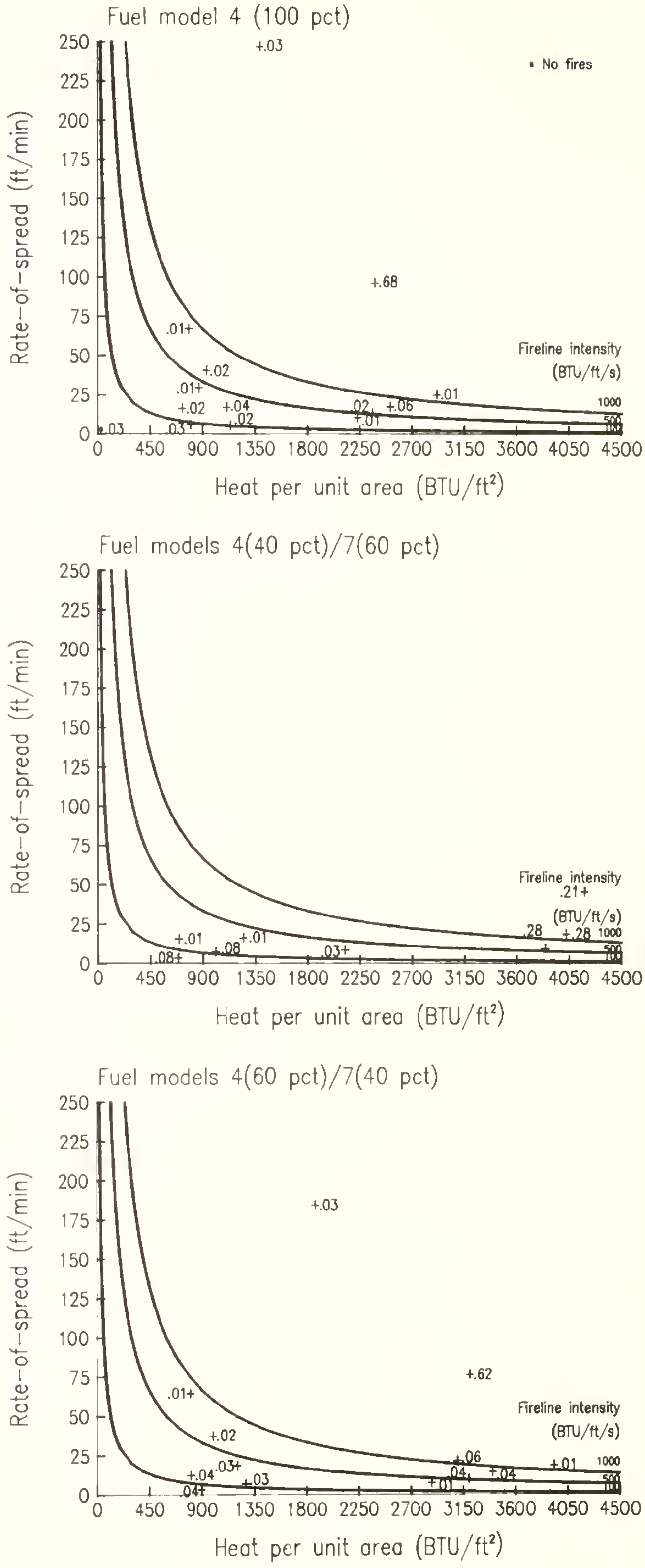


Figure 4

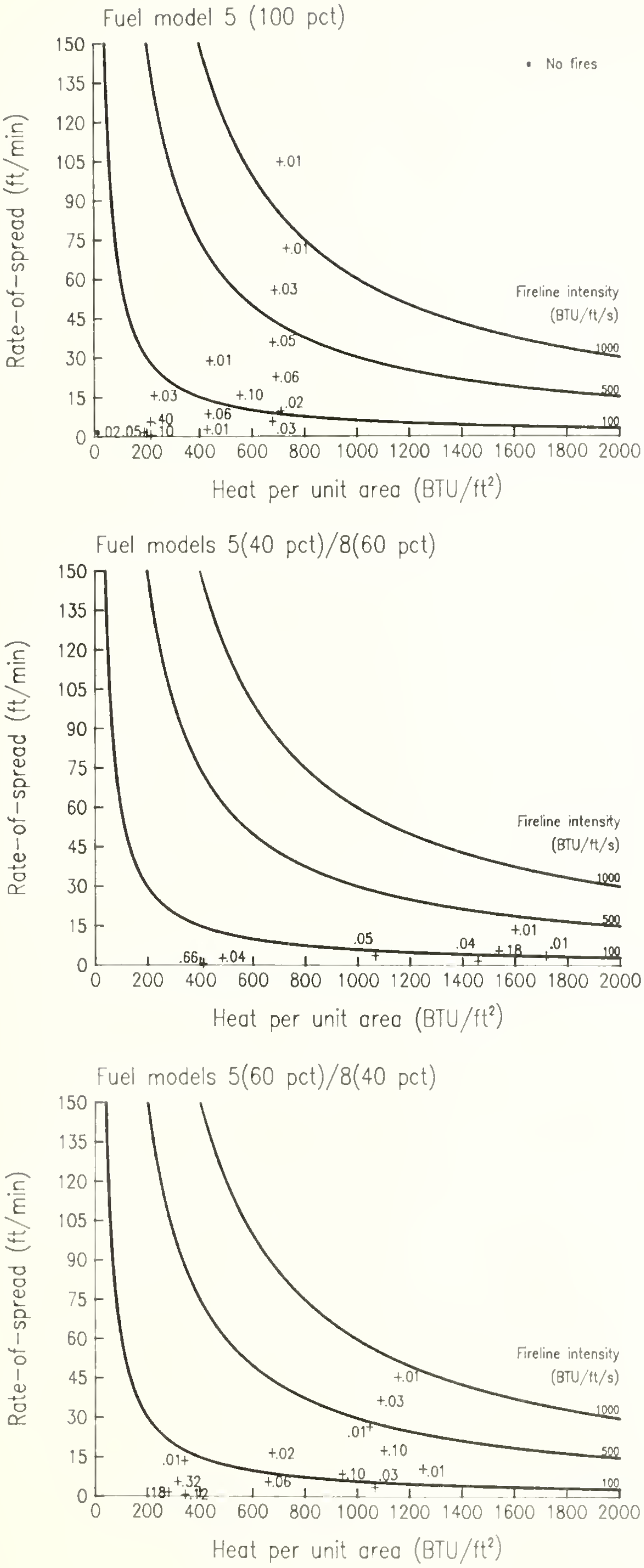


Figure 5

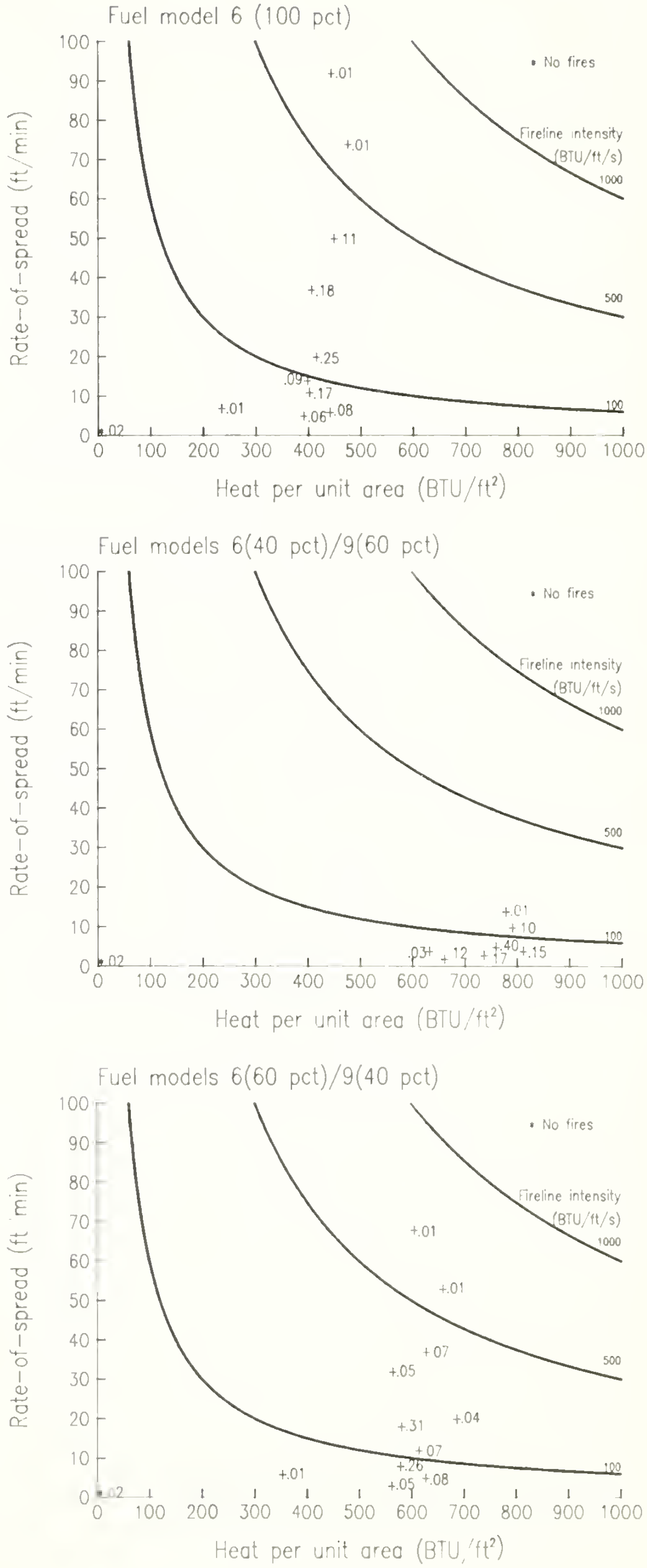


Figure 6

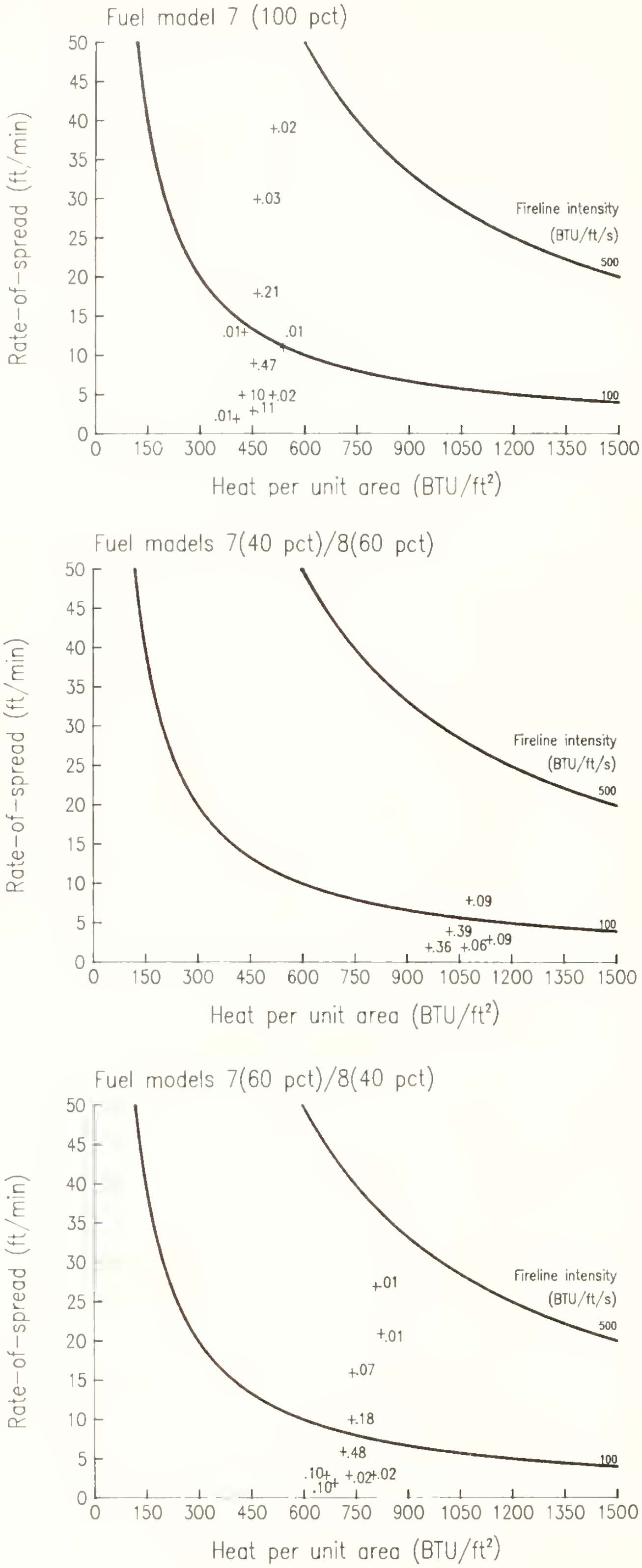


Figure 7

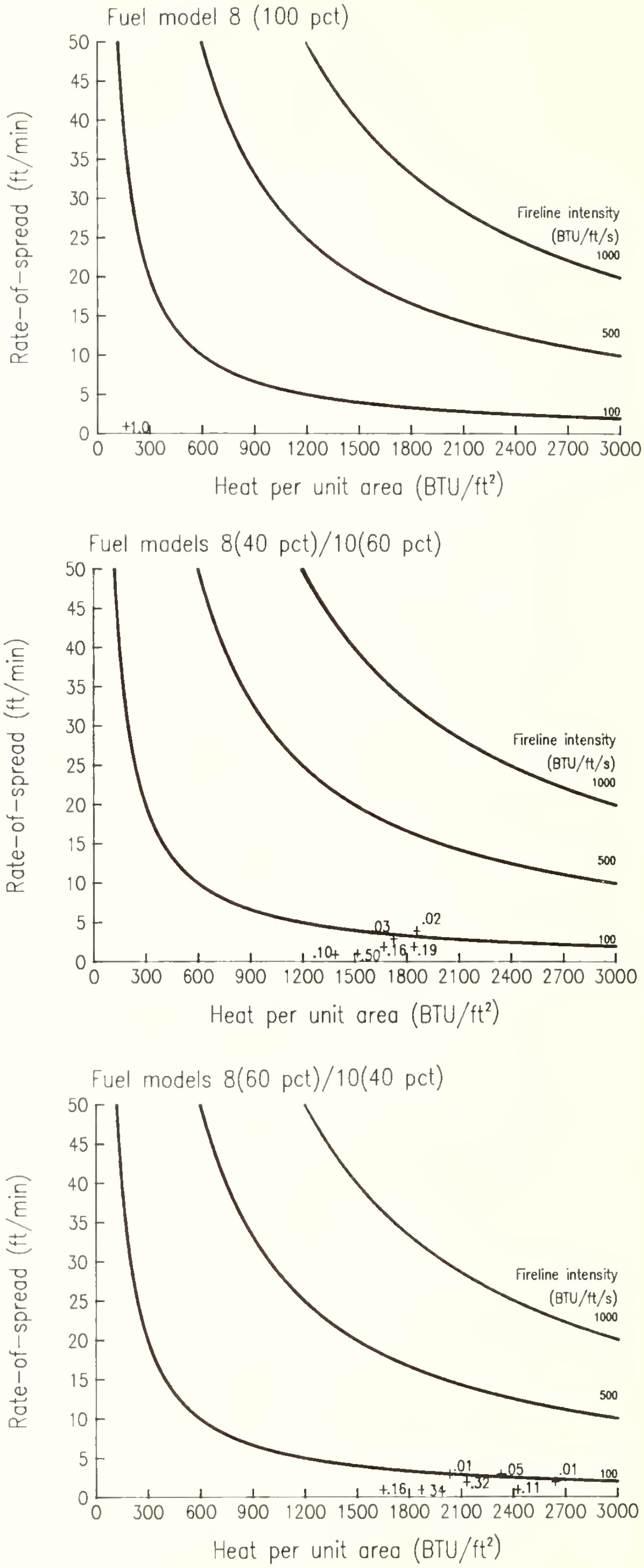


Figure 8

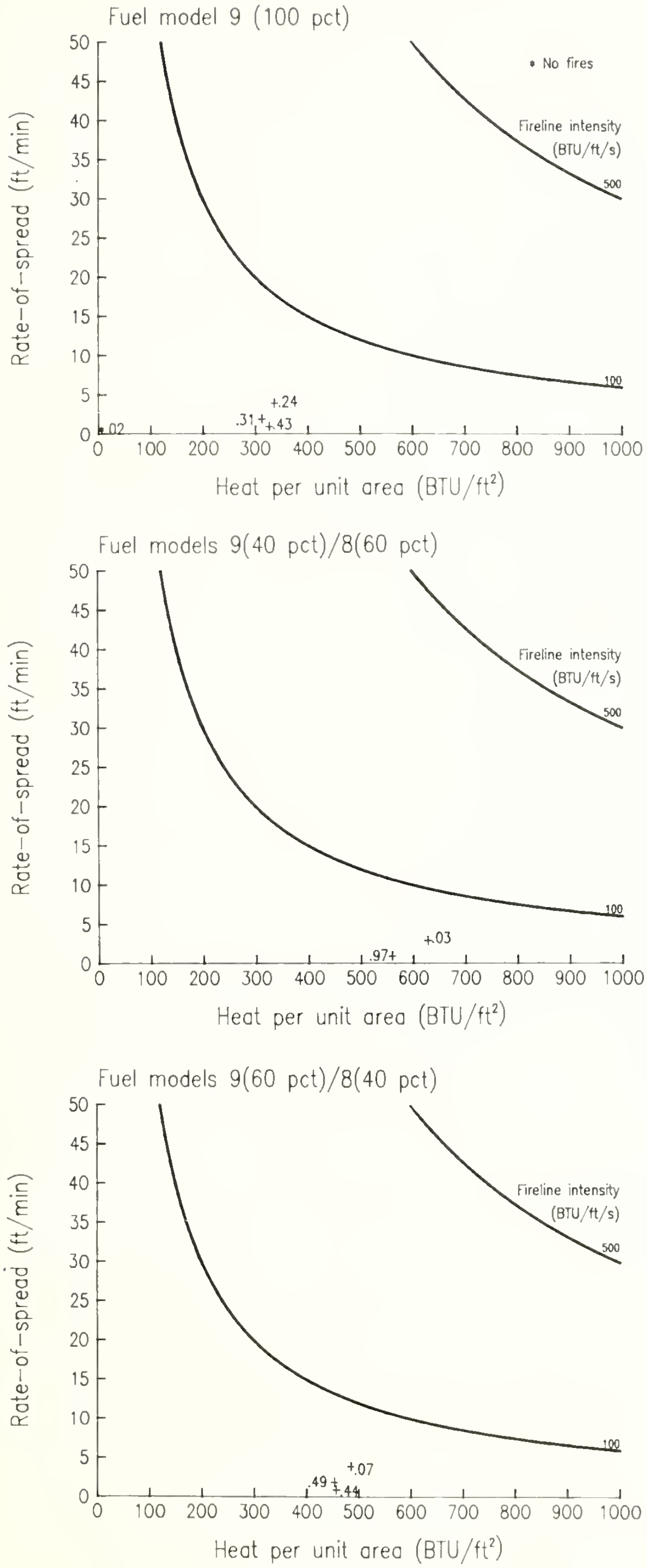


Figure 9

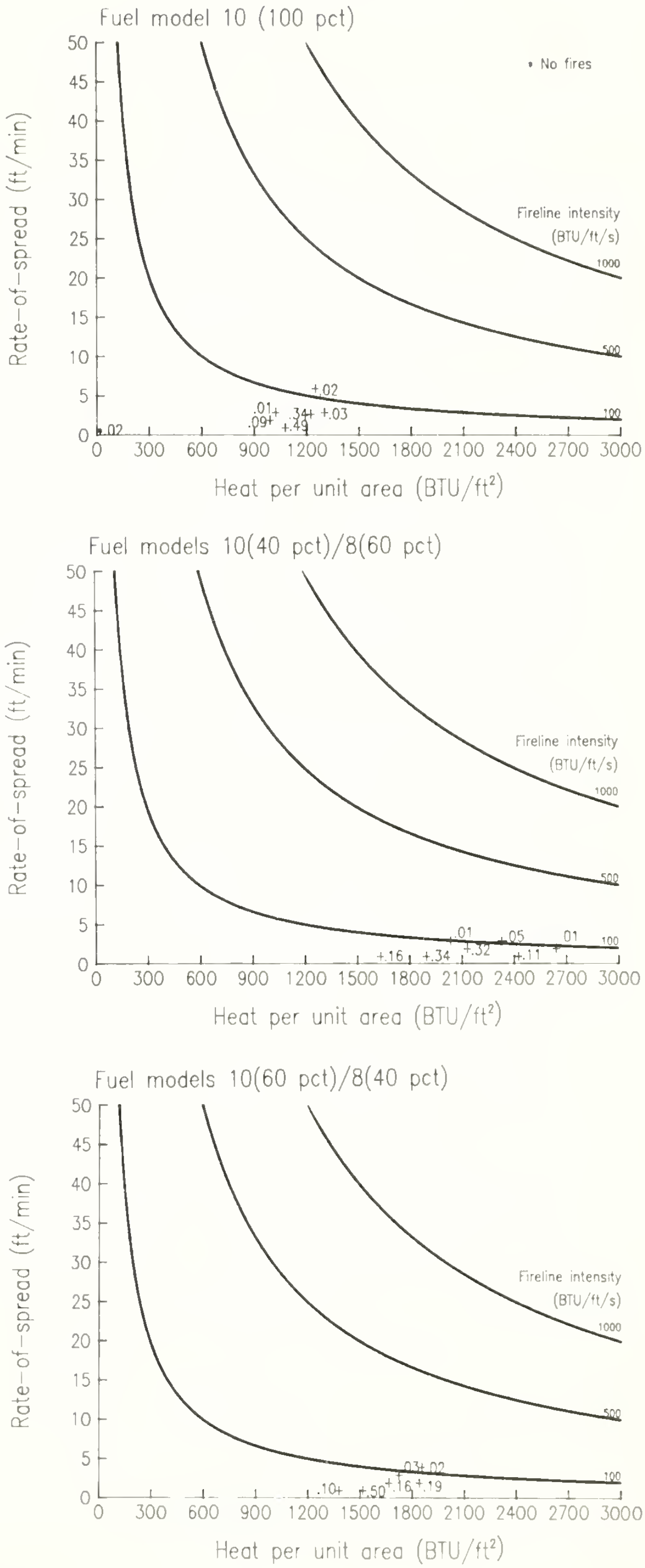


Figure 10

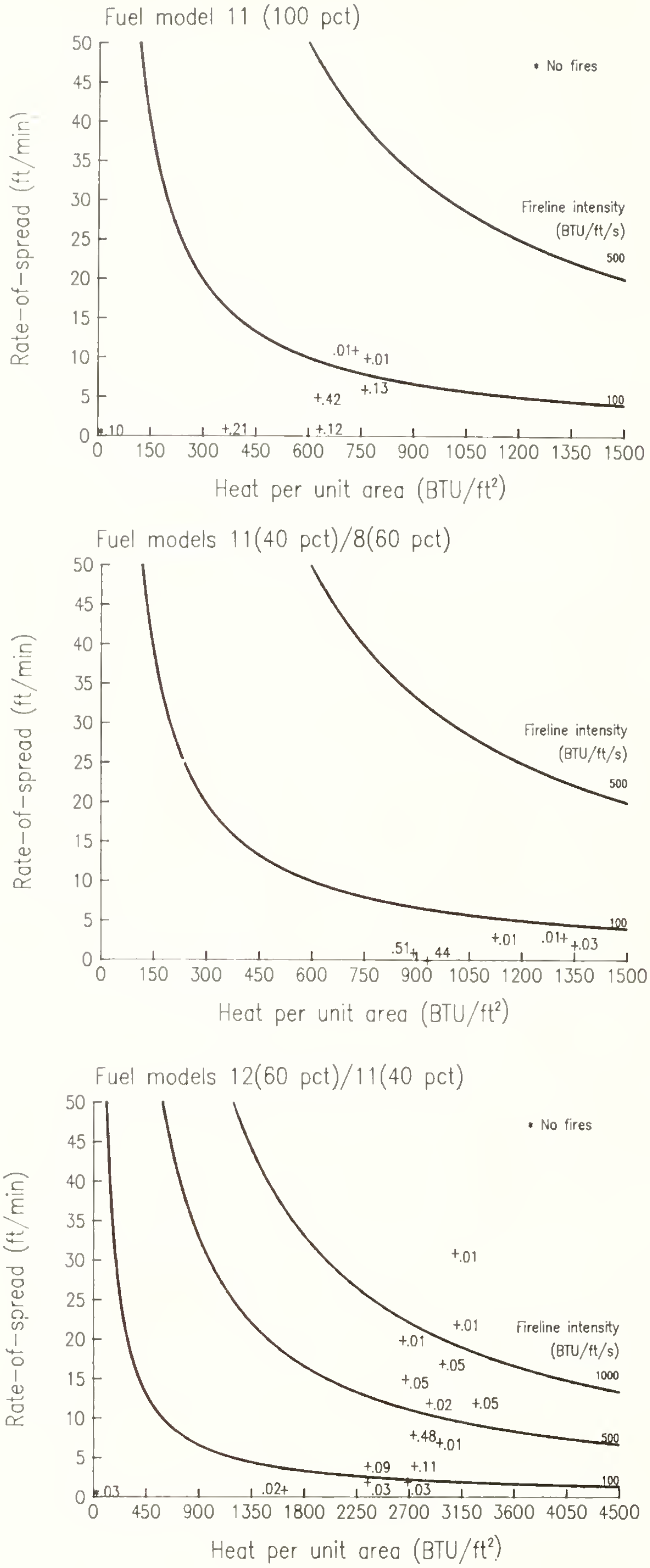


Figure 11

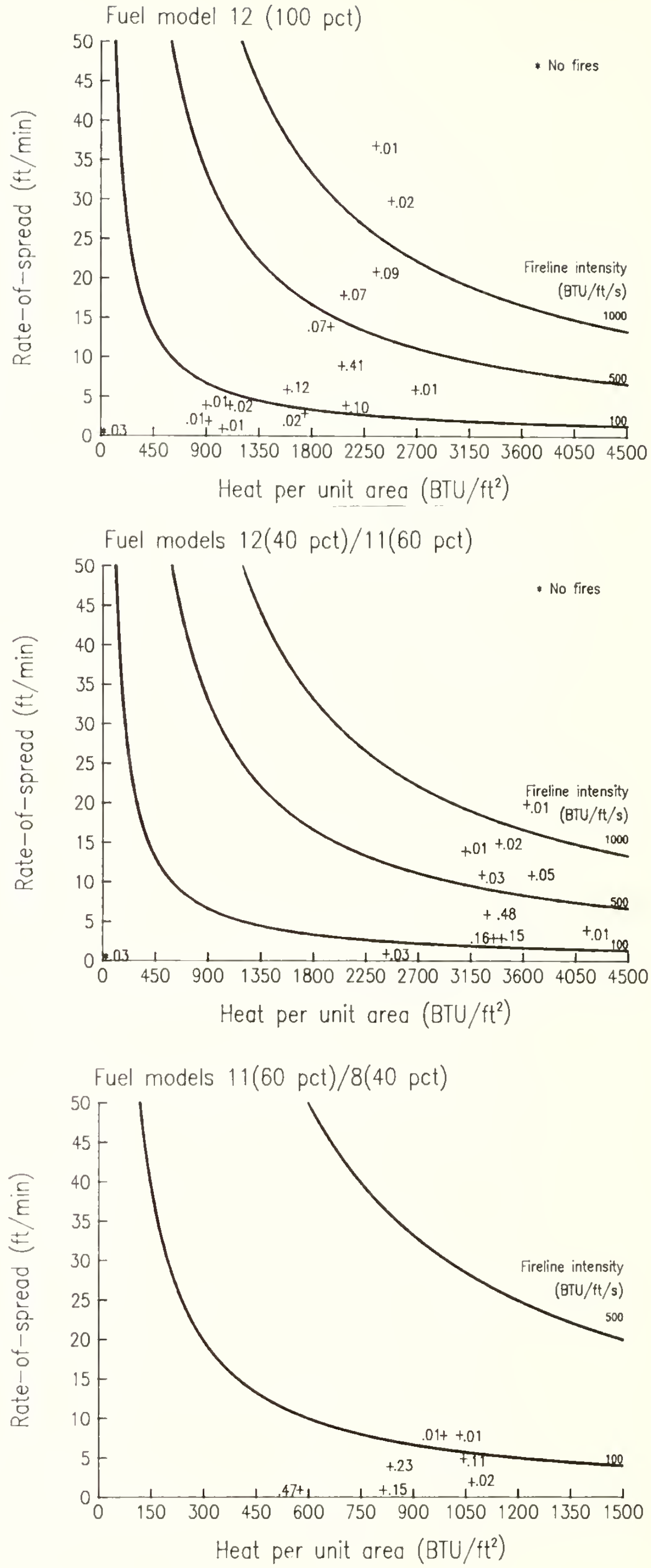


Figure 12

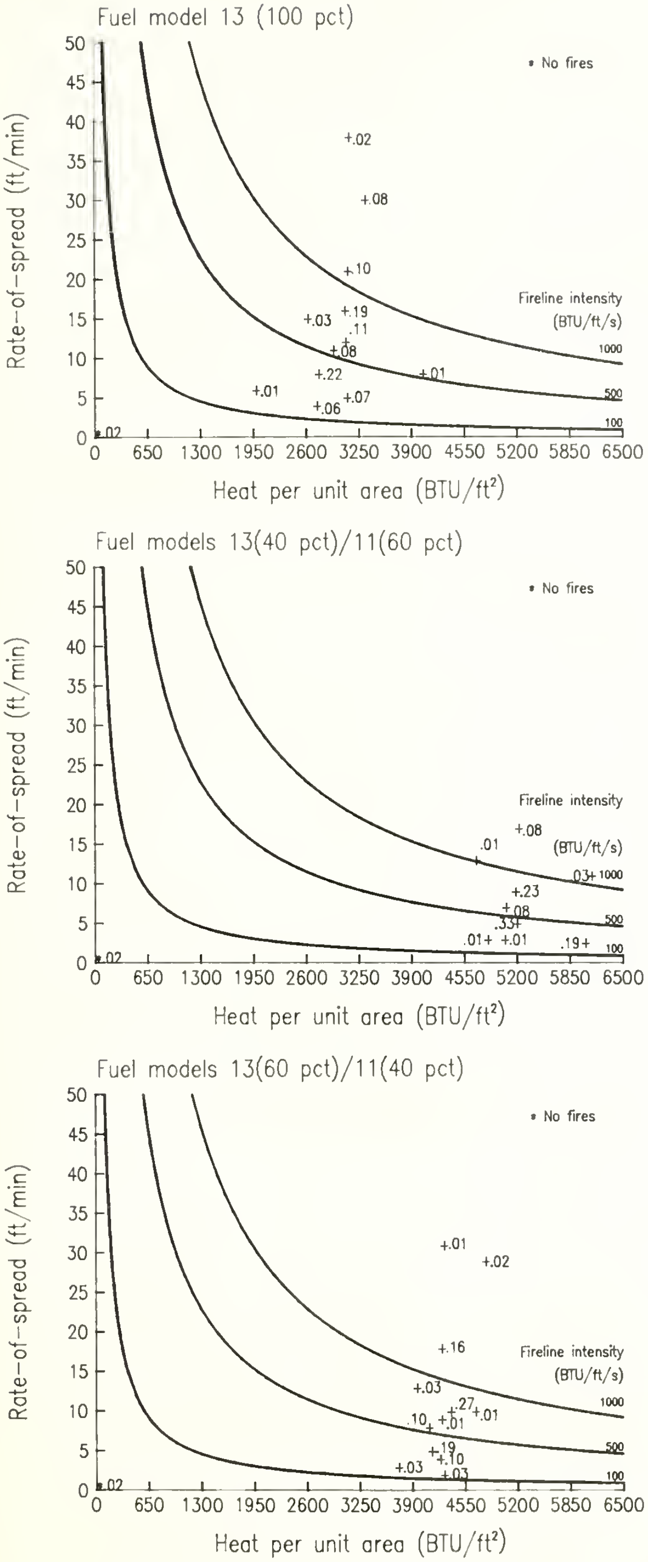


Figure 13

REFERENCES

Albini, Frank A. **Estimating wildfire behavior and effects.** Gen. Tech. Rep. INT-30. Ogden, UT. Intermountain Forest and Range Experiment Station. Forest Service, U.S. Department of Agriculture; 1976. 92 p.

Anderson, Hal E. **Aids to determining fuel models for estimating fire behavior.** Gen. Tech. Rep. INT-122. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 20 p.

Andrews, Patricia L.; Rothermel, Richard C. **Charts for interpreting wildland fire behavior characteristics.** Gen. Tech. Rep. INT-131. Ogden, UT. Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 21 p.

Baughman, Robert G.; Albini, Frank A. **Estimating midflame windspeeds.** In: Proceedings of the sixth conference on fire and forest meteorology; 1980 April 22–24; Seattle, WA. Washington, DC: Soc. Am. For.; 1980: 88–92.

Bradshaw, Larry S.; Deeming, John E.; Burgan, Robert E.; Cohen, Jack D., compilers. **The 1978 National Fire Danger Rating System: technical documentation.** Gen. Tech. Rep. INT-169. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1984. 44 p.

Burgan, Robert E.; Rothermel, Richard C. **BEHAVE: fire behavior prediction and fuel modeling system—FUEL subsystem.** Gen. Tech. Rep. INT-167. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1984. 126 p.

Main, William A.; Haines, Donald A. **Determining appropriate fuel models from field observations and a fire characteristics chart.** In: Proceedings of the seventh national conference on fire and forest meteorology; 1983 April 25-29; Fort Collins, CO. Boston, MA: American Meteorological Society; 1983: 47-52.

Rothermel, Richard C. **A mathematical model for predicting fire spread in wildland fuels.** Res. Paper INT-115. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1972. 40 p.

Rothermel, Richard C. **How to predict the spread and intensity of forest and range fires.** Gen. Tech. Rep. INT-143. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983. 161 p.

Rothermel, Richard C.; Rinehart, George C. **Field procedures for verification and adjustment of fire behavior predictions.** Gen. Tech. Rep. INT-142. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983. 25 p.

Salazar, Lucy A.; Bradshaw, Larry S. **Display and interpretation of fire behavior probabilities for long-term planning.** In preparation.

Salazar, Lucy A.; Bradshaw, Larry S. **Changes in fire weather distributions: effects on predicted fire behavior.** Res. Paper PSW-174. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1984. 11 p.

Schroeder, Mark J.; Glovinsky, Monte; Hendricks, Virgil F.; and others. **Synoptic weather types associated with critical fire weather.** Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1964. 492 p.

Salazar, Lucy A. **Sensitivity of fire behavior simulations to fuel model variations.** Res. Paper PSW-178. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1985. 11 p.

Fire behavior is often simulated with stylized fuel models as input information. These fuel models are often selected on the basis of their assigned typical fuel bed description, but their variability under different weather conditions may not be sufficiently considered. In a fire management planning context, the sensitivity of simulated fire behavior variables to 13 fuel models and two-fuel-model alternatives was analyzed under specific weather, topographic, and temporal conditions. Distributions of these variables were graphically displayed on the fire behavior characteristics chart, allowing for easy comparisons. For most of the fuel models tested, the fire behavior simulations produced a wide range of outcomes. The two-fuel-model concept demonstrated the effect of combining models on simulated fire behavior. Variations in fuel area coverages apparently can dramatically influence the effectiveness of a simulated initial attack.

Retrieval Terms: fire behavior, fuel models, probabilistic fire modeling, wildfire

United States
Department of
Agriculture

Forest Service

**Pacific Southwest
Forest and Range
Experiment Station**

Research Paper
PSW-179

Timber Net Value and Physical Output Changes Following Wildfire in the Northern Rocky Mountains: estimates for specific fire situations

Patrick J. Flowers Patricia B. Shinkle Daria A. Cain Thomas J. Mills

The Authors:

at the time of this study were with the Station's unit studying fire management planning and economics, with headquarters at Riverside, Calif. **PATRICK J. FLOWERS** is now forest economist with the Division of Forestry, Department of Lands, Montana. He earned degrees at the University of Montana (bachelor's in forest management, 1978; master's in forest economics, 1981). **PATRICIA B. SHINKLE,** a computer specialist, is a computer science graduate (1983) of the University of California, Riverside. She has been with the Station since 1976. **DARIA A. CAIN,** research forester, earned a bachelor's degree in biological sciences (1973) at the University of Maryland and a master's degree in forest management (1975) at Colorado State University. **THOMAS J. MILLS** is now leader of the Renewable Resources Economics Group of the Forest Service's Resources Economics Research Staff, Washington, D.C. He earned degrees at Michigan State University: bachelor's in forestry (1968), and master's (1969) and doctorate (1972) in forest economics.

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

December 1985

Timber Net Value and Physical Output Changes Following Wildfire in the Northern Rocky Mountains: estimates for specific fire situations

Patrick J. Flowers Patricia B. Shinkle Daria A. Cain Thomas J. Mills

CONTENTS

IN BRIEF . . .

Flowers, Patrick J.; Shinkle, Patricia B.; Cain, Daria A.; Mills, Thomas J. **Timber net value and physical output changes following wildfire in the northern Rocky Mountains: estimates for specific fire situations.** Res. Paper PSW-179. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1985. 25 p.

Retrieval Terms: fire effects, economies-to-scale, fire size, timber management regime

Estimates of timber net value change due to wildfire are sensitive to characteristics of the fire site, fire severity, and the timber management regime. Reflecting this sensitivity in value change estimates requires detailed data collection and computations. For this reason, the variability of the timber resource must be considered in detail when fire management programs are analyzed. The extensive data collection and computation efforts necessary to incorporate this required detail are generally not possible under the constraints of escaped fire situation analysis and may not be possible under long-term fire management planning situations if analytical resources are limited.

An efficient alternative to estimating site-specific net value change is calculating changes in timber net value and timber output at a centralized location for a variety of nonsite-specific fire and management situations. The resulting estimates can then be consolidated and used in the form of reference tables representing the likely range of fire and management situations. This approach eliminates the inefficiency of duplicating site-specific calculations, and the detailed data are preferable to highly aggregative potential loss averages that are applied to broad heterogeneous areas. These highly aggregative estimates do not adequately reflect variability in the resource base and management regimes, which materially affect the net value changes.

Estimates of the timber net value change and timber output change resulting from wildfire were calculated for 9828 situation-specific fire and management conditions in the northern Rocky Mountains. After slight aggregation across the less sensitive situation parameters, reference tables with estimates of net value change and timber output change were prepared for 1764 roaded situations. They are defined by timber management emphasis, cover type, productivity class, stand size, mortality class, and fire size, with adjustments for access status.

INTRODUCTION

In the last decade, the fire management program of the Forest Service, U.S. Department of Agriculture, has come under closer scrutiny because of ever-rising program costs. The Forest Service has responded by conducting several studies analyzing the economic efficiency of its fire management program. Some components of the analytical models have been difficult to develop, particularly changes in the net value and output of timber caused by wildfire.

The timber net value change calculation can be complex because of the long timber production time and the substantial impact of the management context on the timing of management costs and harvests. The timber computation is critical, because the change in the timber resource accounts for a large share of the total net value change due to fire: nationwide, 60 percent on National Forest land and 75 percent on State protected lands (U.S. Dep. Agric., Forest Serv. 1980, 1982).

Numerous approaches have been proposed for estimating timber net value change (Flint 1924, Lindenmuth and others 1951, Mactavish 1966, Marty and Barney 1981, Van Wagner 1983). The computations vary substantially in how they reflect fire-caused changes in both the magnitude and timing of the management costs and harvests, and in how certain conceptual issues, such as the substitution of unburned for burned timber, are addressed. For example, a relatively simple formulation of the timber net value change calculation ignores price differentials between green and salvaged timber, and the possibility for retention and future harvest of partially destroyed immature timber stands (Schweitzer and others 1982). On the other hand, one of the more complete formulations includes harvest timing differentials in immature stands, salvage and green price differentials, and adjustments in the management costs required if the fire removes a natural seed source (Mactavish 1966).

Although these past studies include ample discussion of methodology, the estimates of timber net value change they contain are only illustrative and too few to demonstrate how the net value change behaves under a wide range of circumstances. Therefore, we calculated change in timber net value and in timber output due to wildfire for a broad range of specific fire and management situations.

This paper summarizes trends in estimates of timber net value changes and timber output changes due to wildfire for 1764 roaded situations in the northern Rocky Mountains. Actual values are listed in extensive reference tables and have four potential uses (Mills 1983): (1) analyses of long-term fire management program options, such as those in the National Fire Management Analysis and Planning Handbook (U.S. Dep. Agric., Forest Serv. 1982) or the Fire Economics Evaluation System (Mills and Bratten 1982); (2) establishment of fire dispatching priorities; (3) analysis of escaped fire situations where extensive calculations are often difficult to accomplish because of the real-time demands of the decision process (U.S. Dep. Agric., Forest Serv. 1981; Seaver and others 1983); and (4) analysis of long-term harvest schedules when fire-caused changes in timber yields are required.

METHODS

Calculating Net Value Change

Net value change is the difference between the present net value of resource outputs and management costs "without fire" and the present net value "with fire":

$$NVC = PNV_{w/o} - PNV_{w}$$

in which

NVC = net value change

$PNV_{w/o}$ = present net value without fire

PNV_{w} = present net value with fire

According to this definition, a fire that produces a net gain in present value has a negative NVC and one that produces a loss of value has a positive NVC.

Because the NVC is a present value calculation, any change in the magnitude or timing of the management costs, the harvests, or the stumpage prices affects the NVC. Analysis of the sensitivity of NVC to the completeness with which the fire-caused impacts on these quantities were represented in computations for 24 timber cases in the northern Rocky Mountains, showed that a fairly complete representation of the fire-caused change was necessary to avoid major errors in the estimate (Mills and Flowers 1983).

The computational model used in the present study contains three types of terms: (1) the existing rotation costs and harvest values, (2) the regenerated rotation costs and harvest values, and (3) one-time costs or revenues created by fire, such as salvage values. The generalized form of the computation was

$$PNV_{wo} = \begin{bmatrix}\text{PNV of infinite series} \\ \text{final harvests in} \\ \text{regenerated stand}\end{bmatrix} - \begin{bmatrix}\text{PNV of infinite series} \\ \text{management costs in} \\ \text{regenerated stand}\end{bmatrix} + \begin{bmatrix}\text{PNV of harvests in} \\ \text{existing stand}\end{bmatrix} - \begin{bmatrix}\text{PNV of management} \\ \text{costs in existing stand}\end{bmatrix}$$

$$PNV_{w} = \begin{bmatrix}\text{PNV of infinite series} \\ \text{final harvests in} \\ \text{regenerated stands} \\ \text{following fire}\end{bmatrix} - \begin{bmatrix}\text{PNV of infinite series} \\ \text{management costs in} \\ \text{regenerated stands} \\ \text{following fire}\end{bmatrix} + \begin{bmatrix}\text{PNV of timber sal-} \\ \text{vaged following fire}\end{bmatrix} - \begin{bmatrix}\text{PNV of management} \\ \text{cost in existing stand}\end{bmatrix} + \begin{bmatrix}\text{PNV of residual} \\ \text{timber remaining} \\ \text{after fire}\end{bmatrix} - \begin{bmatrix}\text{PNV of any single} \\ \text{rotation difference in} \\ \text{management costs} \\ \text{following fire}\end{bmatrix}$$

Not all terms are included in every fire case. For example, the one-time change in regenerated rotation management costs, (such as the removal of a scheduled site preparation because the fire essentially accomplished the site preparation, or the inclusion of a planting rather than a natural regeneration because the fire removed the seed source) only enter the computation if the stand size, stocking, fire size, and tree mortality are of certain levels. Similarly, the salvage transaction enters the computation only under certain conditions of stand size, volume per acre, and fire size. The first two terms make the with- and without-fire cash flows comparable despite dissimilar rotation lengths or unmatched sequencing of without- and with-fire rotations.

A major assumption imbedded in our net value change computation concerns the geographic area from which the fire-induced change in the resource output is measured. Two options exist: measuring the effect on only the fire site plus direct physical and biological effects offsite (Althaus and Mills 1982); or measuring the effects on the entire management area or market area in which the fire occurs (Van Wagner 1983). Our analysis measured the fire-induced changes on the fire site only because the fire site analysis most closely reflects the impact of fire on the basic productivity of the timber growing site, relatively unencumbered by management constraints.

Timber net value change was estimated at three discount rates: 4.0, 7.875, and 10.0 percent. The 4.0 percent rate was an approximation of the real return on investments in the private sector (Row and others 1981), and is being used by the Forest Service in land management planning; 7.875 percent was the 1983 discount rate for Federal water project evaluations (U.S. Dep. Agric., Soil Conservation Serv. 1982); and 10 percent was the rate recommended by the U.S. Office of Management and Budget (1972) as the real rate of return on investments in the private sector.

In addition to the timber net value change, we calculated the timber output change for the first 200 years following fire. Timber output change is the difference between the scheduled timber yield without fire and with fire.

Scope of Analysis

The analysis was structured to evaluate situation-specific cases defined by a combination of values for the following parameters that characterize the fire site, the timber management context in which the fire occurs, and the fire severity: access, slope, management emphasis, cover type, productivity, stand size, fire size, and mortality. After removing parameter combinations not generally found in the northern Rocky Mountains, such as passive private management on high productivity sites, we estimated net value change for 9828 separate situations.

This situation-specific approach, rather than a site-specific analysis, was followed because of the required model complexity and its associated data demands. Errors that will result from extrapolation of these situation-specific estimates to particular sites is expected to be far less than the errors that would result from incomplete model specification or poor data input that would likely occur if the computations were for site-specific conditions with limited analysis resources.

Sources of Data

Four categories of data were required: timber management regimes, timber yields, silviculture treatment costs, and stumpage prices. Most of the data were derived from National Forest sources in the Forest Service's Northern Region (northern Idaho and Montana). The data were developed to follow as closely as possible the input used in land management planning, thereby increasing the applicability of the results to long-term planning on National Forest lands.

Four sets of timber management regimes were developed from selected land management plans in the Northern Region and on recommendation from the Regional silvicultural staff (Wulf 1982): one each for "moderate intensity public," "intense public," "passive private," and "intense private" timber management. The regimes differ in the form of stand establishment, the number of commercial and precommercial thinning entries, rotation age, and the acreage of the without-fire harvest area. Sample data for fire situations in Douglas-fir are in *table 1*.

The moderate intensity public regime reflects a generally nontimber resource objective but where limited commercial timber harvesting still occurs. Rotations are generally extended beyond the culmination of mean annual increment. There are no precommercial thinnings and only one commercial thinning, if one is commercially viable. In the intense public regime, commercial timber harvesting is the primary objective, but here too, the multiple-use management philosophy affects the regime. The rotation approximates or precedes the culmination of mean annual increment. There is a

Table 1—*Selected Douglas-fir management regime and yield characteristics*

Management emphasis, productivity class, and rotation	Precommercial thinnings[1]	Commercial thinnings[1]	Year of final harvest[2]	Mean annual increment[2]
				cu ft/acre/yr
Moderate public				
Low				
Existing	0	1	170	14
Regenerated	0	1	125	70
High				
Existing	0	1	140	30
Regenerated	0	1	118	95
Intense public				
Low				
Existing	1	1	145	15
Regenerated	1	1	114	67
High				
Existing	1	2	115	35
Regenerated	1	2	98	96
Passive private				
Low				
Existing	0	0	101	17
Regenerated	0	0	91	70
Moderate				
Existing	0	0	101	23
Regenerated	0	0	77	60
Intense private				
Low				
Existing	1	0	101	15
Regenerated	1	0	85	68
High				
Existing	1	1	101	38
Regenerated	1	1	63	102

[1]Number of precommercial and commercial thinnings in existing rotation regimes. The actual number in each analysis case was a function of existing stand age at time of fire, i.e., stand age for the cover type and stand size class, and scheduled thinning age.

[2]Mean annual increment was calculated from the sum of the harvest volumes divided by rotation age. First rotation harvest age and mean annual increment are for sawtimber stands only.

precommercial thinning and one or two commercial thinnings, depending on commercial viability.

The passive private regime assumed a final harvest will be the only management activity after stand establishment. The rotation age approximated the financially optimum age and was estimated using the CHEAPO supplement (Medema and Hatch 1982) of the Prognosis timber growth model (Wykoff and others 1982). For the intensive private regime, the rotation age is also set to approximate the maximization of present net worth but in the presence of precommercial thinning and up to two commercial thinnings.

Timber yield estimates for the regenerated or second rotation were developed from a Prognosis projection of 212 sample stands from selected National Forests in the Northern Region, a subset of the sample stands that were used to develop yield estimates for land management planning. Projected yields for individual stands were aggregated into 96 yield sets by cover type, productivity class, and management emphasis. The existing or first rotation yields for existing seedling/sapling and poletimber stands were derived through a percentage reduction of the second rotation yields. This percentage reduction reflects the less intensive management of the existing seedling/sapling and poletimber stands. The first rotation yields for existing sawtimber stands were derived empirically from inventory data on existing sawtimber stands. This derivation implicitly assumes that current seedling/sapling and poletimber stands will, at maturity, more closely resemble the Prognosis projection than the existing sawtimber stands. Viable commercial thinnings were identified using the Northern Region's thinning default option in the Prognosis model.

The cost of silvicultural treatments, such as site preparation, planting, and precommercial thinning, were derived from equations developed from silvicultural service contracts let in the Northern Region from 1975 through 1978 (Mills and others 1985). The only variable retained in the equations was acres treated. The other variables were collapsed into the intercept by setting them equal to their mean sample values. This simplified equation form still permitted a reflection of the economies-of-scale found in larger treatment areas. Real

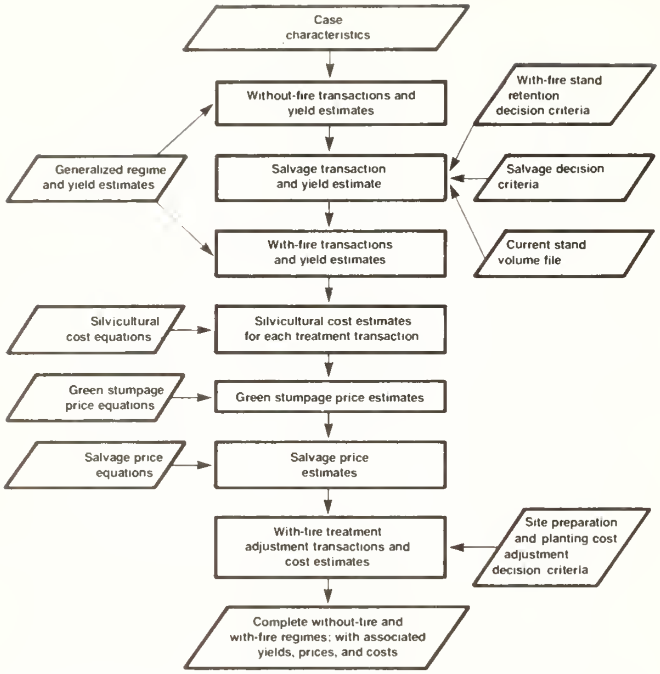


Figure 1—Generalized data were adjusted for individual cases according to decision rules.

increase in treatment cost was assumed to be 1 percent per year through 2030. Costs were held constant thereafter.

Green stumpage price estimates were drawn from regression equations developed from transaction data for 790 Northern Region timber sales on National Forest land (Merzenich 1982), from September 1977 through December 1982. Size of harvest area also influences the green stumpage price through a variable for the total volume of the sale, thus interjecting another scale economy influence. Real stumpage prices increased over time to the year 2030, as a function of lumber price and production cost projections (Adams and Haynes 1980). Real prices were assumed constant after 2030.

The decision to salvage and the subsequent price of the salvage sale were derived from equations based on salvage sale transaction data in the Northern Region (Loveless and Jackson 1983). The salvage sales database extended from 1970 through 1980. The decision to salvage was strongly affected by accessibility and the total fire size. The price of advertised salvage sales was set at 53 percent of the comparable green timber price. Unadvertised salvage sales were sold at the "green slip" price of $1 per 1,000 board feet.

Management regimes, timber yields, treatment costs, and stumpage prices were adjusted using a number of internalized decision rules that considered characteristics of individual analysis cases *(fig. 1)*. For example, the decision to retain a partially destroyed stand was based on a comparison of the postfire stocking with minimum stocking standards for manageable stands. This methodology permitted a fairly efficient analysis while still addressing appropriate adjustment for individual case differences. The individual transactions in the regime were developed using the regime, yield, cost, and price information, adjusted by the internalized decision rules. The net value change was then estimated using the SASSY financial return computer program (Goforth and Mills 1975).

EXAMPLES OF ANALYSIS CASES

The net result of combining the varied and numerous types of data used in this analysis can most easily be seen through several illustrative cases. Although not a statistical sample, these cases represent some of the important patterns of behavior in the timber NVC calculations. Four illustrative cases are presented in detail.

The first case represents a seedling/sapling stand that was retained after fire and then interplanted to raise stocking to an acceptable level *(table 2)*. The stand was retained because the minimum stocking standard was met. The number of trees per acre was low enough, however, to require an interplanting. Because of interplanting, the timing of future harvests was delayed by 14 years. When combined with the cost of interplanting, this extension of the rotation caused a net loss due to fire. Net timber output did not change due to fire in this situation. It is the change in timing of transactions along with cost differences, not the magnitude of the loss in yield, that causes a net value change when fire occurs.

The second case illustrates nonretention and no salvage after a high-mortality fire of moderate size in a poletimber stand *(table 3)*. This stand did not have sufficient stocking after the fire to be retained. Based on stand conditions for average diameter at breast height (d.b.h.) and dead volume per acre, no salvage harvest occurred. Establishment of the new postfire stand was delayed by 5 years. This same 5-year delay affected all subsequent with-fire transactions as well. This situation showed a net loss resulting from the foregone without-fire final harvest benefit that would have occurred 40 years hence, and because the loss was not offset by a with-fire salvage harvest.

The third example case also shows nonretention for a moderate size fire of high mortality in a poletimber stand, but volume and d.b.h. were sufficient to support a salvage harvest *(table 4)*. The stand was not retained after fire due to failure of the postfire stand to meet the minimum stocking standards. The determination of whether to sell the salvage harvest as an advertised or unadvertised sale was affected by the average d.b.h. of the stand and the size of the fire. In this case, dead volume was sold as an unadvertised sale at $1 per 1,000 board feet. The final price of the salvage was a weighted average of the live volume at a comparable green timber bid price and the dead volume at the unadvertised "green slip" price. The with-fire stand was salvaged at a weighted bid price ($4 per 100 ft^3 of timber), which was much lower than the full final harvest price ($41 per 100 ft^3) of the without-fire stand just 14 years in the future. The fire causes a reduction in the amount

Table 2—*Example of a Douglas-fir seedling/sapling stand that was retained after fire and interplanted*
Description: < 40 percent slope, very low productivity, moderate intensity public management, 10-99 acres, 60+ percent mortality, roaded
Decisions: retained, interplanted

Years since fire	Harvest	Price	Benefit	Cost	Repetition cycle	Description
	100 cu ft/acre	*$/100 cu ft*	——*$/acre*——		*Years*	
			Without fire			
63	10	151	1,510	——	0	First commercial thin
148	73	183	13,359	——	0	Final harvest
149	——	——	——	392	141	Site preparation
234	12	141	1,692	——	141	First commercial thin
289	78	186	14,508	——	141	Final harvest
			With fire			
1	——	——	——	251	0	Interplant
76	10	151	1,510	——	0	First commercial thin
161	73	183	13,359	——	0	Final harvest
162	——	——	——	392	141	Site preparation
247	12	141	1,692	——	141	First commercial thin
302	78	186	14,508	——	141	Final harvest

Physical output change: 0 (total for first 200 years in 100 cu ft/acre)
Net value change: 307 (1978 dollars/acre at 4 pct discount rate)

Table 3—*Example of a poletimber stand that was not retained after fire and was not salvaged*
Description: <40 percent slope, low productivity, intense private management, 10-99 acres, 60+ percent mortality, roaded
Decisions: not retained, not salvaged

Years since fire	Harvest	Price	Benefit	Cost	Repetition cycle	Description
	100 cu ft/acre	*$/100 cu ft*	——*$/acre*——		*Years*	
			Without fire			
40	49	106	5,194	——	0	Final harvest
42	——	——	——	124	85	Plant
55	——	——	——	129	85	Precommercial thin
125	57	134	7,638	——	85	Final harvest
			With fire			
7	——	——	——	88	85	Plant
20	——	——	——	50	85	Precommercial thin
90	57	134	7,638	——	85	Final harvest

Physical output change: -9 (total for first 200 years in 100 cu ft/acre)
Net value change: 964 (1978 dollars/acre at 4 pct discount rate)

of site preparation required with an associated cost reduction of $70 per acre. This site preparation cost adjustment is a benefit due to fire. The net impact of these forces was a loss of value.

The fourth case represents a sawtimber stand with moderate mortality after a large fire *(table 5)*. In this situation, the net gain results from economies-of-scale and the truncation of an otherwise uneconomical without-fire regime. The postfire stand was not retained after the fire due to insufficient stocking, but stand conditions were adequate to support a postfire salvage harvest. The economies-of-scale associated with a large fire size led to increases in the salvage price and reductions in the stand establishment costs. The per acre costs of site preparation and planting were less with the large burned area (2088 acres) than they would be with the smaller management area (35 acres). The intense public regime in this case had a rotation age that extended beyond the financially optimum age with respect to timber values. The fire reduced the final harvest age to a point nearer the financial optimum. While fire may have had a detrimental effect on nontimber outputs, it had a positive financial impact on the timber output.

Table 4—*Example of a poletimber stand that was not retained after fire but was salvaged*
Description: < 40 percent slope, moderate productivity, passive private management, 10-99 acres, 60+ percent mortality, roaded
Decisions: not retained, salvaged, site preparation cost adjusted

Years since fire	Harvest	Price	Benefit	Cost	Repetition cycle	Description
	100 cu ft/acre	*$/100 cu ft*	——*$/acre*	——	*Years*	
			Without fire			
14	44	41	1,804	——	0	Final harvest
15	——	——	——	94	79	Site preparation
93	63	114	7,182	——	79	Final harvest
			With fire			
1	33	4	132	——	0	Salvage harvest
2	——	——	——	83	79	Site preparation
83	63	114	7,182	——	79	Final harvest
2	——	——	70	——	0	Site preparation cost adjustment

Physical output change: 11 (total for first 200 years in 100 cu ft/acre)
Net value change: 794 (1978 dollars/acre at 4 pct discount rate)

Table 5—*Example of a sawtimber stand that was salvaged after fire*
Description: < 40 percent slope, high productivity, intense public management, 100+ acres, 30-59 percent mortality, roaded
Decisions: not retained, salvaged, site preparation and planting costs adjusted

Years since fire	Harvest	Price	Benefit	Cost	Repetition cycle	Description
	100 cu ft/acre	*$/100 cu ft*	——*$/acre*	——	*Years*	
			Without fire			
14	40	45	1,800	0	0	Final harvest
15	——	——	——	137	98	Site preparation
17	——	——	——	211	98	Plant
32	——	——	——	271	98	Precommercial thin
57	3	79	237		98	First commercial thin
77	12	129	1,548		98	Second commercial thin
112	79	164	12,956		98	Final harvest
			With fire			
1	39	32	1,248	——	0	Salvage harvest
2	——	——	——	121	98	Site preparation
3	——	——	——	184	98	Plant
18	——	——	——	236	98	Precommercial thin
43	3	66	198	——	98	First commercial thin
63	12	129	1,548	——	98	Second commercial thin
98	79	164	12,956	——	98	Final harvest
2	——	——	——	90	0	Site preparation cost adjustment
3	——	——	——	116	0	Planting cost adjustment

Physical output change: -78 (total for first 200 years 100 cu ft/acre)
Net value change: -376 (1978 dollars/acre at 4 pct discount rate)

RESULTS

Specific cases for which timber net value and output changes were calculated were described by the following parameter classes:

Parameter	Classes
Timber management emphasis	Moderate public
	Intense public
	Passive private
	Intense private
Cover type	Douglas-fir
	Ponderosa pine
	Western white pine
	Fir-spruce
	Hemlock
	Larch
	Lodgepole pine
Productivity class	High (120+ cu ft/acre/yr)
	Moderate (85-119 cu ft/acre/yr)
	Low (50-84 cu ft/acre/yr)
	Very low (20-49 cu ft/acre/yr)
Stand size	Seedling-sapling
	Poletimber
	Sawtimber
Mortality	1-29 percent
	30-59 percent
	60+ percent
Fire size	1-99 acres
	100+ acres

Slope and access parameters were originally included in the computations. To reduce the volume of the results, the original 9828 estimates were aggregated by calculating the mean of the two original estimates for slope class. The resolution lost by this aggregation had little impact on the results. The access parameter was handled in a similar way. This aggregation led to estimates for 1764 "roaded" situations and adjustment factors that can be used to estimate the corresponding 1764 "unroaded" situations. The *appendix* lists estimates of timber net value change and timber output change due to fire for the aggregated set of 1764 fire situations under roaded conditions.[1] It also lists the adjustment factors.

The following is a discussion of the aggregated set of 1764 "roaded" situations. General trends within the full set of 9828 situations (Mills and Flowers 1984) and detailed results of a small set of the ponderosa pine and lodgepole pine situations (Mills and Flowers, In press) are discussed elsewhere.

Timber Net Value

Patterns exist in the net value change results but estimates vary significantly among the specific fire situations. The timber net value changes averaged $190 per acre burned, but they ranged from a net loss of $2132 per acre to a net benefit of $-1545 per acre. The majority of the net value changes were net losses, i.e., positive net value changes. Net losses occurred in 82 percent of the situations discounted at 4 percent, and 18 percent of the situations showed net gains. Most situations having a net gain were large fires in sawtimber stands. These net benefits are due to economies-of-scale in stand establishment costs, salvage harvest revenues, and sometimes the truncation of uneconomically long rotations.

The various situation parameters had different impacts on net value change. Management emphasis, stand size, fire size, and mortality rate had major effects. The effect of cover type and productivity class on the estimates was not well defined. Ultimately, it is the combination of the effects or interactions among these parameters that explains the variability among cases.

Management emphasis affected net value change through the sequence and timing of transactions. The timing and sequence of transactions are defined by management emphasis but can be altered by fire. The moderate public management emphasis had the lowest average net value change, $101 per acre burned. The average net change given intense public management was almost twice as large on average, $196 per acre. The passive private and the intense private had average net changes of $173 and $318 per acre, respectively.

Timber net value changes varied by cover type; lodgepole pine displayed the least average net value change and hemlock the greatest *(fig. 2)*. Cover type affected net value change

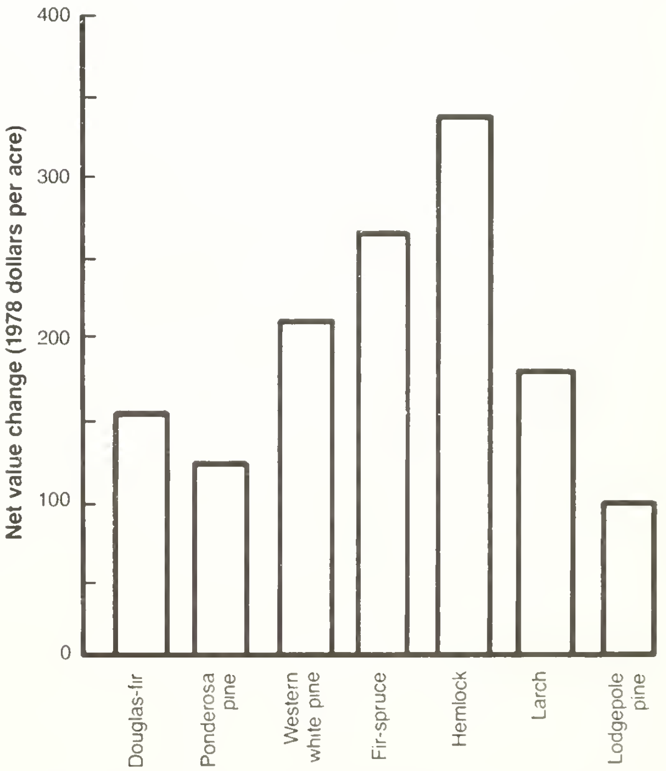


Figure 2—Timber net value changes varied by cover type due to differences in diameter at breast height, stand age, volume and stocking per acre, treatment costs, and stumpage values.

[1]Estimates for the original 9828 situations are available on magnetic computer tape on request from: Patricia B. Shinkle, Pacific Southwest Forest and Range Experiment Station, 4955 Canyon Crest Drive, Riverside, California 92507.

because of differences in d.b.h., stand age, volume per acre, stocking per acre, costs, and stumpage values. Existing stand conditions varied by cover type and productivity class with slight adjustments for management emphasis. This existing stand information came from existing National Forest inventory data.

Site quality affected net value change. Higher quality sites had greater timber volumes at risk which led to greater losses when fires occurred. Overall, high quality sites showed greatest average net value change ($264 per acre), followed by moderate sites ($241), low sites ($147), and very low sites ($106).

Stand size also significantly affected net value change. Poletimber stands had the highest average net change at $290 per acre burned. Seedling/sapling stands had an average net value change of $148, and sawtimber stands had a similar change of $133. Losses in the seedling/sapling stands were generally associated with interplanting costs and delay in harvests. Losses in poletimber stands occurred when the fire removed previously scheduled commercial thinnings or the fire led to nonretention with no salvage harvest. The foregone final harvest in the sawtimber stands was much nearer in the future than in the other two stand sizes, so the foregone present value of the without-fire regime was greater. Part of the loss in sawtimber stands was offset by salvage revenues.

The impact of mortality rate on net value change varied by stand size. Mortality rate had a major impact on the net value change in the seedling/sapling stands because the decision to retain a stand after fire and whether to interplant was determined by postfire stocking. This interplanting cost or delay in harvests caused a net loss when fire occurred. Poletimber stands showed an even greater sensitivity to mortality rate. Poletimber stands were usually retained in low mortality situations, but net losses may still have occurred due to elimination of a previously scheduled commercial thin. At higher mortality rates, the postfire poletimber stand was generally not retained and often the stand was not salvageable. Net losses increased with mortality rate in sawtimber stands too. At moderate and high mortality rates sawtimber stands were usually not retained due to insufficient stocking, but stand conditions were often sufficient for a salvage harvest. The potential for salvage existed at all mortality rates in sawtimber stands, but the proportion of green timber available decreased as the mortality rate increased. At lower mortality rates a salvage harvest may take place, as well as a final harvest of reduced volume.

The impact of the fire size on net value change differed by stand size:

Stand size	Average loss per acre when fire size was . . . 1-99 acres	100+ acres
	Dollars	
Seedling/sapling	148	148
Poletimber	331	248
Sawtimber	237	27

Losses in the large fire situations were generally less than those in small fire situations due to the economies-of-scale in salvage prices and stand establishment costs.

Timber Volume

The change in the timber output was the net change in yields between the without-fire and the with-fire situations. The results for the change in yields in the first 200-year time period showed much of the same variability across the parameters as did the net value change. The timber output changes ranged from a gain of 49 cu ft/acre/year to a loss of 75 cu ft/acre/year during the first 200 years after the fire. The overall average across all the situations analyzed was 0.97 cu ft/acre/year.

The effect of the situation parameters on the timber output changes varied greatly, with mortality rate showing a strong impact, and cover type and management emphasis having less impact. Timber output changes were the same for all productivity classes except the highest site, and the same for all stand sizes except sawtimber. Fire size had no impact on the physical changes.

CONCLUSIONS

The estimates of net value changes and changes in timber output are sensitive to the fire situation and stand classification parameters in various ways. It is the interaction of these parameters that causes the great variability among the cases. Because of this variability situation-specific estimates should be used when describing net value changes, instead of estimates for highly aggregated situations. Use of the situation-specific estimates presented in the reference tables also eliminates the cost of the repetitive calculations needed to produce site-specific estimates.

APPENDIX

Net value change estimates are listed for three discount rates (4.0, 7.875, and 10 percent) *(tables 1A-28A).* Timber output changes are given *(tables 1B-28B)* for the same fire situations for which net value change was estimated. These output changes are measured in ft^3/acre/year for four different time periods (0-24, 25-49, 50-99, 100-200 years) and a total for the first 200 years of the analysis. Positive values in the tables represent net losses due to fire. Negative values represent net benefits due to fire.

The net value change estimates are presented in 1978 dollars because that was the base year for National Forest planning at the time the study was started. Implicit GNP deflators can be used to convert the net value change estimates from 1978 dollars to estimates for other years from 1972 to 1984:

Year	Deflator
1972	100.0
1973	105.8
1974	115.1
1975	125.8
1976	132.3
1977	140.1
1978	150.4
1979	163.4
1980	178.6
1981	195.5
1982	207.2
1983	215.3
1984	223.4

Given a timber net value change of $150 per acre burned in 1978 dollars, to determine the net value change in 1980 dollars, set up a ratio between the 1980 deflator of 178.6 and the 1978 deflator of 150.4. Multiply this ratio, 178.6/150.4 or 1.19, by the $150 per acre burned in 1978 dollars for a timber net value change of $178.5 dollars per acre burned in 1980 dollars.

To locate a particular fire situation in the tables, identify the management emphasis and cover type, then use the following index to locate the appropriate table:

	Management emphasis			
Cover type	Moderate public	Intense public	Passive private	Intense private
	(table number)			
Douglas-fir	1	8	15	22
Ponderosa pine	2	9	16	23
Western white pine	3	10	17	24
Fir-spruce	4	11	18	25
Hemlock	5	12	19	26
Larch	6	13	20	27
Lodgepole pine	7	14	21	28

The following example shows how to locate the net value change at the 4 percent discount rate for a fire situation described as follows:

Management emphasis—"moderate public"
Cover type—ponderosa pine
Productivity—low
Stand size—poletimber
Mortality—60 percent plus
Fire size—100 acres or more
Access—roaded

The index shows that the fire situation is in *table 2*. In *table 2A*, locate the appropriate productivity, stand size, and mortality class in the left hand column, and then the appropriate fire size and discount rate. The net value change is a loss of $143 per acre burned.

To estimate the net value change for unroaded situations, use the factors given in *tables 29* and *30* to adjust the estimates for roaded situations. Unique sets of adjustment factors are used when the net value change of the roaded situation is negative *(table 29)* and when it is positive *(table 30).* The adjustment factors are stratified by management emphasis, stand size, mortality class, and fire size.

The roaded, ponderosa pine fire situation given as an example above had a positive net value change of $143 per acre burned. To adjust this value to an unroaded estimate, turn to *table 30*. The adjustment factor for the moderate public management, poletimber stands with 60+ percent mortality, and fire size 100+ acres, at the 4 percent discount rate is 1.18. Multiply the roaded net value change times the adjustment factor—$143 per acre × 1.18 = net value change of $169 per acre burned in the unroaded situation.

Table 1A--Fire-caused changes in net value of Douglas-fir stands under moderate public management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7.875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	241	147	133	241	147	133
Poletimber:						
1-29	176	104	79	11	-55	-78
30-59	173	101	76	-128	-189	-209
60+	457	190	146	-385	-609	-632
Sawtimber:						
1-29	-3	-3	-3	-140	-135	-133
30-59	359	21	-64	-488	-786	-851
60+	527	160	69	-297	-622	-692
Moderate (85-119):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	0	0	0	0	0	0
Poletimber:						
1-29	49	21	13	49	21	13
30-59	49	21	13	49	21	13
60+	507	199	166	394	104	80
Sawtimber:						
1-29	-2	-2	-2	-79	-76	-75
30-59	437	176	113	-170	-397	-444
60+	465	181	113	-64	-311	-361
Low (50-84):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	247	192	184	247	192	184
Poletimber:						
1-29	163	46	23	163	46	23
30-59	161	45	22	161	45	22
60+	434	194	153	293	78	49
Sawtimber:						
1-29	-1	-1	-1	-43	-42	-41
30-59	232	189	168	-122	-138	-147
60+	293	142	117	-66	-183	-193
Very low (20-49):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	308	241	231	308	241	231
Poletimber:						
1-29	234	66	33	140	-24	-56
30-59	87	-72	-104	-258	-405	-430
60+	240	62	29	-177	-341	-366
Sawtimber:						
1-29	-222	-254	-257	-438	-462	-462
30-59	-141	-171	-176	-314	-338	-340
60+	-194	-237	-239	-336	-375	-374

[1] Negative (-) values = gains; positive values = losses; 0 = no net fire impact.

Table 1B--Fire-caused changes in net timber output of Douglas-fir stands under moderate public management, northern Rocky Mountains, by fire size and time period

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/year[1]									
High (120+):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	40	-20	0	0	0	40	-20	0	0
Poletimber:										
1-29	-4	0	0	0	0	-4	0	0	0	0
30-59	-36	0	0	0	-4	-36	0	0	0	-4
60+	-128	0	116	-99	-37	-128	0	116	-99	-37
Sawtimber:										
1-29	-32	0	0	0	-4	-32	0	0	0	-4
30-59	-156	168	-24	0	-4	-156	168	-24	0	-4
60+	-156	168	-24	0	-4	-156	168	-24	0	-4
Moderate (85-119):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	16	0	0	0	2	16	0	0	0	2
30-59	16	0	0	0	2	16	0	0	0	2
60+	16	0	118	-77	-7	16	0	118	-77	-7
Sawtimber:										
1-29	-20	0	0	0	-2	-20	0	0	0	-2
30-59	-104	124	-10	0	0	-104	124	-10	0	0
60+	-104	124	-10	0	0	-104	124	-10	0	0
Low (50-84):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	-24	32	0	0	1	-24	32	0	0	1
30-59	-40	32	0	0	-1	-40	32	0	0	-1
60+	-96	32	0	22	3	-96	32	0	22	3
Sawtimber:										
1-29	-12	0	0	0	-1	-12	0	0	0	-1
30-59	-60	0	22	12	4	-60	0	22	12	4
60+	-60	0	46	34	21	-60	0	46	34	21
Very low (20-49):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	-24	36	0	0	1	-24	36	0	0	1
30-59	-96	36	-26	-15	-21	-96	36	-26	-15	-21
60+	-96	36	-26	-15	-21	-96	36	-26	-15	-21
Sawtimber:										
1-29	-64	0	16	-64	-36	-64	0	16	-64	-36
30-59	-64	0	16	-64	-36	-64	0	16	-64	-36
60+	-64	0	16	-64	-36	-64	0	16	-64	-36

[1] Negative (-) values = gains; positive values = losses; 0 = no net fire impact.

Table 2A--Fire-caused changes in net value of ponderosa pine stands under moderate public management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7.875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	230	128	113	230	128	113
Poletimber:						
1-29	195	65	37	195	65	37
30-59	193	63	35	193	63	35
60+	166	44	11	22	-84	-110
Sawtimber:						
1-29	-681	-841	-867	-1545	-1662	-1665
30-59	-324	-485	-515	-1317	-1431	-1438
60+	10	-183	-222	-1004	-1150	-1165
Moderate (85-119):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	0	0	0	0	0	0
Poletimber:						
1-29	52	12	6	52	12	6
30-59	486	355	337	197	81	70
60+	320	170	149	214	81	69
Sawtimber:						
1-29	1	-221	-258	-624	-806	-824
30-59	185	-35	-74	-504	-686	-705
60+	251	11	-31	-337	-539	-562
Low (50-84):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	219	160	153	219	160	153
Poletimber:						
1-29	129	21	8	129	21	8
30-59	129	21	8	129	21	8
60+	264	193	168	143	92	77
Sawtimber:						
1-29	-54	-23	-28	-231	-194	-196
30-59	193	204	187	-135	-100	-105
60+	147	147	129	-206	-175	-177
Very low (20-49):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	0	0	0	0	0	0
Poletimber:						
1-29	176	28	11	176	28	11
30-59	176	28	11	176	28	11
60+	183	76	58	183	76	58
Sawtimber:						
1-29	-55	10	6	-223	-152	-154
30-59	28	100	94	-173	-93	-96
60+	-32	29	27	-272	-203	-201

[1] Negative (-) values = gains; positive values = losses; 0 = no net fire impact.

Table 2B--Fire-caused changes in net timber output of ponderosa pine stands under moderate public management, northern Rocky Mountains, by fire size and time period

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/year[1]									
High (120+):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	40	-20	0	0	0	40	-20	0	0
Poletimber:										
1-29	0	36	0	0	4	0	36	0	0	4
30-59	-32	36	0	0	0	-32	36	0	0	0
60+	-100	36	-24	-30	-29	-100	36	-24	-30	-29
Sawtimber:										
1-29	-140	0	40	0	-7	-140	0	40	0	-7
30-59	-140	0	40	0	-7	-140	0	40	0	-7
60+	-140	0	40	0	-7	-140	0	40	0	-7
Moderate (85-119):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	0	16	0	0	2	0	16	0	0	2
30-59	0	16	-10	-14	-7	0	16	-10	-14	-7
60+	0	16	-10	-14	-7	0	16	-10	-14	-7
Sawtimber:										
1-29	-80	0	38	0	0	-80	0	38	0	0
30-59	-80	0	38	0	0	-80	0	38	0	0
60+	-80	0	38	0	0	-80	0	38	0	0
Low (50-84):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	0	0	16	0	4	0	0	16	0	4
30-59	0	0	16	0	4	0	0	16	0	4
60+	0	0	-8	-12	-8	0	0	-8	-12	-8
Sawtimber:										
1-29	-52	0	20	-62	-33	-52	0	20	-62	-33
30-59	-52	0	20	-62	-33	-52	0	20	-62	-33
60+	-52	0	20	-62	-33	-52	0	20	-62	-33
Very low (20-49):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	0	0	18	0	4	0	0	18	0	4
30-59	0	0	18	0	4	0	0	18	0	4
60+	0	0	-8	-15	-9	0	0	-8	-15	-9
Sawtimber:										
1-29	-56	0	-2	-64	-40	-56	0	-2	-64	-40
30-59	-56	0	-2	-64	-40	-56	0	-2	-64	-40
60+	-56	0	-2	-64	-40	-56	0	-2	-64	-40

[1] Negative (-) values = gains; positive values = losses; 0 = no net fire impact.

Table 3A--Fire-caused changes in net value of western white pine stands under moderate public management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7.875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	326	110	62	238	36	-7
Poletimber:						
1-29	566	406	340	566	406	340
30-59	560	401	334	560	401	334
60+	641	311	236	521	206	138
Sawtimber:						
1-29	-2	-2	-2	-2	-2	-2
30-59	-4	-4	-4	-4	-4	-4
60+	296	-107	-190	124	-263	-338
Moderate (85-119):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	258	140	130	258	140	130
Poletimber:						
1-29	166	56	31	166	56	31
30-59	163	54	29	163	54	29
60+	589	137	85	479	42	-3
Sawtimber:						
1-29	-1	-1	-1	-1	-1	-1
30-59	-2	-2	-2	-2	-2	-2
60+	407	78	10	259	-53	-113
Low (50-84):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	0	0	0	0	0	0
Poletimber:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	130	154	142	32	72	68
Sawtimber:						
1-29	-1	-1	-1	-1	-1	-1
30-59	-3	-3	-3	-3	-3	-3
60+	32	-70	-91	-156	-236	-245
Very low (20-49):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	0	0	0	0	0	0
Poletimber:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	261	190	176	138	88	83
Sawtimber:						
1-29	-1	-1	-1	-1	-1	-1
30-59	-3	-3	-3	-3	-3	-3
60+	11	-150	-167	-200	-333	-339

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact.

Table 3B--Fire-caused changes in net timber output of western white pine stands under moderate public management, northern Rocky Mountains, by fire size and time period

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/year[1]									
High (120+):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	-144	80	-32	-10	-21	-144	80	-32	-10	-21
Poletimber:										
1-29	20	0	0	0	2	20	0	0	0	2
30-59	-40	0	0	0	-5	-40	0	0	0	-5
60+	-160	0	108	10	12	-160	0	108	10	12
Sawtimber:										
1-29	-16	0	0	0	-2	-16	0	0	0	-2
30-59	-44	0	0	0	-5	-44	0	0	0	-5
60+	-140	172	20	-16	1	-140	172	20	-16	1
Moderate (85-119):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	7	3	0	0	0	7	3
Poletimber:										
1-29	-32	32	0	0	0	-32	32	0	0	0
30-59	-64	32	0	0	-4	-64	32	0	0	-4
60+	-132	32	128	-70	-16	-132	32	128	-70	-16
Sawtimber:										
1-29	-12	0	0	0	-1	-12	0	0	0	-1
30-59	-28	0	0	0	-3	-28	0	0	0	-3
60+	-88	132	-10	19	12	-88	132	-10	19	12
Low (50-84):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	-24	-20	-16	0	0	-24	-20	-16
Sawtimber:										
1-29	-12	0	0	0	-1	-12	0	0	0	-1
30-59	-36	0	0	0	-4	-36	0	0	0	-4
60+	-116	0	48	-14	-9	-116	0	48	-14	-9
Very low (20-49):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	17	8	0	0	0	17	8
Sawtimber:										
1-29	-12	0	0	0	-1	-12	0	0	0	-1
30-59	-36	0	0	0	-4	-36	0	0	0	-4
60+	-116	0	68	-35	-15	-116	0	68	-35	-15

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact.

Table 4A--Fire-caused changes in net value of fir-spruce stands under moderate public management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7.875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	3	0	0	3	0	0
30-59	269	100	86	269	100	86
60+	269	100	86	269	100	86
Poletimber:						
1-29	249	71	36	249	71	36
30-59	250	69	34	250	69	34
60+	454	83	32	369	8	-38
Sawtimber:						
1-29	58	1	-2	58	1	-2
30-59	383	14	-100	49	-301	-404
60+	588	193	75	456	73	-40
Moderate (85-119):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	284	129	109	284	129	109
60+	284	129	109	284	129	109
Poletimber:						
1-29	249	106	67	249	106	67
30-59	247	104	65	247	104	65
60+	589	148	86	492	63	8
Sawtimber:						
1-29	-2	-2	-2	-2	-2	-2
30-59	-3	-3	-3	-3	-3	-3
60+	305	142	82	191	41	-13
Low (50-84):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	2	0	0	2	0	0
60+	2	0	0	2	0	0
Poletimber:						
1-29	521	223	141	521	223	141
30-59	523	221	139	523	221	139
60+	654	233	139	540	134	48
Sawtimber:						
1-29	-250	-106	-106	-373	-225	-223
30-59	109	-52	-74	2	-156	-176
60+	357	77	42	250	-15	-43
Very low (20-49):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	0	0	0	0	0	0
Poletimber:						
1-29	558	239	151	558	239	151
30-59	556	237	149	556	237	149
60+	547	145	58	502	101	15
Sawtimber:						
1-29	-1	-1	-1	-1	-1	-1
30-59	-2	-2	-2	-2	-2	-2
60+	97	-53	-68	53	-95	-109

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact.

Table 4B--Fire-caused changes in net timber output of fir-spruce stands under moderate public management, northern Rocky Mountains, by fire size and time period

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/year[1]									
High (120+):										
Seedling/sapling:										
1-29	0	0	0	10	5	0	0	0	10	5
30-59	0	0	0	14	7	0	0	0	14	7
60+	0	0	0	14	7	0	0	0	14	7
Poletimber:										
1-29	-32	44	0	10	6	-32	44	0	10	6
30-59	-56	44	0	14	5	-56	44	0	14	5
60+	-140	44	116	-85	-26	-140	44	116	-85	-26
Sawtimber:										
1-29	-36	0	20	10	5	-36	0	20	10	5
30-59	16	0	28	14	16	16	0	28	14	16
60+	16	0	28	14	16	16	0	28	14	16
Moderate (85-119):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	56	-28	0	0	0	56	-28	0	0
60+	0	56	-28	-1	0	0	56	-28	-1	0
Poletimber:										
1-29	20	0	0	0	2	20	0	0	0	2
30-59	4	0	0	0	0	4	0	0	0	0
60+	-68	0	128	-65	-9	-68	0	128	-65	-9
Sawtimber:										
1-29	-24	0	0	0	-3	-24	0	0	0	-3
30-59	-32	0	0	0	-4	-32	0	0	0	-4
60+	8	0	-2	7	4	8	0	-2	7	4
Low (50-84):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	72	0	0	0	9	72	0	0	0	9
30-59	40	0	0	31	20	40	0	0	31	20
60+	-80	0	0	59	20	-80	0	0	59	20
Sawtimber:										
1-29	-84	0	-32	0	-18	-84	0	-32	0	-18
30-59	-84	0	30	65	30	-84	0	30	65	30
60+	-84	0	54	87	47	-84	0	54	87	47
Very low (20-49):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	68	0	0	0	8	68	0	0	0	8
30-59	40	0	0	0	5	40	0	0	0	5
60+	-72	0	0	31	6	-72	0	0	31	6
Sawtimber:										
1-29	-20	0	0	0	-2	-20	0	0	0	-2
30-59	-28	0	0	0	-3	-28	0	0	0	-3
60+	-84	0	52	0	2	-84	0	52	0	2

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact.

Table 5A--Fire-caused changes in net value of hemlock stands under moderate public management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7.875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	350	214	173	350	214	173
60+	346	208	168	346	208	168
Poletimber:						
1-29	-6	-6	-6	-6	-6	-6
30-59	-12	-12	-11	-12	-12	-11
60+	-48	-289	-304	-168	-398	-408
Sawtimber:						
1-29	108	69	54	-30	-65	-77
30-59	594	352	223	-52	-264	-378
60+	983	580	432	270	-102	-234
Moderate (85-119):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	369	162	128	369	162	128
Poletimber:						
1-29	341	235	192	341	235	192
30-59	336	230	188	336	230	188
60+	497	4	-70	363	-118	-186
Sawtimber:						
1-29	102	64	50	102	64	50
30-59	261	166	129	261	166	129
60+	803	511	383	708	428	306
Low (50-84):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	3	0	0	3	0	0
60+	3	0	0	3	0	0
Poletimber:						
1-29	0	0	0	0	0	0
30-59	7	0	0	7	0	0
60+	375	144	116	316	96	73
Sawtimber:						
1-29	104	80	70	104	80	70
30-59	406	235	183	341	172	122
60+	629	430	365	546	360	302
Very low (20-49):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	2	0	0	2	0	0
Poletimber:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	1	-3	-3	1	-3	-3
Sawtimber:						
1-29	-2	-2	-2	-2	-2	-2
30-59	-5	-5	-5	-5	-5	-5
60+	443	117	33	418	93	10

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact.

Table 5B--Fire-caused changes in net timber output of hemlock stands under moderate public management, northern Rocky Mountains, by fire size and time period

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/year[1]									
High (120+):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	-48	-92	160	-79	-17	-48	-92	160	-79	-17
60+	-108	-92	160	-69	-20	-108	-92	160	-69	-20
Poletimber:										
1-29	-64	0	0	0	-8	-64	0	0	0	-8
30-59	-120	0	0	0	-15	-120	0	0	0	-15
60+	-280	0	108	10	-3	-280	0	108	10	-3
Sawtimber:										
1-29	-28	0	0	0	-3	-28	0	0	0	-3
30-59	12	0	0	0	1	12	0	0	0	1
60+	12	0	20	10	11	12	0	20	10	11
Moderate (85-119):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	-140	68	126	-79	-17	-140	68	126	-79	-17
Poletimber:										
1-29	-4	0	0	0	0	-4	0	0	0	0
30-59	-60	0	0	0	-7	-60	0	0	0	-7
60+	-220	0	116	0	1	-220	0	116	0	1
Sawtimber:										
1-29	-28	0	0	0	-3	-28	0	0	0	-3
30-59	-68	0	0	0	-8	-68	0	0	0	-8
60+	4	0	0	-12	-5	4	0	0	-12	-5
Low (50-84):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	12	6	0	0	0	12	6
60+	0	0	0	12	6	0	0	0	12	6
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	27	13	0	0	0	27	13
60+	0	0	78	26	32	0	0	78	26	32
Sawtimber:										
1-29	-8	0	0	0	-1	-8	0	0	0	-1
30-59	4	0	24	14	13	4	0	24	14	13
60+	4	0	24	14	13	4	0	24	14	13
Very low (20-49):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	13	6	0	0	0	13	6
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	-56	0	0	-22	-18	-56	0	0	-22	-18
Sawtimber:										
1-29	-24	0	0	0	-3	-24	0	0	0	-3
30-59	-60	0	0	0	-7	-60	0	0	0	-7
60+	8	0	0	55	29	8	0	0	55	29

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact.

Table 6A--Fire-caused changes in net value of larch stands under moderate public management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7.875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	258	156	137	258	156	137
60+	255	154	134	255	154	134
Poletimber:						
1-29	260	186	155	260	186	155
30-59	258	183	152	258	183	152
60+	282	74	34	73	-113	-143
Sawtimber:						
1-29	-3	-3	-3	-101	-98	-96
30-59	378	30	-52	-295	-607	-671
60+	533	155	66	-120	-461	-530
Moderate (85-119):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	289	169	158	289	169	158
Poletimber:						
1-29	157	53	29	157	53	29
30-59	156	52	28	156	52	28
60+	557	153	101	384	2	-40
Sawtimber:						
1-29	-1	-1	-1	-1	-1	-1
30-59	351	82	21	145	-113	-169
60+	524	224	151	370	91	28
Low (50-84):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	0	0	0	0	0	0
Poletimber:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	263	188	171	128	75	68
Sawtimber:						
1-29	-2	-2	-2	-2	-2	-2
30-59	75	-109	-124	-76	-254	-267
60+	322	104	74	139	-51	-68
Very low (20-49):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	0	0	0	0	0	0
Poletimber:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	300	220	202	136	83	77
Sawtimber:						
1-29	-2	-2	-2	-2	-2	-2
30-59	-6	-145	-153	-156	-288	-294
60+	285	104	77	75	-73	-85

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact.

Table 6B--Fire-caused changes in net timber output of larch stands under moderate public management, northern Rocky Mountains, by fire size and time period

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/year[1]									
High (120+):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	-84	48	-24	0	-10	-84	48	-24	0	-10
60+	-116	48	-24	0	-14	-116	48	-24	0	-14
Poletimber:										
1-29	-24	0	0	0	-3	-24	0	0	0	-3
30-59	-48	0	0	0	-6	-48	0	0	0	-6
60+	-188	0	108	0	3	-188	0	108	0	3
Sawtimber:										
1-29	-28	0	0	0	-3	-28	0	0	0	-3
30-59	-140	172	0	-16	-4	-140	172	0	-16	-4
60+	-140	172	0	-16	-4	-140	172	0	-16	-4
Moderate (85-119):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	-40	32	0	0	-1	-40	32	0	0	-1
30-59	-52	32	0	0	-2	-52	32	0	0	-2
60+	-132	32	114	-89	-29	-132	32	114	-89	-29
Sawtimber:										
1-29	-16	0	0	0	-2	-16	0	0	0	-2
30-59	-88	132	-24	0	0	-88	132	-24	0	0
60+	-88	132	-24	0	0	-88	132	-24	0	0
Low (50-84):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	-6	-3	0	0	0	-6	-3
Sawtimber:										
1-29	-24	0	0	0	-3	-24	0	0	0	-3
30-59	-116	0	72	0	3	-116	0	72	0	3
60+	-116	0	72	0	3	-116	0	72	0	3
Very low (20-49):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	17	8	0	0	0	17	8
Sawtimber:										
1-29	-24	0	0	0	-3	-24	0	0	0	-3
30-59	-116	0	68	-65	-30	-116	0	68	-65	-30
60+	-116	0	68	-35	-15	-116	0	68	-35	-15

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact.

Table 7A--Fire-caused changes in net value of lodgepole pine stands under moderate public management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7.875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	231	121	110	251	124	111
Poletimber:						
1-29	71	30	19	90	39	25
30-59	71	30	19	90	39	25
60+	719	234	157	616	140	69
Sawtimber:						
1-29	-2	-2	-2	-2	-2	-2
30-59	-3	-3	-3	-3	-3	-3
60+	404	269	192	261	137	65
Moderate (85-119):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	168	113	107	168	113	107
Poletimber:						
1-29	34	15	10	34	15	10
30-59	34	15	10	34	15	10
60+	347	179	149	258	96	70
Sawtimber:						
1-29	-1	-1	-1	-1	-1	-1
30-59	-2	-2	-2	-2	-2	-2
60+	334	191	135	212	78	27
Low (50-84):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	141	111	106	141	111	106
Poletimber:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	149	37	16	149	37	16
Sawtimber:						
1-29	16	10	7	16	10	7
30-59	26	16	12	26	16	12
60+	171	103	73	143	76	47
Very low (20-49):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	0	0	0	0	0	0
Poletimber:						
1-29	0	0	0	0	0	0
30-59	135	28	11	135	28	11
60+	137	28	11	137	28	11
Sawtimber:						
1-29	3	1	1	3	1	1
30-59	102	24	-5	30	-46	-73
60+	162	80	50	142	60	31

[1] Negative (-) values = gains; positive values = losses; 0 = no net fire impact.

Table 7B--Fire-caused changes in net timber output of lodgepole pine stands under moderate public management, northern Rocky Mountains, by fire size and time period

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/year[1]									
High (120+):										
Seedling/sapling:										
1-29	-4	0	0	0	0	0	0	0	0	0
30-59	-8	0	0	0	-1	0	0	0	0	0
60+	-12	0	52	19	21	0	0	0	95	48
Poletimber:										
1-29	16	0	0	0	2	28	0	0	0	3
30-59	16	0	0	0	2	28	0	0	0	3
60+	-60	0	88	-4	12	-60	0	88	-4	12
Sawtimber:										
1-29	-24	0	0	0	-3	-24	0	0	0	-3
30-59	-40	0	0	0	-5	-40	0	0	0	-5
60+	44	0	-8	-16	-4	44	0	-8	-16	-4
Moderate (85-119):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	104	-58	-3	0	0	104	-58	-3
Poletimber:										
1-29	16	0	0	0	2	16	0	0	0	2
30-59	16	0	0	0	2	16	0	0	0	2
60+	16	0	54	-19	6	16	0	54	-19	6
Sawtimber:										
1-29	-20	0	0	0	-2	-20	0	0	0	-2
30-59	-32	0	0	0	-4	-32	0	0	0	-4
60+	-92	136	-24	-19	-10	-92	136	-24	-19	-10
Low (50-84):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	88	0	0	11	0	88	0	0	11
Sawtimber:										
1-29	-12	0	0	0	-1	-12	0	0	0	-1
30-59	-20	0	0	0	-2	-20	0	0	0	-2
60+	8	0	0	0	1	8	0	0	0	1
Very low (20-49):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	60	0	0	7	0	60	0	0	7
60+	0	60	0	0	7	0	60	0	0	7
Sawtimber:										
1-29	-8	0	0	0	-1	-8	0	0	0	-1
30-59	8	0	0	0	1	8	0	0	0	1
60+	8	0	0	0	1	8	0	0	0	1

[1] Negative (-) values = gains; positive values = losses; 0 = no net fire impact.

Table 8A--Fire-caused changes in net value of Douglas-fir stands under intense public management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7.875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	402	176	148	402	176	148
Poletimber:						
1-29	269	159	120	55	-47	-82
30-59	265	156	117	-125	-220	-251
60+	1328	390	242	269	-620	-742
Sawtimber:						
1-29	58	34	25	-79	-98	-105
30-59	489	343	237	-358	-464	-550
60+	661	476	364	-163	-306	-398
Moderate (85-119):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	297	152	140	297	152	140
Poletimber:						
1-29	11	7	5	11	7	5
30-59	130	41	23	130	41	23
60+	1074	340	231	972	256	154
Sawtimber:						
1-29	31	18	14	-34	-45	-48
30-59	447	355	289	-77	-139	-191
60+	459	337	268	7	-83	-137
Low (50-84):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	240	162	156	240	162	156
60+	240	162	156	240	162	156
Poletimber:						
1-29	95	26	13	4	-63	-75
30-59	94	25	11	-74	-137	-147
60+	574	166	124	47	-325	-349
Sawtimber:						
1-29	-1	-1	-1	-43	-42	-41
30-59	335	211	164	3	-98	-134
60+	372	169	124	32	-141	-173
Very low (20-49):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	272	191	184	272	191	184
Poletimber:						
1-29	-11	-371	-395	-443	-788	-804
30-59	125	-240	-267	-346	-694	-712
60+	407	27	-4	-172	-531	-551
Sawtimber:						
1-29	59	-229	-267	-155	-434	-468
30-59	146	-145	-185	-25	-309	-346
60+	110	-185	-222	-31	-321	-355

[1] Negative (-) values = gains; positive values = losses; 0 = no net fire impact.

Table 8B--Fire-caused changes in net timber output of Douglas-fir standa under intense public management, northern Rocky Mountains, by fire size and time period

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/year[1]									
High (120+):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	12	36	160	-91	0	12	36	160	-91	0
Poletimber:										
1-29	-8	0	0	0	-1	-8	0	0	0	-1
30-59	-44	0	0	0	-5	-44	0	0	0	-5
60+	-152	-12	132	-75	-25	-152	-12	132	-75	-25
Sawtimber:										
1-29	-24	0	0	0	-3	-24	0	0	0	-3
30-59	4	-12	-152	0	-39	4	-12	-152	0	-39
60+	4	-12	6	-78	-39	4	-12	6	-78	-39
Moderate (85-119):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	4	128	-9	28	0	4	128	-9	28
Poletimber:										
1-29	4	0	0	0	0	4	0	0	0	0
30-59	4	24	0	0	3	4	24	0	0	3
60+	4	24	94	0	27	4	24	94	0	27
Sawtimber:										
1-29	-16	0	0	0	-2	-16	0	0	0	-2
30-59	20	0	0	0	2	20	0	0	0	2
60+	20	0	0	0	2	20	0	0	0	2
Low (50-84):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	-28	20	0	0	-1	-28	20	0	0	-1
30-59	-48	20	0	0	-3	-48	20	0	0	-3
60+	-112	20	144	-38	5	-112	20	144	-38	5
Sawtimber:										
1-29	-12	0	0	0	-1	-12	0	0	0	-1
30-59	-60	84	-12	0	0	-60	84	-12	0	0
60+	-60	84	0	33	19	-60	84	0	33	19
Very low (20-49):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	-112	20	140	-25	11	-112	20	140	-25	11
30-59	-112	20	140	-25	11	-112	20	140	-25	11
60+	-112	20	140	-25	11	-112	20	140	-25	11
Sawtimber:										
1-29	-64	84	0	49	27	-64	84	0	49	27
30-59	-64	84	0	49	27	-64	84	0	49	27
60+	-64	84	0	49	27	-64	84	0	49	27

[1] Negative (-) values = gains; positive values = losses; 0 = no net fire impact.

Table 9A--Fire-caused changes in net value of ponderosa pine stands under intense public management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7.875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	401	162	131	401	162	131
Poletimber:						
1-29	331	131	83	219	23	-22
30-59	330	130	82	166	-28	-73
60+	597	110	34	-26	-479	-539
Sawtimber:						
1-29	-209	-550	-674	-1074	-1370	-1472
30-59	145	-193	-320	-848	-1139	-1243
60+	485	108	-30	-529	-860	-972
Moderate (85-119):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	289	130	116	289	130	116
Poletimber:						
1-29	741	377	330	483	135	96
30-59	740	388	343	478	139	101
60+	589	210	163	493	130	90
Sawtimber:						
1-29	271	-4	-101	-387	-622	-700
30-59	491	220	121	-244	-477	-557
60+	620	319	215	-49	-311	-396
Low (50-84):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	217	135	128	217	135	128
60+	217	135	128	217	135	128
Poletimber:						
1-29	77	13	5	77	13	5
30-59	77	13	5	77	13	5
60+	350	190	161	243	101	80
Sawtimber:						
1-29	188	106	72	-93	-151	-173
30-59	273	198	164	-38	-91	-114
60+	255	166	132	-83	-142	-164
Very low (20-49):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	-1	0	0	-1	0	0
60+	253	160	152	253	160	152
Poletimber:						
1-29	105	17	6	105	17	6
30-59	104	17	6	104	17	6
60+	243	69	50	243	69	50
Sawtimber:						
1-29	37	4	-23	-130	-157	-180
30-59	35	72	55	-164	-120	-134
60+	27	39	26	-213	-192	-201

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact.

Table 9B--Fire-caused changes in net timber output of ponderosa pine stands under intense public management, northern Rocky Mountains, by fire size and time period

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/year[1]									
High (120+):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	12	36	160	-91	0	12	36	160	-91	0
Poletimber:										
1-29	-20	40	0	0	2	-20	40	0	0	2
30-59	-32	40	0	0	1	-32	40	0	0	1
60+	-120	28	132	-78	-18	-120	28	132	-78	-18
Sawtimber:										
1-29	-140	132	-152	0	-39	-140	132	-152	0	-39
30-59	-140	132	-152	0	-39	-140	132	-152	0	-39
60+	-140	132	6	-78	-39	-140	132	6	-78	-39
Moderate (85-119):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	4	128	-9	28	0	4	128	-9	28
Poletimber:										
1-29	0	4	106	0	27	0	4	106	0	27
30-59	0	4	106	0	27	0	4	106	0	27
60+	0	4	106	0	27	0	4	106	0	27
Sawtimber:										
1-29	-72	96	-14	0	0	-96	96	-14	0	-3
30-59	-72	96	-14	0	0	-96	96	-14	0	-3
60+	-96	96	-14	0	-3	-96	96	-14	0	-3
Low (50-84):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	6	3	0	0	0	6	3
60+	0	0	0	6	3	0	0	0	6	3
Poletimber:										
1-29	0	0	10	0	2	0	0	10	0	2
30-59	0	0	10	0	2	0	0	10	0	2
60+	0	0	-2	1	0	0	0	-2	1	0
Sawtimber:										
1-29	-52	0	26	0	0	-52	0	26	0	0
30-59	-52	0	26	0	0	-52	0	26	0	0
60+	-52	0	26	0	0	-52	0	26	0	0
Very low (20-49):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	0	0	10	0	2	0	0	10	0	2
30-59	0	0	10	0	2	0	0	10	0	2
60+	0	0	-2	2	0	0	0	-2	2	0
Sawtimber:										
1-29	-56	0	14	6	0	-56	0	14	6	0
30-59	-56	0	14	6	0	-56	0	14	6	0
60+	-56	0	14	6	0	-56	0	14	6	0

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact.

Table 10A--Fire-caused changes in net value of western white pine stands under intense public management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7.875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	136	102	87	136	102	87
30-59	136	102	87	136	102	87
60+	635	241	164	539	158	88
Poletimber:						
1-29	-5	-5	-5	-5	-5	-5
30-59	-11	-11	-10	-11	-11	-10
60+	967	85	-30	846	-21	-130
Sawtimber:						
1-29	29	16	12	29	16	12
30-59	74	41	30	74	41	30
60+	530	246	122	357	90	-27
Moderate (85-119):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	335	136	119	335	136	119
Poletimber:						
1-29	139	47	25	139	47	25
30-59	679	-88	-195	418	-337	-437
60+	1133	272	141	1032	184	58
Sawtimber:						
1-29	15	8	6	15	8	6
30-59	38	21	15	38	21	15
60+	496	284	193	360	163	79
Low (50-84):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	185	131	127	185	131	127
Poletimber:						
1-29	-1	-1	-1	-1	-1	-1
30-59	281	55	34	226	2	-18
60+	399	172	133	305	92	60
Sawtimber:						
1-29	-1	-1	-1	-1	-1	-1
30-59	-3	-3	-3	-3	-3	-3
60+	394	47	-33	223	-108	-179
Very low (20-49):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	0	0	0	0	0	0
Poletimber:						
1-29	-1	-1	-1	-1	-1	-1
30-59	-2	-2	-2	-2	-2	-2
60+	363	128	105	258	42	28
Sawtimber:						
1-29	-1	-1	-1	-1	-1	-1
30-59	-3	-3	-3	-3	-3	-3
60+	278	-109	-166	93	-271	-318

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact.

Table 10B--Fire-caused changes in net timber output of western white pine stands under intense public management, northern Rocky Mountains, by fire size and time period

Stand productivity (cu ft/acre/yr) stand size, and mortality class (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/yea[1]									
High (120+):										
Seedling/sapling:										
1-29	24	0	0	0	3	24	0	0	0	3
30-59	24	0	0	0	3	24	0	0	0	3
60+	-156	28	166	-84	-17	-156	26	166	-84	-17
Poletimber:										
1-29	-44	0	0	0	-5	-44	0	0	0	-5
30-59	-92	0	0	0	-11	-92	0	0	0	-11
60+	-196	-24	148	-84	-33	-196	-24	148	-84	-33
Sawtimber:										
1-29	-12	0	0	0	-1	-12	0	0	0	-1
30-59	-32	0	0	0	-4	-32	0	0	0	-4
60+	12	0	0	-84	-41	12	0	0	-84	-41
Moderate (85-119):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	4	-4	0	59	30	4	-4	0	59	30
Poletimber:										
1-29	-28	24	0	0	0	-28	24	0	0	0
30-59	-120	20	104	-1	13	-120	20	104	-1	13
60+	-120	24	102	3	15	-120	24	102	3	15
Sawtimber:										
1-29	-8	0	0	0	-1	-8	0	0	0	-1
30-59	-20	0	0	0	-2	-20	0	0	0	-2
60+	24	0	0	4	5	24	0	0	4	5
Low (50-84):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	-16	0	0	0	-2	-16	0	0	0	-2
30-59	-76	0	122	0	21	-76	0	122	0	21
60+	-76	0	110	-19	8	-76	0	110	-19	8
Sawtimber:										
1-29	-12	0	0	0	-1	-12	0	0	0	-1
30-59	-36	0	0	0	-4	-36	0	0	0	-4
60+	-116	140	-12	-19	-9	-116	140	-12	-19	-9
Very low (20-49):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	-16	0	0	0	-2	-16	0	0	0	-2
30-59	-36	0	0	0	-4	-36	0	0	0	-4
60+	-72	0	122	-31	6	-72	0	122	-31	6
Sawtimber:										
1-29	-12	0	0	0	-1	-12	0	0	0	-1
30-59	-36	0	0	0	-4	-36	0	0	0	-4
60+	-116	0	68	29	17	-116	0	68	29	17

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact.

Table 11A--Fire-caused changes in net value of fir-spruce stands under intense public management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7.875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	463	132	102	463	132	102
30-59	467	132	102	467	132	102
60+	460	125	95	460	125	95
Poletimber:						
1-29	161	62	38	161	62	38
30-59	179	60	36	179	60	36
60+	1235	222	84	1141	139	6
Sawtimber:						
1-29	204	116	99	-197	-264	-270
30-59	498	303	262	164	-12	-43
60+	709	477	431	576	356	316
Moderate (85-119):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	429	126	98	429	126	98
60+	426	126	98	426	126	98
Poletimber:						
1-29	296	87	44	296	87	44
30-59	293	84	42	293	84	42
60+	1189	214	83	1094	130	5
Sawtimber:						
1-29	2	3	4	-225	-209	-201
30-59	20	30	31	-200	-176	-169
60+	87	101	114	-19	7	26
Low (50-84):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	252	137	114	252	137	114
Poletimber:						
1-29	266	164	127	266	164	127
30-59	263	161	124	263	161	124
60+	616	156	95	502	56	1
Sawtimber:						
1-29	232	97	34	57	-64	-119
30-59	259	130	67	97	-19	-75
60+	292	127	77	194	43	-1
Very low (20-49):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	368	163	133	368	163	133
Poletimber:						
1-29	458	195	123	458	195	123
30-59	455	192	120	455	192	120
60+	749	127	34	624	19	-66
Sawtimber:						
1-29	-1	-1	-1	-1	-1	-1
30-59	-2	-2	-2	-2	-2	-2
60+	316	94	38	211	6	-42

[1] Negative (-) values = gains; positive values = losses; 0 = no net fire impact.

Table 11B--Fire-caused changes in net timber output of fir-spruce stands under intense public management, northern Rocky Mountains, by fire size and time period

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/year[1]									
High (120+):										
Seedling/sapling:										
1-29	12	20	-16	0	0	12	20	-16	0	0
30-59	12	20	-16	10	5	12	20	-16	10	5
60+	-92	20	-16	10	-8	-92	20	-16	10	-8
Poletimber:										
1-29	-12	0	0	0	-1	-12	0	0	0	-1
30-59	-40	0	12	8	2	-40	0	12	8	2
60+	-140	-12	158	-68	-14	-140	-12	158	-68	-14
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	12	16	11	11	0	12	16	11	11
60+	0	12	172	-68	10	0	12	172	-68	10
Moderate (85-119):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	55	28	0	0	0	55	28
60+	0	0	0	58	29	0	0	0	58	29
Poletimber:										
1-29	-32	60	0	0	3	-32	60	0	0	3
30-59	-56	60	0	0	0	-56	60	0	0	0
60+	-140	60	130	-6	19	-140	60	130	-6	19
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	6	-6	-1	0	0	6	-6	-1
Low (50-84):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	-104	80	-40	6	-10	-104	80	-40	6	-10
Poletimber:										
1-29	12	0	0	0	1	12	0	0	0	1
30-59	-28	0	0	0	-3	-28	0	0	0	-3
60+	-176	0	170	-38	1	-176	0	170	-38	1
Sawtimber:										
1-29	-84	96	-12	6	1	-84	96	-12	6	1
30-59	-84	96	-12	0	-1	-84	96	-12	0	-1
60+	-84	96	0	33	18	-84	96	0	33	18
Very low (20-49):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	76	-38	0	0	0	76	-38	0	0
Poletimber:										
1-29	4	0	0	0	0	4	0	0	0	0
30-59	-40	0	0	0	-5	-40	0	0	0	-5
60+	-200	0	170	0	17	-200	0	170	0	17
Sawtimber:										
1-29	-20	0	0	0	-2	-20	0	0	0	-2
30-59	-28	0	0	0	-3	-28	0	0	0	-3
60+	-84	96	0	0	1	-84	96	0	0	1

[1] Negative (-) values = gains; positive values = losses; 0 = no net fire impact.

Table 12A--Fire-caused changes in net value of hemlock stands under intense public management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7.875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	630	238	195	630	238	195
30-59	622	230	187	622	230	187
60+	751	154	63	660	72	-15
Poletimber:						
1-29	-8	-8	-8	-8	-8	-8
30-59	-15	-15	-14	-15	-15	-14
60+	862	-120	-282	721	-249	-406
Sawtimber:						
1-29	129	124	122	-200	-186	-180
30-59	697	672	659	46	51	52
60+	1078	925	888	357	236	216
Moderate (85-119):						
Seedling/sapling:						
1-29	772	203	135	772	203	135
30-59	765	196	128	765	196	128
60+	1126	186	77	1056	125	20
Poletimber:						
1-29	223	104	60	223	104	68
30-59	217	98	63	217	98	63
60+	1465	101	-134	1326	-27	-256
Sawtimber:						
1-29	83	81	80	-183	-169	-162
30-59	270	272	269	44	59	62
60+	922	838	812	836	762	741
Low (50-84):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	2	0	0	2	0	0
60+	193	101	96	193	101	96
Poletimber:						
1-29	-1	-1	-1	-1	-1	-1
30-59	3	-3	-3	3	-3	-3
60+	375	71	30	305	13	-24
Sawtimber:						
1-29	19	9	6	19	9	6
30-59	409	176	86	296	74	-11
60+	522	276	184	449	215	129
Very low (20-49):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	197	114	110	197	114	110
Poletimber:						
1-29	-1	-1	-1	-1	-1	-1
30-59	-3	-2	-2	-3	-2	-2
60+	247	0	-24	171	-61	-78
Sawtimber:						
1-29	-2	-2	-2	-2	-2	-2
30-59	-5	-5	-5	-5	-5	-5
60+	519	201	105	439	136	46

[1] Negative (-) values = gains; positive values = losses; 0 = no net fire impact.

Table 12B--Fire-caused changes in net timber output of hemlock stands under intense public management, northern Rocky Mountains, by fire size and time period

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/year[1]									
High (120+):										
Seedling/sapling:										
1-29	-40	-60	0	6	-9	-40	-60	0	6	-9
30-59	-116	-60	0	6	-19	-116	-60	0	6	-19
60+	-200	-24	174	-78	-24	-200	-24	174	-78	-24
Poletimber:										
1-29	-68	0	0	0	-8	-68	0	0	0	-8
30-59	-128	0	0	0	-16	-128	0	0	0	-16
60+	-300	316	12	-84	-37	-300	316	12	-84	-37
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	170	-84	0	0	0	170	-84	0
Moderate (85-119):										
Seedling/sapling:										
1-29	8	36	-22	0	0	8	36	-22	0	0
30-59	-80	36	-22	0	-11	-80	36	-22	0	-11
60+	-144	40	186	0	33	-144	40	186	0	33
Poletimber:										
1-29	-20	0	0	0	-2	-20	0	0	0	-2
30-59	-72	0	0	0	-9	-72	0	0	0	-9
60+	-224	336	-12	0	11	-224	336	-12	0	11
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Low (50-84):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	120	-59	0	0	0	120	-59	0
Poletimber:										
1-29	-20	0	0	0	-2	-20	0	0	0	-2
30-59	-40	0	0	0	-5	-40	0	0	0	-5
60+	-96	0	102	0	13	-96	0	102	0	13
Sawtimber:										
1-29	-20	0	0	0	-2	-20	0	0	0	-2
30-59	8	0	0	0	1	8	0	0	0	1
60+	8	0	0	0	1	8	0	0	0	1
Very low (20-49):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	6	3	0	0	0	6	3
Poletimber:										
1-29	-20	0	0	0	-2	-20	0	0	0	2
30-59	-40	0	0	0	-5	-40	0	0	0	-5
60+	-92	0	102	49	38	-92	0	102	49	38
Sawtimber:										
1-29	-24	0	0	0	-3	-24	0	0	0	-3
30-59	-60	0	0	0	-7	-60	0	0	0	-7
60+	8	0	0	49	25	8	0	0	49	2[illegible]

[1] Negative (-) values = gains; positive values = losses; 0 = no net fire impact.

Table 13A--Fire-caused changes in net value of larch stands under intense public management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7.875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	421	237	209	421	237	209
30-59	412	229	201	412	229	201
60+	408	225	198	408	225	198
Poletimber:						
1-29	-7	-6	-6	-7	-6	-6
30-59	-9	-9	-9	-9	-9	-9
60+	842	54	-55	631	-134	-232
Sawtimber:						
1-29	40	22	16	-59	-73	-77
30-59	414	282	189	-260	-355	-429
60+	578	404	304	-76	-211	-292
Moderate (85-119):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	347	160	143	347	160	143
Poletimber:						
1-29	131	43	23	131	43	23
30-59	129	42	22	129	42	22
60+	1064	278	151	899	133	16
Sawtimber:						
1-29	21	12	8	21	12	8
30-59	394	322	262	91	43	-4
60+	391	311	251	250	189	138
Low (50-84):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	0	0	0	0	0	0
Poletimber:						
1-29	-1	-1	-1	-1	-1	-1
30-59	-2	-2	-2	-2	-2	-2
60+	513	200	156	373	81	46
Sawtimber:						
1-29	-2	-2	-2	-2	-2	-2
30-59	420	10	-67	275	-131	-205
60+	671	229	139	504	83	3
Very low (20-49):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	-1	0	0	-1	0	0
Poletimber:						
1-29	-1	-1	-1	-1	-1	-1
30-59	-1	-1	-1	-1	-1	-1
60+	389	153	127	237	29	14
Sawtimber:						
1-29	-2	-2	-2	-2	-2	-2
30-59	346	-72	-138	200	-212	-275
60+	544	146	80	363	-8	-61

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact.

Table 13B--Fire-caused changes in net timber output of larch stands under intense public management, northern Rocky Mountains, by fire size and time period

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/year[1]									
High (120+):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	-108	0	0	0	-13	-108	0	0	0	-13
60+	-144	0	0	0	-18	-144	0	0	0	-18
Poletimber:										
1-29	-56	0	0	0	-7	-56	0	0	0	-7
30-59	-80	0	0	0	-10	-80	0	0	0	-10
60+	-196	-24	148	-84	-33	-196	-24	148	-84	-33
Sawtimber:										
1-29	-20	0	0	0	-2	-20	0	0	0	-2
30-59	12	0	-170	0	-41	12	0	-170	0	-41
60+	12	0	0	-84	-41	12	0	0	-84	-41
Moderate (85-119):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	4	-4	0	59	30	4	-4	0	59	30
Poletimber:										
1-29	-36	24	0	0	-1	-36	24	0	0	-1
30-59	-48	24	0	0	-3	-48	24	0	0	-3
60+	-120	20	104	0	13	-120	20	104	0	13
Sawtimber:										
1-29	-12	0	0	0	-1	-12	0	0	0	-1
30-59	24	-4	2	0	3	24	-4	2	0	3
60+	24	-4	2	0	3	24	-4	2	0	3
Low (50-84):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	-24	0	0	0	-3	-24	0	0	0	-3
30-59	-32	0	0	0	-4	-32	0	0	0	-4
60+	-76	0	122	0	21	-76	0	122	0	21
Sawtimber:										
1-29	-24	0	0	0	-3	-24	0	0	0	-3
30-59	-116	140	0	0	3	-116	140	0	0	3
60+	-116	140	0	0	3	-116	140	0	0	3
Very low (20-49):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	-20	0	0	0	-2	-20	0	0	0	-2
30-59	-28	0	0	0	-3	-28	0	0	0	-3
60+	-72	0	122	-31	6	-72	0	122	-31	6
Sawtimber:										
1-29	-24	0	0	0	-3	-24	0	0	0	-3
30-59	-116	0	68	0	2	-116	0	68	0	2
60+	-116	0	68	29	17	-116	0	68	29	17

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact.

Table 14A--Fire-caused changes in net value of lodgepole pine stands under intense public management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7.875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	274	119	102	274	119	102
Poletimber:						
1-29	20	5	2	20	5	2
30-59	973	305	160	795	142	3
60+	875	327	205	777	237	120
Sawtimber:						
1-29	147	118	107	147	118	107
30-59	174	135	120	174	135	120
60+	335	391	342	195	261	216
Moderate (85-119):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	204	117	108	204	117	108
Poletimber:						
1-29	42	13	7	42	13	7
30-59	39	10	4	39	10	4
60+	754	264	176	642	162	79
Sawtimber:						
1-29	56	50	47	56	50	47
30-59	55	49	46	55	49	46
60+	367	297	235	235	176	119
Low (50-84):						
Seedling/sapling:						
1-29	-263	-253	-248	-263	-253	-248
30-59	-263	-253	-248	-263	-253	-248
60+	-110	-141	-141	-110	-141	-141
Poletimber:						
1-29	0	0	0	0	.0	0
30-59	446	279	220	353	195	141
60+	335	190	142	254	122	80
Sawtimber:						
1-29	16	10	7	16	10	7
30-59	26	16	12	26	16	12
60+	108	131	114	1	41	31
Very low (20-49):						
Seedling/sapling:						
1-29	-49	-47	-46	-49	-47	-46
30-59	-49	-47	-46	-49	-47	-46
60+	118	79	74	118	79	74
Poletimber:						
1-29	247	65	31	247	65	31
30-59	245	66	31	245	66	31
60+	248	65	30	248	65	30
Sawtimber:						
1-29	12	7	5	12	7	5
30-59	81	36	12	8	-34	-56
60+	141	90	65	121	71	46

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact.

Table 14B--Fire-caused changes in net timber output of lodgepole pine stands under intense public management, northern Rocky Mountains, by fire size and time period

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/year[1]									
High (120+):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	-10	-5	0	0	0	-10	-5
Poletimber:										
1-29	-24	8	0	0	-2	-24	8	0	0	-2
30-59	-104	276	-176	0	-22	-104	276	-176	0	-22
60+	-104	260	-190	-10	-33	-104	260	-190	-10	-33
Sawtimber:										
1-29	20	0	0	0	2	20	0	0	0	2
30-59	4	0	0	0	0	4	0	0	0	0
60+	36	-24	-166	-10	-45	0	-24	-166	-10	-49
Moderate (85-119):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	-4	-2	0	0	0	-4	-2
Poletimber:										
1-29	0	16	0	0	2	0	16	0	0	2
30-59	-44	16	0	0	-3	-44	16	0	0	-3
60+	-96	12	90	-4	10	-96	12	90	-4	10
Sawtimber:										
1-29	4	0	0	0	0	4	0	0	0	0
30-59	-12	0	0	0	-1	-12	0	0	0	-1
60+	36	-4	-12	-4	-1	8	-4	-12	-4	-4
Low (50-84):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	120	-12	0	12	0	120	-12	0	12
60+	0	120	-12	0	12	0	120	-12	0	12
Sawtimber:										
1-29	-12	0	0	0	-1	-12	0	0	0	-1
30-59	-20	0	0	0	-2	-20	0	0	0	-2
60+	8	0	0	-6	-2	8	0	0	-6	-2
Very low (20-49):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	0	76	0	0	9	0	76	0	0	9
30-59	0	76	0	0	9	0	76	0	0	9
60+	0	76	0	0	9	0	76	0	0	9
Sawtimber:										
1-29	-4	0	0	0	0	-4	0	0	0	0
30-59	8	0	0	0	1	8	0	0	0	1
60+	8	0	0	0	1	8	0	0	0	1

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact.

Table 15A--Fire-caused changes in net value of Douglas-fir stands under passive private management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7.875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Poletimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Sawtimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Moderate (85-119):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	-22	0	0	-22	0	0
Poletimber:						
1-29	4	2	1	4	2	1
30-59	6	3	2	6	3	2
60+	351	322	259	291	269	209
Sawtimber:						
1-29	53	51	50	-280	-266	-259
30-59	313	302	296	-139	-130	-126
60+	274	362	355	-170	-61	-56
Low (50-84):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	345	120	89	345	120	89
Poletimber:						
1-29	-2	-2	-1	-2	-2	-1
30-59	-3	-3	-3	-3	-3	-3
60+	1066	341	184	1056	331	174
Sawtimber:						
1-29	-6	6	9	-143	-126	-122
30-59	191	196	194	-43	-30	-27
60+	478	301	292	207	39	35
Very low (20-49):						
Seedling/sapling:						
1-29	27	0	0	27	0	0
30-59	27	0	0	27	0	0
60+	425	126	86	425	126	86
Poletimber:						
1-29	81	-1	-2	-10	-88	-87
30-59	1143	163	-45	867	-104	-306
60+	1457	459	245	1061	78	-129
Sawtimber:						
1-29	271	36	30	120	-110	-113
30-59	383	142	134	262	26	20
60+	467	219	209	368	123	115

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact; — = situation not analyzed.

Table 15B--Fire-caused changes in net timber output of Douglas-fir stands under passive private management, northern Rocky Mountains, by fire size and time period

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/year[1]									
High (120+):										
Seedling/sapling:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Poletimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Sawtimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Moderate (85-119):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	-18	-9	0	0	0	-18	-9
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	128	0	-36	-18	-2	128	0	-36	-18	-2
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	-36	-18	-18	0	0	-36	-18	-18
Low (50-84):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	21	10	0	0	0	21	10
Poletimber:										
1-29	-24	0	0	0	-3	-24	0	0	0	-3
30-59	-40	0	0	0	-5	-40	0	0	0	-5
60+	-96	180	0	21	21	-96	180	0	21	21
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	128	21	42	0	0	128	21	42
Very low (20-49):										
Seedling/sapling:										
1-29	0	0	0	39	19	0	0	0	39	19
30-59	0	0	0	39	19	0	0	0	39	19
60+	0	0	0	39	19	0	0	0	39	19
Poletimber:										
1-29	-24	0	0	39	16	-24	0	0	39	16
30-59	-96	184	0	39	30	-96	184	0	39	30
60+	-96	184	0	39	30	-96	184	0	39	30
Sawtimber:										
1-29	0	0	132	39	52	0	0	132	39	52
30-59	0	0	132	39	52	0	0	132	39	52
60+	0	0	132	39	52	0	0	132	39	52

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact; — = situation not analyzed.

Table 16A--Fire-caused changes in net value of ponderosa pine stands under passive private management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7.875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Poletimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Sawtimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Moderate (85-119):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	0	0	0	0	0	0
Poletimber:						
1-29	0	0	0	0	0	0
30-59	543	322	259	413	196	135
60+	468	229	163	417	184	120
Sawtimber:						
1-29	192	185	182	-304	-289	-281
30-59	445	429	421	-150	-140	-135
60+	684	644	629	46	33	33
Low (50-84):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	350	114	78	350	114	78
Poletimber:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	647	157	72	647	157	72
Sawtimber:						
1-29	26	38	39	-114	-98	-94
30-59	130	138	138	-53	-38	-35
60+	283	257	254	48	31	31
Very low (20-49):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	0	0	0	0	0	0
Poletimber:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	C
60+	839	199	88	839	199	88
Sawtimber:						
1-29	38	41	42	-82	-75	-71
30-59	131	141	141	-34	-18	-15
60+	313	269	264	93	57	56

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact; — = situation not analyzed.

Table 16B--Fire-caused changes in net timber output of ponderosa pine stands under passive private management, northern Rocky Mountains, by fire size and time period

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/year[1]									
High (120+):										
Seedling/sapling:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Poletimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Sawtimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-55	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Moderate (85-119):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	128	-92	46	16	0	128	-92	46	16
60+	0	128	-92	46	16	0	128	-92	46	16
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Low (50-84):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	180	-128	0	-9	0	180	-128	0	-9
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Very low (20-49):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	184	-132	0	-10	0	184	-132	0	-10
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact; — = situation not analyzed.

Table 17A--Fire-caused changes in net value of western white pine stands under passive private management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7.875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Poletimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Sawtimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Moderate (85-119):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	437	188	128	437	188	128
Poletimber:						
1-29	62	36	28	62	36	28
30-59	129	76	57	129	76	57
60+	1062	584	428	1040	562	407
Sawtimber:						
1-29	42	40	40	-210	-200	-195
30-59	108	104	102	-127	-120	-116
60+	572	402	389	509	341	329
Low (50-84):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	18	1	0	18	1	0
Poletimber:						
1-29	-23	-17	-15	-68	-61	-58
30-59	-4	5	7	-43	-34	-30
60+	205	155	150	205	155	150
Sawtimber:						
1-29	6	10	12	-160	-150	-145
30-59	80	85	86	-70	-60	-57
60+	587	523	510	530	467	455
Very low (20-49):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	17	1	0	17	1	0
Poletimber:						
1-29	-15	-11	-8	-47	-41	-38
30-59	13	17	19	-14	-10	-8
60+	256	205	199	256	205	199
Sawtimber:						
1-29	23	26	28	-107	-99	-95
30-59	124	124	124	7	12	13
60+	768	697	681	723	654	638

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact; — = situation not analyzed.

Table 17B--Fire-caused changes in net timber output of western white pine stands under passive private management, northern Rocky Mountains, by fire size and time period

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/year[1]									
High (120+):										
Seedling/sapling:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Poletimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Sawtimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Moderate (85-119):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	204	-102	18	9	0	204	-102	18	9
Poletimber:										
1-29	-24	0	0	0	-3	-24	0	0	0	-3
30-59	-44	0	0	0	-5	-44	0	0	0	-5
60+	44	0	36	18	23	44	0	36	18	23
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	36	18	18	0	0	36	18	18
Low (50-84):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	40	-23	-1	0	0	40	-23	-1
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	60	0	40	-23	6	60	0	40	-23	6
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	40	-23	-1	0	0	40	-23	-1
Very low (20-49):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	38	-8	5	0	0	38	-8	5
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	56	0	38	-8	12	56	0	38	-8	12
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	38	-8	5	0	0	38	-8	5

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact; — = situation not analyzed.

Table 18A--Fire-caused changes in net value of fir-spruce stands under passive private management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7.875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Poletimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Sawtimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Moderate (85-119):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	441	122	82	441	122	82
60+	441	122	82	441	122	82
Poletimber:						
1-29	-3	-2	-2	-3	-2	-2
30-59	1	-5	-4	1	-5	-4
60+	1070	258	103	1020	215	64
Sawtimber:						
1-29	13	14	14	-152	-141	-136
30-59	53	25	32	-104	-122	-111
60+	314	256	255	248	197	200
Low (50-84):						
Seedling/sapling:						
1-29	-3	-3	-2	-3	-3	-2
30-59	22	-3	-2	25	0	0
60+	25	0	0	25	0	0
Poletimber:						
1-29	-2	-2	-2	-2	-2	-2
30-59	58	-2	-3	58	-2	-3
60+	1334	455	241	1305	428	214
Sawtimber:						
1-29	80	77	75	12	12	12
30-59	395	123	112	336	67	56
60+	545	263	248	521	240	225
Very low (20-49):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	0	0	0	0	0	0
Poletimber:						
1-29	-3	-3	-3	-3	-3	-3
30-59	-5	-5	-5	-5	-5	-5
60+	1265	470	250	1246	452	233
Sawtimber:						
1-29	46	44	44	-11	-10	-10
30-59	66	64	63	12	13	13
60+	318	304	298	300	287	282

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact; — = situation not analyzed.

Table 18B--Fire-caused changes in net timber output of fir-spruce stands under passive private management, northern Rocky Mountains, by fire size and time period

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/year[1]									
High (120+):										
Seedling/sapling:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Poletimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Sawtimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Moderate (85-119):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	45	22	0	0	0	45	22
60+	0	0	0	45	22	0	0	0	45	22
Poletimber:										
1-29	-28	0	0	0	-3	-28	0	0	0	-3
30-59	-44	0	0	6	-2	-44	0	0	6	-2
60+	-116	236	-78	45	18	-116	236	-78	45	18
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	-78	45	3	0	0	-78	45	3
60+	0	0	-78	45	3	0	0	-78	45	3
Low (50-84):										
Seedling/sapling:										
1-29	-36	0	0	0	-4	-36	0	0	0	-4
30-59	-36	0	0	24	7	0	0	0	24	12
60+	0	0	0	24	12	0	0	0	24	12
Poletimber:										
1-29	-24	0	0	0	-3	-24	0	0	0	-3
30-59	-40	0	0	68	29	-40	0	0	68	29
60+	52	0	0	136	75	52	0	0	136	75
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	180	47	68	0	0	180	47	68
60+	0	0	180	47	68	0	0	180	47	68
Very low (20-49):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	-44	0	0	0	-5	-44	0	0	0	-5
30-59	-72	0	0	0	-9	-72	0	0	0	-9
60+	60	0	0	0	7	60	0	0	0	7
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact; — = situation not analyzed.

Table 19A--Fire-caused changes in net value of hemlock stands under passive private management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7.875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Poletimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Sawtimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Moderate (85-119):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	716	526	369	716	526	369
Poletimber:						
1-29	203	-48	-169	1	-243	-360
30-59	396	139	14	215	-36	-158
60+	1554	1240	1093	1505	1192	1046
Sawtimber:						
1-29	105	102	101	-33	-31	-29
30-59	331	321	315	219	212	209
60+	1084	1031	1011	1058	1006	986
Low (50-84):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	113	3	0	113	3	0
Poletimber:						
1-29	53	51	50	29	28	27
30-59	98	95	93	77	74	73
60+	553	366	354	547	361	348
Sawtimber:						
1-29	87	84	82	50	49	48
30-59	470	454	445	453	437	428
60+	865	667	649	858	660	642
Very low (20-49):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	150	3	0	150	3	0
Poletimber:						
1-29	40	39	38	38	37	36
30-59	64	72	71	63	70	69
60+	369	138	130	367	137	128
Sawtimber:						
1-29	108	104	101	102	99	96
30-59	268	267	263	263	263	259
60+	1086	830	808	1085	829	807

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact; — = situation not analyzed.

Table 19B--Fire-caused changes in net timber output of hemlock stands under passive private management, northern Rocky Mountains, by fire size and time period

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/year[1]									
High (120+):										
Seedling/sapling:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Poletimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Sawtimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Moderate (85-119):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	-140	320	-160	46	5	-140	320	-160	46	5
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Low (50-84):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	84	42	0	0	0	84	42
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	128	21	42	0	0	128	21	42
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	128	21	42	0	0	128	21	42
Very low (20-49):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	104	52	0	0	0	104	52
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	132	39	52	0	0	132	39	52
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	132	39	52	0	0	132	39	52

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact; — = situation not analyzed.

Table 20A--Fire-caused changes in net value of larch stands under passive private management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7.875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Poletimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Sawtimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Moderate (85-119):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	437	207	147	437	207	147
Poletimber:						
1-29	67	39	29	67	39	29
30-59	92	54	40	92	54	40
60+	745	457	329	701	414	287
Sawtimber:						
1-29	49	47	46	-192	-183	-179
30-59	258	260	256	111	120	120
60+	400	357	349	366	324	316
Low (50-84):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	18	1	0	18	1	0
Poletimber:						
1-29	-17	-13	-11	-67	-61	-58
30-59	-13	-6	-3	-60	-51	-48
60+	164	116	111	164	116	111
Sawtimber:						
1-29	30	32	34	-154	-144	-139
30-59	332	327	323	237	235	233
60+	603	539	526	571	508	495
Very low (20-49):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	18	1	0	18	1	0
Poletimber:						
1-29	-17	-13	-11	-38	-46	-44
30-59	-9	-5	-3	-28	-36	-35
60+	164	121	117	171	122	117
Sawtimber:						
1-29	37	39	40	-96	-101	-99
30-59	375	366	360	314	294	288
60+	667	604	590	647	579	565

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact; — = situation not analyzed.

Table 20B--Fire-caused changes in net timber output of larch stands under passive private management, northern Rocky Mountains, by fire size and time period

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/year[1]									
High (120+):										
Seedling/sapling:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Poletimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Sawtimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Moderate (85-119):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	204	-102	0	0	0	204	-102	0	0
Poletimber:										
1-29	-28	0	0	0	-3	-28	0	0	0	-3
30-59	-36	0	0	0	-4	-36	0	0	0	-4
60+	44	0	0	0	5	44	0	0	0	5
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Low (50-84):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	40	-23	-1	0	0	40	-23	-1
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	60	0	40	-23	6	60	0	40	-23	6
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	40	-23	-1	0	0	40	-23	-1
Very low (20-49):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	38	-8	5	0	0	38	-8	5
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	56	0	38	-8	12	56	0	38	-8	12
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	38	-8	5	0	0	38	-8	5

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact; -- = situation not analyzed.

Table 21A--Fire-caused changes in net value of lodgepole pine stands under passive private management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7.875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Poletimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Sawtimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Moderate (85-119):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	144	116	103	144	116	103
Poletimber:						
1-29	18	12	9	18	12	9
30-59	34	21	16	34	21	16
60+	175	151	123	175	151	123
Sawtimber:						
1-29	40	38	37	-158	-152	-149
30-59	64	62	61	-120	-116	-113
60+	322	310	305	282	272	267
Low (50-84):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	121	92	88	121	92	88
Poletimber:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	157	28	10	157	28	10
Sawtimber:						
1-29	-1	-1	-1	-1	-1	-1
30-59	-2	-2	-2	-2	-2	-2
60+	193	71	31	169	48	8
Very low (20-49):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	0	0	0	0	0	0
Poletimber:						
1-29	0	0	0	0	0	0
30-59	122	22	8	122	22	8
60+	125	22	8	125	22	8
Sawtimber:						
1-29	-1	-1	-1	-1	-1	-1
30-59	91	4	-25	29	-57	-84
60+	152	60	30	135	44	14

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact; -- = situation not analyzed.

Table 21B--Fire-caused changes in net timber output of lodgepole pine stands under passive private management, northern Rocky Mountains, by fire size and time period

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/year[1]									
High (120+):										
Seedling/sapling:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Poletimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Sawtimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Moderate (85-119):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	124	-62	0	0	0	124	-62	0	0
Poletimber:										
1-29	4	0	0	0	0	4	0	0	0	0
30-59	12	0	0	0	1	12	0	0	0	1
60+	96	0	0	0	12	96	0	0	0	12
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	.0	0	0	0	0	0	0	0	0	0
Low (50-84):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	52	0	13	0	0	52	0	13
Sawtimber:										
1-29	-16	0	0	0	-2	-16	0	0	0	-2
30-59	-28	0	0	0	-3	-28	0	0	0	-3
60+	12	0	0	0	1	12	0	0	0	1
Very low (20-49):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	32	0	8	0	0	32	0	8
60+	0	0	32	0	8	0	0	32	0	8
Sawtimber:										
1-29	-8	0	0	0	-1	-8	0	0	0	-1
30-59	12	0	0	0	1	12	0	0	0	1
60+	12	0	0	0	1	12	0	0	0	1

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact; -- = situation not analyzed.

Table 22A--Fire-caused changes in net value of Douglas-fir stands under intense private management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7.875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	516	355	267	516	355	267
Poletimber:						
1-29	430	320	243	-219	-297	-357
30-59	527	442	368	-71	-128	-188
60+	1583	1404	1302	465	337	261
Sawtimber:						
1-29	108	104	102	-421	-397	-385
30-59	611	618	612	-164	-123	-112
60+	944	882	860	85	65	64
Moderate (85-119):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	350	161	121	350	161	121
Poletimber:						
1-29	6	3	2	6	3	2
30-59	10	5	3	10	5	3
60+	787	491	369	731	444	326
Sawtimber:						
1-29	51	50	49	-223	-209	-203
30-59	302	291	286	-87	-79	-74
60+	445	408	396	17	4	5
Low (50-84):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	455	156	105	455	156	105
60+	465	157	105	465	157	105
Poletimber:						
1-29	-2	-2	-2	-103	-99	-97
30-59	-4	-4	-3	-185	-179	-175
60+	1303	553	347	830	104	-91
Sawtimber:						
1-29	29	41	42	-129	-110	-106
30-59	203	208	207	-41	-25	-22
60+	433	269	254	163	15	8
Very low (20-49):						
Seedling/sapling:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Poletimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Sawtimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact; -- = situation not analyzed.

Table 22B--Fire-caused changes in net timber output of Douglas-fir stands under intense private management, northern Rocky Mountains, by fire size and time period

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/year[1]									
High (120+):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	12	-12	124	-61	0	12	-12	124	-61	0
Poletimber:										
1-29	16	0	0	0	2	-192	0	0	0	-24
30-59	16	0	0	0	2	16	0	0	0	2
60+	16	0	0	0	2	16	0	0	0	2
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Moderate (85-119):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	168	-84	1	0	0	168	-84	1	0
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	144	0	0	0	18	144	0	0	0	18
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Low (50-84):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	19	9	0	0	0	19	9
Poletimber:										
1-29	-28	0	0	0	-3	-28	0	0	0	-3
30-59	-48	0	0	0	-6	-48	0	0	0	-6
60+	84	0	-78	76	29	84	0	-78	76	29
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	38	19	19	0	0	38	19	19
Very low (20-49):										
Seedling/sapling:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Poletimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Sawtimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact; -- = situation not analyzed.

Table 23A--Fire-caused changes in net value of ponderosa pine stands under intense private management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7.875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	592	398	292	592	398	292
Poletimber:						
1-29	64	44	36	-56	-72	-77
30-59	63	43	35	-113	-126	-131
60+	1202	666	438	568	65	-148
Sawtimber:						
1-29	308	297	291	-387	-366	-355
30-59	690	691	683	-162	-124	-114
60+	1239	1169	1142	203	179	175
Moderate (85-119):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	331	151	108	331	151	108
Poletimber:						
1-29	690	301	200	640	256	158
30-59	690	301	200	640	256	158
60+	700	290	185	652	250	149
Sawtimber:						
1-29	192	185	182	-227	-214	-207
30-59	445	429	421	-72	-65	-61
60+	767	720	703	131	115	113
Low (50-84):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	480	155	97	480	155	97
60+	478	155	97	478	155	97
Poletimber:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	941	292	160	915	272	142
Sawtimber:						
1-29	72	82	82	-99	-82	-78
30-59	177	183	181	-37	-22	-19
60+	327	269	262	67	24	23
Very low (20-49):						
Seedling/sapling:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Poletimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Sawtimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact; -- = situation not analyzed.

Table 23B--Fire-caused changes in net timber output of ponderosa pine stands under intense private management, northern Rocky Mountains, by fire size and time period

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/year[1]									
High (120+):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	12	-12	124	-61	0	12	-12	124	-61	0
Poletimber:										
1-29	-20	0	0	0	-2	-20	0	0	0	-2
30-59	-32	0	0	0	-4	-32	0	0	0	-4
60+	88	-12	6	0	11	88	-12	6	0	11
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Moderate (85-119):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	168	-84	1	0	0	168	-84	1	0
Poletimber:										
1-29	0	144	-86	43	18	0	144	-86	43	18
30-59	0	144	-86	43	18	0	144	86	43	18
60+	0	144	-86	43	18	0	144	-86	43	18
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Low (50-84):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	196	-116	0	-4	0	196	-116	0	-4
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Very low (20-49):										
Seedling/sapling:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Poletimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Sawtimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact; -- = situation not analyzed.

Table 24A--Fire-caused changes in net value of western white pine stands under intense private management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7.875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	785	617	488	785	617	488
30-59	785	617	488	785	617	488
60+	1657	834	548	1569	760	479
Poletimber:						
1-29	234	226	223	-299	-281	-273
30-59	491	474	465	20	26	30
60+	2132	1919	1859	2020	1821	1766
Sawtimber:						
1-29	66	64	63	-287	-270	-261
30-59	177	171	168	-148	-136	-130
60+	1008	836	796	848	691	658
Moderate (85-119):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	441	229	159	441	229	159
Poletimber:						
1-29	149	107	89	149	107	89
30-59	818	525	378	692	403	259
60+	1486	1002	825	1419	946	774
Sawtimber:						
1-29	34	33	33	-118	-114	-112
30-59	89	85	84	-49	-47	-47
60+	675	485	454	580	401	376
Low (50-84):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	322	127	87	322	127	87
Poletimber:						
1-29	5	2	1	5	2	1
30-59	590	288	173	528	231	118
60+	643	402	281	613	378	260
Sawtimber:						
1-29	50	48	47	-116	-112	-110
30-59	196	187	181	20	20	18
60+	574	615	597	494	543	528
Very low (20-49):						
Seedling/sapling:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Poletimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Sawtimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact; -- = situation not analyzed.

Table 24B--Fire-caused changes in net timber output of western white pine stands under intense private management, northern Rocky Mountains, by fire size and time period

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/year[1]									
High (120+):										
Seedling/sapling:										
1-29	52	-52	114	0	28	52	-52	114	0	28
30-59	52	-52	114	0	28	52	-52	114	0	28
60+	-104	204	0	6	15	-104	204	0	6	15
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Moderate (85-119):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	4	172	-86	46	23	4	172	-86	46	23
Poletimber:										
1-29	-12	0	0	0	-1	-12	0	0	0	-1
30-59	28	-4	2	0	3	28	-4	2	0	3
60+	28	0	4	2	5	28	0	4	2	5
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	4	2	2	2	0	4	2	2	2
Low (50-84):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	156	-78	-19	-9	0	156	-78	-19	-9
Poletimber:										
1-29	-16	0	0	0	-2	-16	0	0	0	-2
30-59	56	0	-78	39	7	56	0	-78	39	7
60+	56	0	-116	20	-12	56	0	-116	20	-12
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	-38	-19	-19	0	0	-38	-19	-19
Very low (20-49):										
Seedling/sapling:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Poletimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Sawtimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact; -- = situation not analyzed.

Table 25A--Fire-caused changes in net value of fir-spruce stands under intense private management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7.875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	458	334	247	458	334	247
30-59	458	334	247	458	334	247
60+	450	327	240	450	327	240
Poletimber:						
1-29	192	143	122	192	143	122
30-59	324	241	205	324	241	205
60+	1337	1054	899	1255	982	832
Sawtimber:						
1-29	90	87	86	-191	-180	-175
30-59	275	265	260	52	54	55
60+	663	586	567	548	483	469
Moderate (85-119):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	593	164	100	593	164	100
60+	593	164	100	593	164	100
Poletimber:						
1-29	-3	-3	-3	-3	-3	-3
30-59	-6	-5	-5	-6	-5	-5
60+	1362	417	198	1302	364	148
Sawtimber:						
1-29	50	48	47	-113	-106	-102
30-59	69	76	77	-88	-72	-68
60+	344	322	314	276	260	256
Low (50-84):						
Seedling/aapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	458	276	179	458	276	179
Poletimber:						
1-29	116	71	54	116	71	54
30-59	196	120	91	196	120	91
60+	1348	844	629	1301	801	588
Sawtimber:						
1-29	80	77	75	-2	1	2
30-59	108	116	115	36	48	49
60+	267	247	241	229	213	209
Very low (20-49):						
Seedling/aapling:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Poletimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Sawtimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--

[1] Negative (-) values = gains; positive values = losses; 0 = no net fire impact; — = situation not analyzed.

Table 25B--Fire-caused changes in net timber output of fir-spruce stands under intense private management, northern Rocky Mountains, by fire size and time period

Stand productivity (cu ft/acre/yr), stand size, and mortality clasa (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/year[1]									
High (120+):										
Seedling/sapling:										
1-29	12	-12	124	-61	0	12	-12	124	-61	0
30-59	12	-12	124	-61	0	12	-12	124	-61	0
60+	-92	-12	124	-61	-13	-92	-12	124	-61	-13
Poletimber:										
1-29	-12	0	0	0	-1	-12	0	0	0	-1
30-59	-24	0	0	0	-3	-24	0	0	0	-3
60+	32	-12	6	0	4	32	-12	6	0	4
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Moderate (85-119):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	-32	0	0	0	-4	-32	0	0	0	-4
30-59	-56	0	0	0	-7	-56	0	0	0	-7
60+	-140	268	-86	43	16	-140	268	-86	43	16
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Low (50-84):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	-104	332	-166	0	-13	-104	332	-166	0	-13
Poletimber:										
1-29	-36	0	0	0	-4	-36	0	0	0	-4
30-59	-64	0	0	0	-8	-64	0	0	0	-8
60+	36	0	0	0	4	36	0	0	0	4
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Very low (20-49):										
Seedling/sapling:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Poletimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Sawtimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--

[1] Negative (-) values = gains; positive values = losses; 0 = no net fire impact; — = situation not analyzed.

Table 26A--Fire-caused changes in net value of hemlock stands under intense private management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7.875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	921	1062	974	921	1062	974
30-59	913	1054	966	913	1054	966
60+	1620	1224	959	1548	1160	899
Poletimber:						
1-29	283	273	267	-57	-51	-48
30-59	528	509	499	221	217	214
60+	1766	1881	1863	1658	1782	1769
Sawtimber:						
1-29	149	144	141	-55	-49	-47
30-59	812	783	768	214	210	208
60+	939	1084	1081	173	350	364
Moderate (85-119):						
Seedling/aapling:						
1-29	824	768	591	824	768	591
30-59	817	761	584	817	761	584
60+	1926	927	591	1891	897	562
Poletimber:						
1-29	273	263	258	14	16	17
30-59	506	498	490	273	275	272
60+	1823	1857	1827	1746	1785	1758
Sawtimber:						
1-29	143	138	135	-14	-11	-9
30-59	366	363	357	235	238	236
60+	1011	1073	1059	966	1034	1021
Low (50-84):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	344	186	133	344	186	133
Poletimber:						
1-29	78	54	44	78	54	44
30-59	146	101	82	146	101	82
60+	737	458	363	724	447	353
Sawtimber:						
1-29	87	84	82	44	43	43
30-59	463	458	450	439	436	429
60+	810	661	643	797	649	633
Very low (20-49):						
Seedling/sapling:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Poletimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Sawtimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--

[1] Negative (-) values = gains; positive values = losses; 0 = no net fire impact; — = situation not analyzed.

Table 26B--Fire-caused changes in net timber output of hemlock stands unoer intense private management, northern Rocky Mountains, by fire size and time perioc

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/year[1]									
High (120+):										
Seedling/sapling:										
1-29	212	-312	0	0	-12	212	-312	0	0	-12
30-59	136	-312	0	0	-22	136	-312	0	0	-22
60+	52	-24	-22	-5	-4	52	-24	-22	-5	-4
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	-12	-28	-5	-11	0	-12	-28	-5	-11
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	-12	-28	-5	-11	0	-12	-28	-5	-11
Moderate (85-119):										
Seedling/sapling:										
1-29	320	-320	2	41	21	320	-320	2	41	21
30-59	232	-320	2	41	10	232	-320	2	41	10
60+	168	-4	-86	40	19	168	-4	-86	40	19
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	-4	-2	-2	-2	0	-4	-2	-2	-2
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	-4	-2	-2	-2	0	-4	-2	-2	-2
Low (50-84):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	136	-68	19	9	0	136	-68	19	9
Poletimber:										
1-29	-8	0	0	0	-1	-8	0	0	0	-1
30-59	-20	0	0	0	-2	-20	0	0	0	-2
60+	20	0	38	19	21	20	0	38	19	21
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	38	19	19	0	0	38	19	19
Very low (20-49):										
Seedling/sapling:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Poletimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Sawtimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--

[1] Negative (-) values = gains; positive values = losses; 0 = no net fire impact; — = npact; situation not analyzed.

INTRODUCTION

In the last decade, the fire management program of the Forest Service, U.S. Department of Agriculture, has come under closer scrutiny because of ever-rising program costs. The Forest Service has responded by conducting several studies analyzing the economic efficiency of its fire management program. Some components of the analytical models have been difficult to develop, particularly changes in the net value and output of timber caused by wildfire.

The timber net value change calculation can be complex because of the long timber production time and the substantial impact of the management context on the timing of management costs and harvests. The timber computation is critical, because the change in the timber resource accounts for a large share of the total net value change due to fire: nationwide, 60 percent on National Forest land and 75 percent on State protected lands (U.S. Dep. Agric., Forest Serv. 1980, 1982).

Numerous approaches have been proposed for estimating timber net value change (Flint 1924, Lindenmuth and others 1951, Mactavish 1966, Marty and Barney 1981, Van Wagner 1983). The computations vary substantially in how they reflect fire-caused changes in both the magnitude and timing of the management costs and harvests, and in how certain conceptual issues, such as the substitution of unburned for burned timber, are addressed. For example, a relatively simple formulation of the timber net value change calculation ignores price differentials between green and salvaged timber, and the possibility for retention and future harvest of partially destroyed immature timber stands (Schweitzer and others 1982). On the other hand, one of the more complete formulations includes harvest timing differentials in immature stands, salvage and green price differentials, and adjustments in the management costs required if the fire removes a natural seed source (Mactavish 1966).

Although these past studies include ample discussion of methodology, the estimates of timber net value change they contain are only illustrative and too few to demonstrate how the net value change behaves under a wide range of circumstances. Therefore, we calculated change in timber net value and in timber output due to wildfire for a broad range of specific fire and management situations.

This paper summarizes trends in estimates of timber net value changes and timber output changes due to wildfire for 1764 roaded situations in the northern Rocky Mountains. Actual values are listed in extensive reference tables and have four potential uses (Mills 1983): (1) analyses of long-term fire management program options, such as those in the National Fire Management Analysis and Planning Handbook (U.S. Dep. Agric., Forest Serv. 1982) or the Fire Economics Evaluation System (Mills and Bratten 1982); (2) establishment of fire dispatching priorities; (3) analysis of escaped fire situations where extensive calculations are often difficult to accomplish because of the real-time demands of the decision process (U.S. Dep. Agric., Forest Serv. 1981; Seaver and others 1983); and (4) analysis of long-term harvest schedules when fire-caused changes in timber yields are required.

METHODS

Calculating Net Value Change

Net value change is the difference between the present net value of resource outputs and management costs "without fire" and the present net value "with fire":

$$NVC = PNV_{w/o} - PNV_{w}$$

in which

NVC = net value change

$PNV_{w/o}$ = present net value without fire

PNV_{w} = present net value with fire

According to this definition, a fire that produces a net gain in present value has a negative NVC and one that produces a loss of value has a positive NVC.

Because the NVC is a present value calculation, any change in the magnitude or timing of the management costs, the harvests, or the stumpage prices affects the NVC. Analysis of the sensitivity of NVC to the completeness with which the fire-caused impacts on these quantities were represented in computations for 24 timber cases in the northern Rocky Mountains, showed that a fairly complete representation of the fire-caused change was necessary to avoid major errors in the estimate (Mills and Flowers 1983).

The computational model used in the present study contains three types of terms: (1) the existing rotation costs and harvest values, (2) the regenerated rotation costs and harvest values, and (3) one-time costs or revenues created by fire, such as salvage values. The generalized form of the computation was

$$PNV_{wo} = \text{PNV of infinite series final harvests in regenerated stand} - \text{PNV of infinite series management costs in regenerated stand} + \text{PNV of harvests in existing stand} - \text{PNV of management costs in existing stand}$$

$$PNV_{w} = \text{PNV of infinite series final harvests in regenerated stands following fire} - \text{PNV of infinite series management costs in regenerated stands following fire} + \text{PNV of timber salvaged following fire} - \text{PNV of management cost in existing stand} + \text{PNV of residual timber remaining after fire} - \text{PNV of any single rotation difference in management costs following fire}$$

Not all terms are included in every fire case. For example, the one-time change in regenerated rotation management costs, (such as the removal of a scheduled site preparation because the fire essentially accomplished the site preparation, or the inclusion of a planting rather than a natural regeneration because the fire removed the seed source) only enter the computation if the stand size, stocking, fire size, and tree mortality are of certain levels. Similarly, the salvage transaction enters the computation only under certain conditions of stand size, volume per acre, and fire size. The first two terms make the with- and without-fire cash flows comparable despite dissimilar rotation lengths or unmatched sequencing of without- and with-fire rotations.

A major assumption imbedded in our net value change computation concerns the geographic area from which the fire-induced change in the resource output is measured. Two options exist: measuring the effect on only the fire site plus direct physical and biological effects offsite (Althaus and Mills 1982); or measuring the effects on the entire management area or market area in which the fire occurs (Van Wagner 1983). Our analysis measured the fire-induced changes on the fire site only because the fire site analysis most closely reflects the impact of fire on the basic productivity of the timber growing site, relatively unencumbered by management constraints.

Timber net value change was estimated at three discount rates: 4.0, 7.875, and 10.0 percent. The 4.0 percent rate was an approximation of the real return on investments in the private sector (Row and others 1981), and is being used by the Forest Service in land management planning; 7.875 percent was the 1983 discount rate for Federal water project evaluations (U.S. Dep. Agric., Soil Conservation Serv. 1982); and 10 percent was the rate recommended by the U.S. Office of Management and Budget (1972) as the real rate of return on investments in the private sector.

In addition to the timber net value change, we calculated the timber output change for the first 200 years following fire. Timber output change is the difference between the scheduled timber yield without fire and with fire.

Scope of Analysis

The analysis was structured to evaluate situation-specific cases defined by a combination of values for the following parameters that characterize the fire site, the timber management context in which the fire occurs, and the fire severity: access, slope, management emphasis, cover type, productivity, stand size, fire size, and mortality. After removing parameter combinations not generally found in the northern Rocky Mountains, such as passive private management on high productivity sites, we estimated net value change for 9828 separate situations.

This situation-specific approach, rather than a site-specific analysis, was followed because of the required model complexity and its associated data demands. Errors that will result from extrapolation of these situation-specific estimates to particular sites is expected to be far less than the errors that would result from incomplete model specification or poor data input that would likely occur if the computations were for site-specific conditions with limited analysis resources.

Sources of Data

Four categories of data were required: timber management regimes, timber yields, silviculture treatment costs, and stumpage prices. Most of the data were derived from National Forest sources in the Forest Service's Northern Region (northern Idaho and Montana). The data were developed to follow as closely as possible the input used in land management planning, thereby increasing the applicability of the results to long-term planning on National Forest lands.

Four sets of timber management regimes were developed from selected land management plans in the Northern Region and on recommendation from the Regional silvicultural staff (Wulf 1982): one each for "moderate intensity public," "intense public," "passive private," and "intense private" timber management. The regimes differ in the form of stand establishment, the number of commercial and precommercial thinning entries, rotation age, and the acreage of the without-fire harvest area. Sample data for fire situations in Douglas-fir are in *table 1*.

The moderate intensity public regime reflects a generally nontimber resource objective but where limited commercial timber harvesting still occurs. Rotations are generally extended beyond the culmination of mean annual increment. There are no precommercial thinnings and only one commercial thinning, if one is commercially viable. In the intense public regime, commercial timber harvesting is the primary objective, but here too, the multiple-use management philosophy affects the regime. The rotation approximates or precedes the culmination of mean annual increment. There is a

Table 27A--Fire-caused changes in net value of larch stands under intense private management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7 875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	611	551	450	611	551	450
30-59	602	542	442	602	542	442
60+	599	539	439	599	539	439
Poletimber:						
1-29	219	211	207	-368	-346	-335
30-59	302	292	286	-255	-237	-228
60+	1362	1244	1209	1177	1080	1052
Sawtimber:						
1-29	85	82	81	-306	-286	-276
30-59	475	458	449	-113	-100	-94
60+	816	718	692	138	78	70
Moderate (85-119):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	380	233	170	380	233	170
Poletimber:						
1-29	159	113	95	159	113	95
30-59	219	156	130	219	156	130
60+	1010	756	628	909	667	545
Sawtimber:						
1-29	40	39	38	-179	-167	-161
30-59	222	214	210	82	84	85
60+	366	324	313	285	254	248
Low (50-84):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	0	0	0	0	0	0
Poletimber:						
1-29	5	2	1	5	2	1
30-59	8	3	2	8	3	2
60+	702	388	270	658	352	237
Sawtimber:						
1-29	67	65	63	-116	-112	-110
30-59	369	361	355	274	270	265
60+	685	633	613	623	580	563
Very low (20-49):						
Seedling/sapling:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Poletimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Sawtimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact; — = situation not analyzed.

Table 27B--Fire-caused changes in net timber output of larch stands under intense private management, northern Rocky Mountains, by fire size and time period

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/year[1]									
High (120+):										
Seedling/sapling:										
1-29	52	-52	114	0	28	52	-52	114	0	28
30-59	-56	-52	114	13	21	-56	-52	114	13	21
60+	-92	-52	114	13	17	-92	-52	114	13	17
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Moderate (85-119):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	4	172	-88	0	0	4	172	-88	0	0
Poletimber:										
1-29	-16	0	0	0	-2	-16	0	0	0	-2
30-59	-20	0	0	0	-2	-20	0	0	0	-2
60+	28	-4	2	0	3	28	-4	2	0	3
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Low (50-84):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	-24	0	0	0	-3	-24	0	0	0	-3
30-59	-32	0	0	0	-4	-32	0	0	0	-4
60+	56	0	-78	39	7	56	0	-78	39	7
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Very low (20-49):										
Seedling/sapling:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Poletimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Sawtimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact; — = situation not analyzed.

Table 28A--Fire-caused changes in net value of lodgepole pine stands under intense private management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7.875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	155	139	117	155	139	117
Poletimber:						
1-29	37	22	17	37	22	17
30-59	302	317	255	151	178	121
60+	77	378	351	-10	299	276
Sawtimber:						
1-29	64	61	60	-286	-269	-261
30-59	102	99	97	-228	-213	-206
60+	174	446	474	50	331	363
Moderate (85-119):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	180	136	114	180	136	114
Poletimber:						
1-29	36	22	17	36	22	17
30-59	64	39	30	64	39	30
60+	397	290	225	375	269	204
Sawtimber:						
1-29	40	38	37	-158	-152	-149
30-59	64	62	61	-120	-116	-113
60+	322	310	305	282	272	267
Low (50-84):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	152	104	94	152	104	94
Poletimber:						
1-29	0	0	0	0	0	0
30-59	176	99	66	176	99	66
60+	173	99	67	173	99	67
Sawtimber:						
1-29	23	22	22	-100	-96	-94
30-59	37	35	35	-77	-75	-73
60+	180	177	174	156	153	151
Very low (20-49):						
Seedling/sapling:						
1-29	--	--	--	-	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Poletimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Sawtimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact; — = situation not analyzed.

Table 28B--Fire-caused changes in net timber output of lodgepole pine stands under intense private management, northern Rocky Mountains, by fire size and time period

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/year[1]									
High (120+):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	212	-112	-19	-11	0	212	-112	-19	-11
Poletimber:										
1-29	-16	0	0	0	-2	-16	0	0	0	-2
30-59	64	-12	6	0	8	64	-12	6	0	8
60+	64	-24	-22	-5	-3	64	-24	-22	-5	-3
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	-12	-28	-5	-11	0	-12	-28	-5	-11
Moderate (85-119):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	168	-84	0	0	0	168	-84	0	0
Poletimber:										
1-29	8	0	0	0	1	8	0	0	0	1
30-59	-28	0	0	0	-3	-28	0	0	0	-3
60+	36	0	0	0	4	36	0	0	0	4
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Low (50-84):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	26	13	0	0	0	26	13
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	84	0	0	0	10	84	0	0	0	10
60+	84	0	0	0	10	84	0	0	0	10
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Very low (20-49):										
Seedling/sapling:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	-	--	--	--	-
60+	--	--	--	--	--	--	--	--	--	--
Poletimber:										
1-29	--	--	--	--	--	--	-	--	--	--
30-59	--	--	--	--	--	--	-	--	--	--
60+	--	--	--	--	--	--	-	--	--	--
Sawtimber:										
1-29	--	--	--	--	--	-	-	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	-	--	--	--	--	--	--	--	-

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact; — = situation not analyzed.

Table 29—*Factors for adjusting roaded net value change estimates to unroaded estimates when roaded value is negative*

Management emphasis, stand size, mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)			Discount rate (pct)		
	4.0	7.875	10.0	4.0	7.875	10.0
Moderate public						
Seedling/sapling						
1-29		—	—	—	—	—
30-59	—	—	—	—	—	—
60+	—	—	—	—	—	—
Poletimber						
1-29	0	0	0	0	0	0
30-59	0	0.86	0.90	0.28	0.55	0.58
60+	1.00	1.00	.99	1.00	1.00	1.00
Sawtimber						
1-29	94	.95	95	.77	.78	.79
30-59	.92	.84	.87	.49	.63	.67
60+	—	1.00	1.00	.42	.62	67
Intense public						
Seedling/sapling						
1-29	1.00	1.00	1.00	1.00	1.00	1.00
30-59	1.00	1.00	1.00	1.00	1.00	1.00
60+	1.00	1.00	1.00	1.00	1.00	1.00
Poletimber						
1-29	.30	.94	.94	.63	.79	.80
30-59	0	.88	.91	.24	.73	.77
60+	—	1.00	1.00	—	50	.71
Sawtimber						
1-29	.95	.92	.94	.79	.85	.87
30-59	0	.63	.79	.51	.48	.54
60+	—	1.00	1.00	1.00	.38	.50
Passive private						
Seedling/sapling						
1-29	0	0	0	0	0	0
30-59	—	0	0	.95	—	
60+	1.00	—		1.00	—	—
Poletimber						
1-29	.88	.92	.96	.96	.98	.86
30-59	.75	.49	.78	—	.93	.70
60+						
Sawtimber						
1-29	73	0	0	.89	.86	.86
30-59	0	0	.93	.99	1.00	1.00
60+						
Intense private						
Seedling/sapling						
1-29						
30-59						
60+						
Poletimber						
1-29	0	0	0	.90	.91	.91
30-59	0	0	0	.63	.67	.70
60+						
Sawtimber						
1-29	—			.89	.88	.88
30-59		—	—	1.00	1.00	1.00
60+	—	—	—	—	—	—

Table 30—*Factors for adjusting roaded net value change estimates to unroaded estimates when roaded value is positive*

Management emphasis, stand size, mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)			Discount rate (pct)		
	4.0	7.875	10.0	4.0	7.875	10.0
Moderate public						
Seedling/sapling						
1-29	1.00	1.00	0	1.00	1.00	0
30-59	1.02	1.03	1.04	1.02	1.03	1.04
60+	1.03	1.05	1.06	1.03	1.06	1.02
Poletimber						
1-29	1.01	1.03	1.03	1.07	1.02	1.03
30-59	1.02	1.03	1.05	1.02	1.03	1.05
60+	1.10	1.28	1.38	1.18	1.61	1.60
Sawtimber						
1-29	1.04	1.06	1.06	1.04	1.07	1.05
30-59	1.00	1.01	1.01	1.01	1.03	1.04
60+	1.17	1.41	1.55	1.43	1.52	1.91
Intense public						
Seedling/sapling						
1-29	1.00	1.01	1.01	1.00	1.01	1.01
30-59	1.01	1.02	1.03	1.01	1.02	1.03
60+	1.05	1.14	1.17	1.06	1.18	1.11
Poletimber						
1-29	1.01	1.03	1.04	1.16	1.14	1.05
30-59	1.01	1.03	1.04	1.04	1.04	1.06
60+	1.06	1.30	1.36	1.20	1.52	2.03
Sawtimber						
1-29	1.04	1.02	1.03	1.03	1.05	1.06
30-59	1.02	1.00	1.00	1.38	1.90	2.28
60+	1.16	1.25	1.32	1.44	1.60	1.66
Passive private						
Seedling/sapling						
1-29	1.00	1.00	0	1.00	1.00	0
30-59	1.05	1.00	1.00	1.05	1.00	1.00
60+	1.01	1.01	1.01	1.01	1.01	1.01
Poletimber						
1-29	1.01	1.03	1.03	1.03	1.04	1.04
30-59	1.03	1.01	1.01	1.12	1.02	1.02
60+	1.04	1.08	1.11	1.08	1.18	1.14
Sawtimber						
1-29	1.05	1.06	1.06	1.31	1.00	1.00
30-59	1.04	1.05	1.05	1.11	1.14	1.14
60+	1.18	1.22	1.23	1.41	1.52	1.53
Intense private						
Seedling/sapling						
1-29	1.00	1.00	1.00	1.00	1.00	1.00
30-59	1.01	1.01	1.01	1.01	1.01	1.01
60+	1.04	1.08	1.11	1.04	1.09	1.13
Poletimber						
1-29	1.01	1.01	1.01	1.01	1.02	1.03
30-59	1.00	1.01	1.01	1.01	1.01	1.01
60+	1.05	1.07	1.08	1.17	1.24	1.21
Sawtimber						
1-29	1.00	1.00	1.00	1.00	1.00	1.00
30-59	1.00	1.00	1.00	1.36	1.34	1.34
60+	1.10	1.12	1.12	1.82	1.86	1.86

Table 27A--Fire-caused changes in net value of larch stands under intense private management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7.875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	611	551	450	611	551	450
30-59	602	542	442	602	542	442
60+	599	539	439	599	539	439
Poletimber:						
1-29	219	211	207	-368	-346	-335
30-59	302	292	286	-255	-237	-228
60+	1362	1244	1209	1177	1080	1052
Sawtimber:						
1-29	85	82	81	-306	-286	-276
30-59	475	458	449	-113	-100	-94
60+	816	718	692	138	78	70
Moderate (85-119):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	380	233	170	380	233	170
Poletimber:						
1-29	159	113	95	159	113	95
30-59	219	156	130	219	156	130
60+	1010	756	628	909	667	545
Sawtimber:						
1-29	40	39	38	-179	-167	-161
30-59	222	214	210	82	84	85
60+	366	324	313	285	254	248
Low (50-84):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	0	0	0	0	0	0
Poletimber:						
1-29	5	2	1	5	2	1
30-59	8	3	2	8	3	2
60+	702	388	270	658	352	237
Sawtimber:						
1-29	67	65	63	-116	-112	-110
30-59	369	361	355	274	270	265
60+	685	633	613	623	580	563
Very low (20-49):						
Seedling/sapling:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Poletimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Sawtimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact; — = situation not analyzed.

Table 27B--Fire-caused changes in net timber output of larch stands under intense private management, northern Rocky Mountains, by fire size and time period

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/year[1]									
High (120+):										
Seedling/sapling:										
1-29	52	-52	114	0	28	52	-52	114	0	28
30-59	-56	-52	114	13	21	-56	-52	114	13	21
60+	-92	-52	114	13	17	-92	-52	114	13	17
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Moderate (85-119):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	4	172	-88	0	0	4	172	-88	0	0
Poletimber:										
1-29	-16	0	0	0	-2	-16	0	0	0	-2
30-59	-20	0	0	0	-2	-20	0	0	0	-2
60+	28	-4	2	0	3	28	-4	2	0	3
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Low (50-84):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Poletimber:										
1-29	-24	0	0	0	-3	-24	0	0	0	-3
30-59	-32	0	0	0	-4	-32	0	0	0	-4
60+	56	0	-78	39	7	56	0	-78	39	7
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Very low (20-49):										
Seedling/sapling:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Poletimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Sawtimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact; — = situation not analyzed.

Table 28A--Fire-caused changes in net value of lodgepole pine stands under intense private management, northern Rocky Mountains, by fire size and discount rate

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)					
	4.0	7.875	10.0	4.0	7.875	10.0
	1978 dollars/acre burned[1]					
High (120+):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	155	139	117	155	139	117
Poletimber:						
1-29	37	22	17	37	22	17
30-59	302	317	255	151	178	121
60+	77	378	351	-10	299	276
Sawtimber:						
1-29	64	61	60	-286	-269	-261
30-59	102	99	97	-228	-213	-206
60+	174	446	474	50	331	363
Moderate (85-119):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	180	136	114	180	136	114
Poletimber:						
1-29	36	22	17	36	22	17
30-59	64	39	30	64	39	30
60+	397	290	225	375	269	204
Sawtimber:						
1-29	40	38	37	-158	-152	-149
30-59	64	62	61	-120	-116	-113
60+	322	310	305	282	272	267
Low (50-84):						
Seedling/sapling:						
1-29	0	0	0	0	0	0
30-59	0	0	0	0	0	0
60+	152	104	94	152	104	94
Poletimber:						
1-29	0	0	0	0	0	0
30-59	176	99	66	176	99	66
60+	173	99	67	173	99	67
Sawtimber:						
1-29	23	22	22	-100	-96	-94
30-59	37	35	35	-77	-75	-73
60+	180	177	174	156	153	151
Very low (20-49):						
Seedling/sapling:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Poletimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--
Sawtimber:						
1-29	--	--	--	--	--	--
30-59	--	--	--	--	--	--
60+	--	--	--	--	--	--

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact; — = situation not analyzed.

Table 28B--Fire-caused changes in net timber output of lodgepole pine stands under intense private management, northern Rocky Mountains, by fire size and time period

Stand productivity (cu ft/acre/yr), stand size, and mortality class (pct)	Fire size: 1-99 acres					Fire size: 100+ acres				
	Time period (years)									
	0-24	25-49	50-99	100-200	0-200	0-24	25-49	50-99	100-200	0-200
	Cu ft/acre/year[1]									
High (120+):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	212	-112	-19	-11	0	212	-112	-19	-11
Poletimber:										
1-29	-16	0	0	0	-2	-16	0	0	0	-2
30-59	64	-12	6	0	8	64	-12	6	0	8
60+	64	-24	-22	-5	-3	64	-24	-22	-5	-3
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	-12	-28	-5	-11	0	-12	-28	-5	-11
Moderate (85-119):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	168	-84	0	0	0	168	-84	0	0
Poletimber:										
1-29	8	0	0	0	1	8	0	0	0	1
30-59	-28	0	0	0	-3	-28	0	0	0	-3
60+	36	0	0	0	4	36	0	0	0	4
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Low (50-84):										
Seedling/sapling:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	26	13	0	0	0	26	13
Poletimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	84	0	0	0	10	84	0	0	0	10
60+	84	0	0	0	10	84	0	0	0	10
Sawtimber:										
1-29	0	0	0	0	0	0	0	0	0	0
30-59	0	0	0	0	0	0	0	0	0	0
60+	0	0	0	0	0	0	0	0	0	0
Very low (20-49):										
Seedling/sapling:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Poletimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--
Sawtimber:										
1-29	--	--	--	--	--	--	--	--	--	--
30-59	--	--	--	--	--	--	--	--	--	--
60+	--	--	--	--	--	--	--	--	--	--

[1]Negative (-) values = gains; positive values = losses; 0 = no net fire impact; — = situation not analyzed.

Table 29—*Factors for adjusting roaded net value change estimates to unroaded estimates when roaded value is negative*

Management emphasis, stand size, mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)			Discount rate (pct)		
	4.0	7.875	10.0	4.0	7.875	10.0
Moderate public						
Seedling sapling						
1-29	—	—	—	—	—	—
30-59	—	—	—	—	—	—
60+		—		—		
Poletimber						
1-29	0	0	0	0	0	0
30-59	0	0.86	0.90	0.28	0.55	0 58
60+	1.00	1.00	.99	1.00	1.00	1.00
Sawtimber						
1-29	.94	.95	.95	.77	.78	.79
30-59	.92	.84	87	.49	.63	.67
60+		1.00	1.00	42	.62	.67
Intense public						
Seedling/sapling						
1-29	1.00	1.00	1.00	1.00	1.00	1.00
30-59	1.00	1.00	1.00	1.00	1.00	1.00
60+	1.00	1.00	1.00	1.00	1.00	1.00
Poletimber						
1-29	.30	.94	.94	.63	.79	.80
30-59	0	.88	.91	.24	.73	.77
60+	—	1.00	1.00	—	.50	.71
Sawtimber						
1-29	.95	.92	.94	.79	.85	.87
30-59	0	.63	79	.51	.48	.54
60+		1.00	1.00	1.00	.38	50
Passive private						
Seedling/sapling						
1-29	0	0	0	0	0	0
30-59		0	0	.95	—	
60+	1.00			1.00		
Poletimber						
1-29	.88	.92	.96	.96	.98	.86
30-59	.75	.49	.78	—	.93	.70
60+						
Sawtimber						
1-29	73	0	0	89	.86	.86
30-59	0	0	.93	.99	1.00	1.00
60+						
Intense private						
Seedling sapling						
1-29						
30-59						
60+						
Poletimber						
1-29	0	0	0	.90	.91	.91
30-59	0	0	0	.63	.67	.70
60+			—			
Sawtimber						
1-29				.89	.88	.88
30-59		—		1.00	1.00	1.00
60+	—	—	—	—	—	—

Table 30—*Factors for adjusting roaded net value change estimates to unroaded estimates when roaded value is positive*

Management emphasis, stand size, mortality class (pct)	Fire size: 1-99 acres			Fire size: 100+ acres		
	Discount rate (pct)			Discount rate (pct)		
	4.0	7.875	10.0	4.0	7.875	10.0
Moderate public						
Seedling/sapling						
1-29	1.00	1.00	0	1.00	1.00	0
30-59	1.02	1.03	1.04	1.02	1.03	1.04
60+	1.03	1.05	1.06	1.03	1.06	1.02
Poletimber						
1-29	1.01	1.03	1.03	1.07	1.02	1.03
30-59	1.02	1.03	1.05	1.02	1.03	1.05
60+	1.10	1.28	1.38	1.18	1.61	1.60
Sawtimber						
1-29	1.04	1.06	1.06	1.04	1.07	1.05
30-59	1.00	1.01	1.01	1.01	1.03	1.04
60+	1.17	1.41	1.55	1.43	1.52	1.91
Intense public						
Seedling/sapling						
1-29	1.00	1.01	1.01	1.00	1.01	1.01
30-59	1.01	1.02	1.03	1.01	1.02	1.03
60+	1.05	1.14	1.17	1.06	1.18	1.11
Poletimber						
1-29	1.01	1.03	1.04	1.16	1.14	1.05
30-59	1.01	1.03	1.04	1.04	1.04	1.06
60+	1.06	1.30	1.36	1.20	1.52	2.03
Sawtimber						
1-29	1.04	1.02	1.03	1.03	1.05	1.06
30-59	1.02	1.00	1.00	1.38	1.90	2.28
60+	1.16	1.25	1.32	1.44	1.60	1.66
Passive private						
Seedling/sapling						
1-29	1.00	1.00	0	1.00	1.00	0
30-59	1.05	1.00	1.00	1.05	1.00	1.00
60+	1.01	1.01	1.01	1.01	1.01	1.01
Poletimber						
1-29	1.01	1.03	1.03	1.03	1.04	1.04
30-59	1.03	1.01	1.01	1.12	1.02	1.02
60+	1.04	1.08	1.11	1.08	1.18	1.14
Sawtimber						
1-29	1.05	1.06	1.06	1.31	1.00	1.00
30-59	1.04	1.05	1.05	1.11	1.14	1.14
60+	1.18	1.22	1.23	1.41	1.52	1.53
Intense private						
Seedling sapling						
1-29	1.00	1.00	1.00	1.00	1.00	1.00
30-59	1.01	1.01	1.01	1.01	1.01	1.01
60+	1.04	1.08	1.11	1.04	1.09	1.13
Poletimber						
1-29	1.01	1.01	1.01	1.01	1.02	1.03
30-59	1.00	1.01	1.01	1.01	1.01	1.01
60+	1.05	1.07	1.08	1.17	1.24	1.21
Sawtimber						
1-29	1.00	1.00	1.00	1.00	1.00	1.00
30-59	1.00	1.00	1.00	1.36	1.34	1.34
60+	1.10	1.12	1.12	1.82	1.86	1.86

REFERENCES

Adams, D. M.; Haynes, Richard W. **The 1980 softwood timber assessment market model: structure, projections, and policy simulations.** Forest Sci. Monogr. 22; 1980. 64 p.

Althaus, Irene A.; Mills, Thomas J. **Resource values in analyzing fire management programs for economic efficiency.** Gen. Tech. Rep. PSW-57. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 9 p.

Flint, Howard R. **Appraisal of forest fire damages.** J. For. 22(2): 154-161; 1924.

Goforth, Marcus H.; Mills, Thomas J. **A financial return program for forestry investments.** Agric. Handb. 488. Washington, DC: U.S. Department of Agriculture; 1975. 18 p.

Lindenmuth, A. W., Jr.; Keetch, J. J.; Nelson, Ralph M. **Forest fire damage appraisal procedures and tables for the northeast.** Station Paper No. 11. Asheville, NC: Southeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture; 1951. 28 p.

Loveless, Robert S.; Jackson, David H. **Volume and value changes in fire-damaged timber sales.** 1983. Unpublished draft supplied by authors.

Mactavish, J. S. **Appraising fire damage to mature forest stands.** Dep. Pub. 1162. Ottawa, Canada: Forestry Branch, Canada Department of Forestry and Rural Development; 1966. 31 p.

Marty, Robert J.; Barney, Richard J. **Fire cost, losses, and benefits: an economic evaluation procedure.** Gen. Tech. Rep. INT-108. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1981. 11 p.

Medema, Lee E.; Hatch, Charles R. **Computerized help for the economic analysis of Prognosis-model outputs: a user's manual.** Contribution 227. Moscow, ID: Forest, Wildlife, and Range Experiment Station, University of Idaho; 1982. 72 p.

Merzenich, Jim, Operations Research Analyst, Planning Program and Budgeting Staff, Northern Region, Forest Service, U.S. Department of Agriculture, Missoula, Montana. Personal communications. 1982.

Mills, Thomas J. **Integrating fire management analysis into land management planning.** Gen. Tech. Rep. PSW-74. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983. 8 p.

Mills, Thomas J.; Bratten, Frederick W. **FEES: design of a *F*ire *E*conomics *E*valuation *S*ystem.** Gen. Tech. Rep. PSW-65. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 26 p.

Mills, Thomas J.; Flowers, Patrick J. **Completeness of model specification: an illustration with fire-induced timber net value change.** In: Proceedings of the Seventh conference on fire and forest meteorology. Preprint volume; 1983 April 25-28; Fort Collins, CO. Boston, MA: American Meteorological Society; 1983: 153-157.

Mills, Thomas J.; Flowers, Patrick J. **Fire-induced change in the value of timber outputs: a sensitivity analysis.** Can. J. For. [In press].

Mills, Thomas J.; Flowers, Patrick J. **Wildfire induced change in the present net value of timber stands in the northern Rocky Mountains.** 1984. Unpublished draft.

Mills, Thomas J.; Shinkle, Patricia B.; Cox, Gregory L. **Direct costs of silvicultural treatments on National Forests, 1975-78.** Res. Paper WO-40. Washington, DC: U.S. Department of Agriculture, Forest Service; 1985. 16 p.

Office of Management and Budget. Circular A-94. Washington, DC. 1972; 4 p.

Row, Clark F.; Kaiser, F. H.; Sessions, J. **Discount rate for long-term Forest Service investments.** J. For. 79(6): 367-369; 1981.

Schweitzer, Dennis L.; Anderson, Ernest V.; Mills, Thomas J. **Economic efficiency of fire management programs at six National Forests.** Res. Paper PSW-157. Berkeley, CA. Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 29 p.

Seaver, David A.; Roussopoulos, Peter J.; Freeling, Anthony N. S. **The escaped fire situation: a decision analysis approach.** Res. Paper RM-244. Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983. 12 p.

U.S. Department of Agriculture, Forest Service. **U.S. National Forest System fire management budget analysis, 1980 [Aviation and Fire Management Staff].** Washington, DC; 1980. 29 p.

U.S. Department of Agriculture, Forest Service. FSM 5130.3 — **Fire suppression policy.** Washington, DC; 1981.

U.S. Department of Agriculture, Forest Service. FSH 5109.19 — **Fire management analysis and planning handbook.** Washington, DC; 1982.

U.S. Department of Agriculture, Soil Conservation Service. **Interest rates for water and related land resource projects.** Nat. Bull. 200-3-1. Washington, DC; 1982. 3 p.

Van Wagner, C. E. **Simulating the effect of forest fire on long-term annual timber supply.** Can. J. Forest Res. 13: 451-457; 1983.

Wulf, Norman W., Silviculturist, Clearwater Forest, Forest Service, U.S. Department of Agriculture, Orofino, Idaho. Personal communications. 1982.

Wykoff, W. R., Crookston, N. L., Stage, A. P. **User's guide to the stand prognosis model.** Gen. Tech. Rep. INT-133. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 112 p.

The Forest Service, U.S. Department of Agriculture, is responsible for Federal leadership in forestry. It carries out this role through four main activities:

- Protection and management of resources on 191 million acres of National Forest System lands.
- Cooperation with State and local governments, forest industries, and private landowners to help protect and manage non-Federal forest and associated range and watershed lands.
- Participation with other agencies in human resource and community assistance programs to improve living conditions in rural areas.
- Research on all aspects of forestry, rangeland management, and forest resources utilization.

The Pacific Southwest Forest and Range Experiment Station

- Represents the research branch of the Forest Service in California, Hawaii, and the western Pacific.

Flowers, Patrick J.; Shinkle, Patricia B.; Cain, Daria A.; Mills, Thomas J. **Timber net value and physical output changes following wildfire in the northern Rocky Mountains: estimates for specific fire situations.** Res. Paper PSW-179. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1985. 25 p.

One of the major economic effects of wildfire is the change in the net value of timber. Estimates of these changes were calculated for a wide range of fire situations in the northern Rocky Mountains of the United States. The results are presented in reference tables. They are intended as an alternative to calculating estimates for specific sites or to using broad averages. Specific fire situations are identified by management emphasis, cover type, productivity class, stand size, mortality class, fire size, and access parameters. The reference tables have potential uses in planning long-term fire management programs, establishing dispatching priorities, analyzing escaped fire situations, and analyzing wildfire's impact on long-term harvest schedules.

Retrieval Terms: fire effects, economies-to-scale, fire size, timber management regime

United States Department of Agriculture

Forest Service

Pacific Southwest Forest and Range Experiment Station

Research Paper PSW-180

Growth of California Red Fir Advance Regeneration After Overstory Removal and Thinning

William W. Oliver

The Author:

WILLIAM W. OLIVER is in charge of the Station's silvicultural research on California conifer types, with headquarters at Redding, Calif. He earned a bachelor's degree (1956) in forestry from the University of New Hampshire, and a master of forestry degree (1960) from the University of Michigan. He joined the Station in 1962.

Publisher:

Pacific Southwest Forest and Range Experiment Station
1960 Addison Street, Berkeley, California 94704

January 1986

Growth of California Red Fir Advance Regeneration After Overstory Removal and Thinning

William W. Oliver

CONTENTS

IN BRIEF . . .

Oliver, William W. **Growth of California red fir advance regeneration after overstory removal and thinning.** Res. Paper PSW-180. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1985. 6 p.

Retrieval Terms: California red fir, *Abies magnifica*, advance regeneration, tree growth, damage, mortality

Advance regeneration is common under decadent, old-growth stands of California red fir (*Abies magnifica* A. Murr.). Intense competition for the site's resources can create sapling stands of poor vigor and advanced age. When competition is reduced by overstory removal and thinning, suppressed advance regeneration has been shown to respond with increased growth. But, to select leave trees, land managers need to know which tree characteristics are associated with growth after release and thinning. This paper reports those easily measured tree characteristics found to be most closely associated with growth after 8 years, on the Swain Mountain Experimental Forest in northeastern California.

About 400 saplings were monitored after removal of the overstory and thinning on 10 acres, at 6700 ft (2044 m) on the northeast face of Swain Mountain. At this elevation, most of the annual precipitation falls as snow, which usually accumulates to a depth of 6 ft (1.8 m). Site index is 45 ft (14 m) at 50 years.

After trees were thinned to a 6-ft (1.8-m) spacing, about 200 were chosen randomly within 10 study plots to obtain at least nine trees each in nine live crown ratio classes from 10 to 90 percent. A variety of stem and crown characteristics expected to be related to growth was measured on the sample trees, which averaged 1 inch (2.5 cm) in diameter at breast height (d.b.h.), 6.8 ft (2.1 m) tall, and 60 years old. Also, measured annually for d.b.h. only were 200 other saplings of similar size that were randomly selected from among well-formed dominant and codominant trees.

Rates of d.b.h. and height growth increased for most saplings during the 8 years of observation. According to the criteria used, variation in diameter growth was explained best by the easily measured characteristics: 3-year height growth before thinning (3-YHG), the product (PLC • CD) of percent live crown (PLC) and crown diameter (CD), and initial d.b.h. (ID). For height growth, the most effective variables by the same criteria were 3-YHG and PLC • CD. These variable sets were chosen for each of four response periods—0 to 2, 0 to 4, 0 to 6, and 0 to 8 years after thinning. Although regressions were highly significant ($p < 0.01$) for all periods, unexplained variation was high and increased as the period after thinning lengthened. For the 8-year period, the 95 percent confidence limit about the mean was 0.5 to 2.4 inches (1.3 to 6.1 cm) for diameter growth and 0.1 to 4.5 ft (0.03 to 1.37 m) for height growth. These wide ranges of values make predictions based upon the equations unreliable.

Annual precipitation, an uncontrollable variable, affected growth of those trees measured annually for d.b.h. But the effect was negative: more precipitation was associated with less growth in d.b.h. This startling result probably is caused by lingering snowpacks, which critically shorten the growing season.

Although reliable equations to explain growth were not developed, PLC alone may serve as a rough guide for selecting leave trees. Sample trees with PLC of 40 or more suffered less postrelease damage and responded with increased rates of diameter and height growth. Mortality and damage were, in general, more prevalent in trees with smaller PLC. Trees with 20 PLC had an estimated mean mortality rate four times that of deeper-crowned trees. Wounds incurred in logging the overstory were slow to heal. And recent snow bend was four times more prevalent in trees with 30 PLC or less than it was in deeper-crowned trees. Sunscald, seemingly an ideal entry point for rot fungi, was also related to PLC. As a general guide, vigorous, well-formed dominants and codominants with 40 PLC or greater is suggested for choosing potential crop trees in similar stands.

Choosing this advance regeneration shortened the rotation length for the next crop by about 12 years compared with post-harvest regeneration. But before deciding on regeneration, the land manager should weigh the cost of precommercial thinning and the threat of future decay against the savings in rotation length, site preparation, and planting.

INTRODUCTION

Old-growth California red fir (*Abies magnifica* A. Murr.) stands often contain advance regeneration, which tends to form dense clumps of small trees under openings in the overstory. Competition within these clumps and with the overstory for sunlight, moisture, and nutrients can be severe. When competition is reduced, red fir advance regeneration responds well (Gordon 1973).

Advance regeneration, adequately spaced, can shorten the rotation needed for artificial regeneration and reduce the need for site preparation and planting. But if the trees are unable to respond to release, are injured by the release, or if response is long delayed, a shorter rotation and greater yield may be achieved by artificial regeneration. To select leave trees, forest managers need to know what tree characteristics are associated with growth after overstory release and thinning of clumps.

This paper describes the 8-year growth of suppressed red fir saplings after overstory removal and thinning of one stand in the southern Cascade Range of northern California. Crown and stem characteristics were tested for their correlation with growth after stand treatment. Stem defects that seem to be associated with thinning of suppressed advance regeneration are also discussed. Comparison with similar studies conducted elsewhere suggests that the results reported here have wide application.

STUDY AREA

The study area was on the Swain Mountain Experimental Forest, Plumas County, California. The area (lat. 40°25′ N. long. 121°6′ W.) lies near the summit, on the northeast face of Swain Mountain, at an elevation of 6700 ft (2044 m). Study trees were within a 10-acre (4-ha) area on slopes that range from nearly level to about 30 percent.

Average annual precipitation probably is more than 46 inches (1168 mm). Most of the precipitation between November and April falls as snow, which reaches a maximum depth of at least 6 ft (1.8 m) about April 1. Data were recorded by a 200-inch Sacramento-type storage gauge located 1½ miles (2.4 km) north of and 500 ft (152 m) lower in elevation than the study area. Both precipitation and snow depth were measured at elevations lower than the study area and, because precipitation and snow depth increase with increasing elevation in this area, the actual amounts may be greater at the study area.

The soil, derived from Pleistocene basalt, is similar to the Windy Soil Series (cindery, frigid, Typic Dystrandepts). Site index is 45 ft (14 m) at 50 years (Schumacher 1928).

A decadent overstory of old-growth red fir was removed in 1960, yielding 38,000 board feet (Scribner) per acre—about half the volume found in most stands in the experimental forest. A dense stand of suppressed saplings remained. When the study was begun 12 years later, an examination of past height growth indicated little growth since overstory removal, probably because sapling stand density was high— 9700 stems per acre (23,950 per ha), on the average.

Dwarf mistletoe (*Arceuthobium abietinum* f. sp. *magnificae*), the only threatening pathogen, infected the surrounding old growth and the larger poles scattered throughout the stand. Trees sampled in this study were free of infection. Stem deformities caused by heavy snow loads were ubiquitous; more than half of the trees had butt sweep, a deformity common in sapling stands on similar slopes at this elevation (Leaphart and others 1972).

EXPERIMENTAL DESIGN

In dense portions of the stand, 10 plots, 0.2-acre (0.08 ha) in size, were arbitrarily established as part of a spacing study. Pretreatment stand density and mean tree height were estimated from two 0.01-acre (0.004-ha) sample plots located at random within each 0.2-acre (0.08-ha) spacing plot.

In fall 1972, the plots were thinned from below to a uniform spacing of 6 by 6 ft (1.8 by 1.8 m). This "calibration" thinning was designed to improve vigor and remove differences in growth response caused by high stand density. Wherever possible, well-formed dominant and codominant saplings with live crown ratios of 50 percent or greater were selected as leave trees. But because such trees often were missing in areas with high stand densities, suppressed saplings with short crowns were chosen to obtain the required spacing.

For this study, trees were chosen at random from throughout the 10 thinned plots. Suppressed saplings were chosen in many areas where prethinning stand densities had been high. At least nine trees each in nine live crown ratio classes from 10 to 90 percent were selected. Sample trees varied in height from 5 to 12 ft (1.5 to 3.7 m). To determine live crown ratio, crown length was measured from the first whorl of live branches to the top of the tree, and was expressed as a percent of measured tree height. Percent of total height in live crown generally is believed to influence tree growth (Scharpf 1979) and to reflect the competitive position of the tree in the stand. Therefore, by selecting sample trees from a wide range of live crown ratio classes, a wide range of competitive states from suppressed to free-growing should also be selected. Selected trees were 1 inch (2.5 cm) in diameter at breast height (d.b.h.) and 6.8 ft (2.1 m) in height, on the average (*table 1*).

One sample of about 200 trees was tagged and the following were recorded:

• Stem d.b.h. to the nearest 0.1 inch (0.25 cm).

• Total height and 3-year growth before thinning, measured to the nearest 0.1 ft (0.03 m).

• Live crown—height to the first all-living whorl, and crown diameter recorded as the average of two readings taken at right angles—to the nearest 0.1 ft (0.03 m).

• Distance from stump of overstory tree if less than 20 ft (6 m). Distances greater than 20 ft were recorded as 20 ft.

• Epicormic branching and damage, by causal agent.

D.b.h., height growth since the previous measurement, and epicormic branching and damage were recorded biennially for 8 years. Crown volume was estimated as the volume of a cone with base equal to crown width and height equal to crown length. After the final measurement, sample tree stems were severed at ground line and a disk removed to the laboratory for determination of total age.

In another sample, for best crop trees, 200 saplings with diameters of 1 inch (2.5 cm) and live crowns of 60 percent—on the average—were selected at random from throughout the well-formed dominant and codominant component of each of the 10 thinned plots. D.b.h. was measured annually.

DATA ANALYSIS

Of the many variables that affect growth of trees after thinning, I considered only a few that I judged would be useful in identifying potential crop trees. All possible subsets and some squared transformations and combinations of the following independent variables were tested for those trees living through each of the four periods:

- Live crown percent
- Height growth for the 3 years before thinning
- Crown diameter
- Crown volume
- Total height
- D.b.h.
- Age
- Distance from stump of overstory tree

Criteria for selecting the subsets that best explained the variation in height and d.b.h. growth were these: the statistics R^2 and Cp; those with fewest terms; ease of measuring the variables in the field; and, consistency of the subsets' correlation for all periods. The synthesis of these criteria necessarily caused the choice of subsets to be partially subjective. Coefficients for multiple linear equations of the form

$$Y = b_o + b_1x_1 + b_2x_2 \ldots + b_nx_n$$

were calculated for each period and dependent variable. Because of the problem of repeated measures, separate equations were calculated for each period.

Sample correlation coefficients were calculated for other suspected relationships such as diameter growth versus precipitation and various damaging agents versus percent live crown.

Table 1—*Mean characteristics of California red fir advance regeneration immediately after thinning and live trees at the end of the study, by live crown classes, in northeastern California*

Live crown class (pct)	3-year height growth before thinning	D.b.h.	Height	Crown diameter	Age	Live trees at end of study
	Ft	*Inches*	*Ft*	*Ft*	*Yr*	
10	0.12	0.74	5.9	2.3	60	9
20	.28	.98	6.6	2.7	63	16
30	.47	1.22	7.3	2.9	62	24
40	.79	1.31	7.5	3.2	62	21
50	.79	1.03	6.7	3.0	59	21
60	1.06	.98	6.9	3.2	55	19
70	1.39	.83	6.7	2.8	47	28
80	1.50	.79	6.5	2.8	34	20
90	1.89	.79	6.6	2.9	28	28

RESULTS

Variables and Growth

Two subsets of variables, one for d.b.h. and another for height, were selected to explain variation in growth after thinning (*table 2*). For d.b.h. growth, the variables included 3-year height growth before thinning (3-YHG), the product (PLC • CD) of percent live crown (PLC) and crown diameter (CD), and initial d.b.h. (ID) (*fig. 1*). For height growth, the most effective variables were 3-YHG and PLC • CD.

Table 2—*Coefficients of equations explaining growth in diameter at breast height (d.b.h.) and height of California red fir advance regeneration for four periods after thinning, in northeastern California*

Period after thinning (years)	3-YHG[1] (b_1)	PLC • CD[2] (b_2)	ID[3] (b_3)	Intercept (b_0)	Mean (Y)	R^2 adjusted	Standard error of the estimate
	Y = d.b.h. growth for period						
0–2	0.0362	0.0006	−0.0211	0.0711	0.21	0.60	0.0943
0–4	.0494	.0012	.0064	.2734	.55	.58	.1841
0–6	.0410	.0016	.1222	.4100	.86	.40	.2585
0–8	.0414	.0021	.1991	.6225	1.22	.33	.3692
	Y = height growth for period						
0–2	0.0771	0.0010		0.0834	0.37	0.65	0.1634
0–4	.0852	.0029		.2926	.90	.43	.4315
0–6	.0680	.0048		.6379	1.54	.27	.8029
0–8	.0526	.0066		1.0895	2.28	.24	1.0965

[1]3-YHG = Height growth in feet for the 3 years before thinning.
[2]PLC • CD = Product of live crown in percent and crown diameter in feet.
[3]ID = Initial d.b.h. (inches).

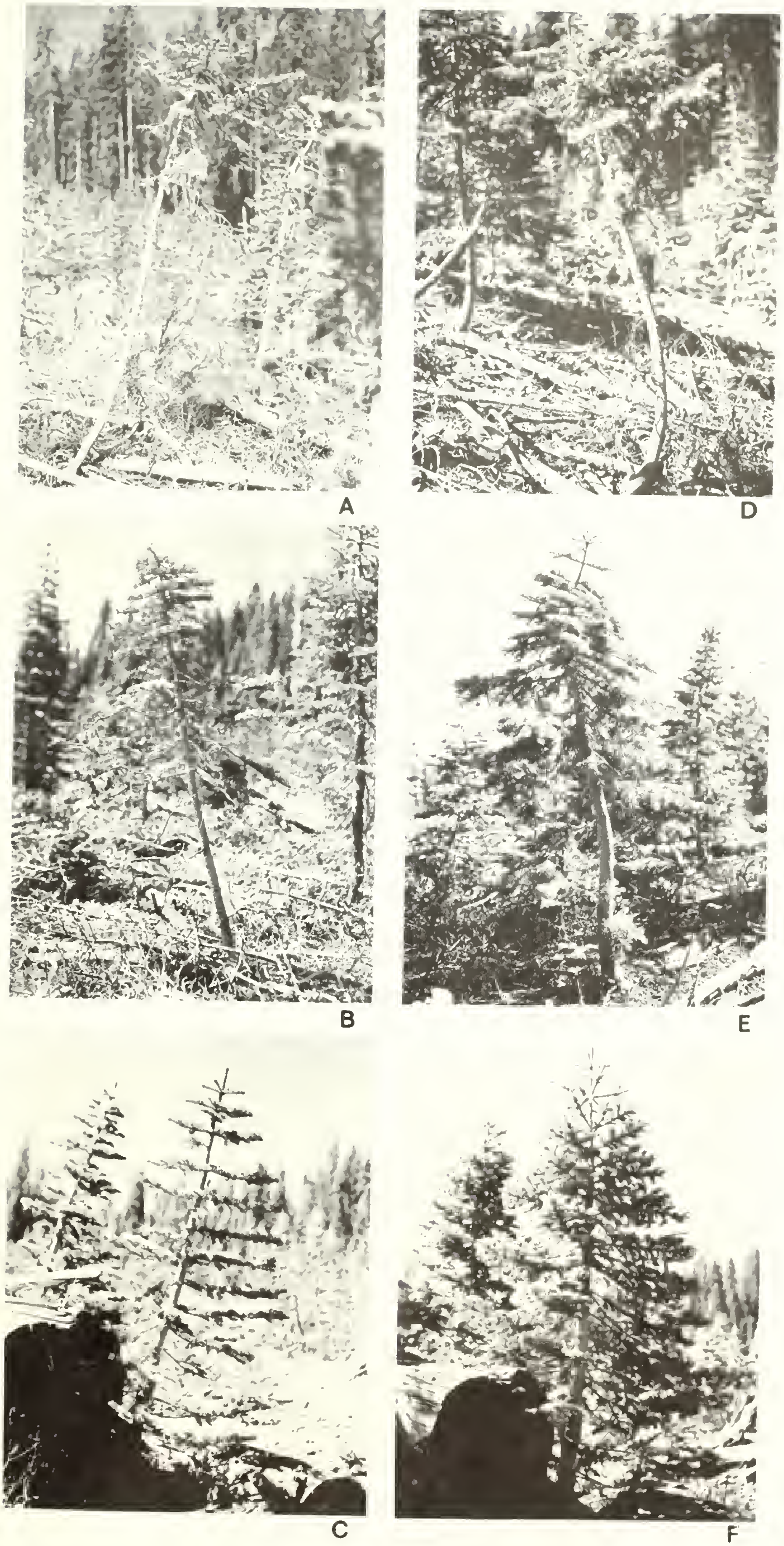


Figure 1—Growth response of California red fir saplings was related to percent live crown (PLC) and 3-year height growth before thinning (3-YHG). Immediately after thinning, (A) PLC was 10 percent and 3-YHG was 0.1 ft, (B) PLC was 50 percent and 3-YHG was 0.5 ft, and (C) PLC was 80 percent and 3-YHG was 1.1 ft. Six years later, these same trees had grown in diameter at breast height (d.b.h.) and in height: (D) 0.4 inch in d.b.h. and 0.2 ft in height, (E) 0.9 inch in d.b.h. and 1.4 ft in height, and (F) 1.3 inches in d.b.h. and 3.3 ft in height.

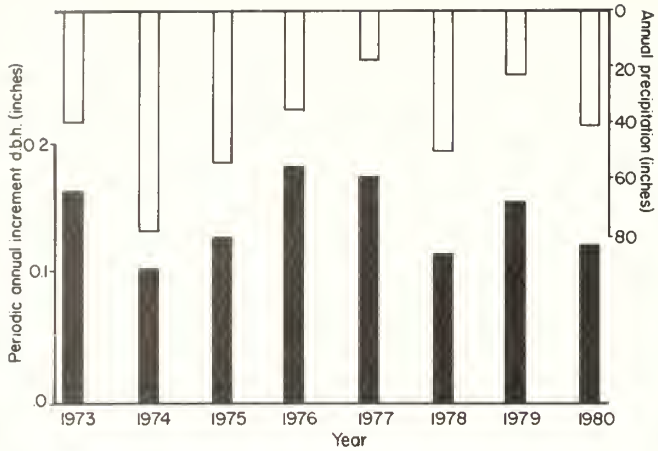


Figure 2—When annual precipitation was less, California red fir saplings grew more in diameter at breast height (d.b.h.), at Swain Mountain Experimental Forest, 1973–1980.

The variables explained more of the variation, and the standard error of the estimates was less when the growth period after thinning was short. For the first 2 years after thinning, the variables explained 60 percent of the variation in d.b.h. growth. Explained variation fell steadily to 33 percent and the standard error of the estimate rose steadily with longer periods after thinning.

These measures of fit were similar for height growth. For the 2 years after thinning, the variables explained 65 percent of the variation. Explained variation fell to 24 percent and the standard error of the estimate rose with longer periods after thinning. Although coefficients of multiple correlation were significant ($p < 0.01$), the variables explained only about one-fourth of the variation in height growth, and the standard error of the estimate increased to more than 0.8 ft (0.24 m) for periods longer than 4 years after thinning.

Total ages of red fir saplings ranged from 10 years, for some trees originating after the overstory was removed, to 97 years. The age of the vast majority (71 pct) of the saplings, however, ranged from 50 to 70 years. Age was significantly ($p < 0.01$) correlated with growth measures. Younger trees tended to grow faster than did older trees. Neither grand fir (*A. grandis* [Dougl. ex D. Don]) in northern Idaho older than 30 years (Ferguson and Adams 1980) nor white fir (*A. concolor* [Gord. & Glend.] Lindl. ex Hildebr.) in northern California older than 45 years (Helms and Standiford 1985) responded to release as well as did younger trees. Nevertheless, age was not chosen as a variable in the equations for two reasons: it was correlated with two of the chosen variables, 3-YHG and PLC; and, age is difficult to measure in the field. Determining age of suppressed saplings is difficult even under ideal conditions because annual rings often are narrow.

Precipitation and Diameter Growth

One uncontrollable variable that accounts for some of the unexplained variation in growth response is precipitation. From the sample of 200 best crop trees measured yearly for d.b.h., annual precipitation was correlated ($r = 0.79$, $p < 0.05$) with mean growth, as expected; but, the correlation was negative—more precipitation was associated with less growth in d.b.h. (*fig. 2*).

The reason for this startling result is not clear, but length of growing season seems likely to be the cause. In the study area, the snowpack often lingers into early summer, delaying the start of growth of sapling red fir. The approximate date when height growth starts, which immediately follows the start of cambial activity, was observed in 3 of the 8 years of the study. In 2 years with above-normal precipitation, shoot growth was delayed until July 10 (1974) and July 1 (1975). Whereas in 1979, a dry year, shoot growth began a month earlier on June 8. Upland conifers tend to require a photoperiod longer than 12 hours for active growth,[1] and a growing season of at least 3½ months for maximum d.b.h. growth (Fowells 1941). A delay in growth initiation until July may cause the growing season to be truncated by short days because effective day length becomes shorter than 12 hours in less than 3 months.

Mortality and Damage

Eight trees died during the 8 years of the study. Cause of death often was not determined but probably was the result of several factors. The most prevalent predisposing factor probably was shock from thinning around weak trees. All but one of the dead trees had live crowns of 20 percent or less.

Much of the advance regeneration was unavoidably damaged in logging the overstory. When the study began 12 years later, open basal wounds were still common, especially on saplings with live crowns of 40 percent or less. Of all such saplings sampled, 31 percent had open wounds. These wounded saplings represented two-thirds of all wounded trees in the study. At the end of the study, 8 years later, incidence of sample trees with open wounds had declined to 7 percent, overall, from the initial 18 percent. Of the trees with logging wounds still open, 85 percent were in live crown classes of 40 percent or less.

Stem deformities caused by the heavy snowpack were common. Many deformities such as butt sweep, "S" curves, and "dog legs" (Leaphart and others 1972) result from a partial recovery from snow damage and were unrelated to live crown ratio. Such deformities were seen on 37 percent of all sample trees. However, recent snow bend, which caused leaning or prostrate trees, was related to live crown ratio. Of the sample trees with live crowns of 30 percent or less, leaning trees averaged 14 percent at each measurement—nearly four times the sample proportion found for trees with live crowns of 40 percent or more.

The original overstory of old-growth red fir was decadent. Many stumps showed rot. And conks of *Heterobasidium annosum* root disease were identified in cavities of stumps with heart rot. Because infection can spread to nearby regeneration through root contacts, I suspected root disease might inhibit

[1]Unpublished data on file, Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Redding, California.

Figure 3—Sunscald immediately kills the cambium, but the bark remains nearly intact and would seem to provide a favorable environment for rapid fungal growth.

growth in some trees. Distance from old-growth stumps, however, was not correlated with measured growth.

Thinning dense stands of trees with short live crowns suddenly exposes many stems to insolation. The cambium on the south and southwest sides of thin-barked trees, such as sapling red fir, often dies when exposed suddenly to full insolation (Levitt 1980). In this study, sunscald and epicormic branching were common and were related significantly ($p < 0.01$) to percent live crown. It explained 82 percent of the variation in sunscald and 77 percent of that in epicormic branching. About one-fourth of the sample trees with less than 20 percent live crowns suffered sunscald. For trees with larger crowns, incidence of sunscald fell to an unimportant 5 percent or less for trees with live crowns of 70 percent or larger.

Sunscald causes an immediate stem defect because the cambium is killed, but the long-term defect can be more serious. Sunscald wounds would seem to be ideal entry points for rot fungi. The bark cracks, allowing spores to enter the wound, and because the bark remains nearly intact (*fig. 3*), the wound provides a moist environment for rapid fungal growth. Also, retention of bark over the wound impedes callus formation. Fungi were not isolated from sunscald wounds, however.

A common response to release of the more severely suppressed red fir saplings was epicormic branching. And those trees with restricted cambial activity, i.e., suppressed trees, are especially prone to such branching (Kozlowski 1971). White fir produces epicormic branches so profusely that pruning to improve lumber quality is not feasible (Cosens 1952). Epicormic branching—to my knowledge—has not been previously reported in red fir. Indeed, pole-size and larger crop trees of red fir may produce epicormic shoots only rarely. The epicormic shoots I observed on suppressed saplings may be ephemeral only. Many shoots were dying 8 years after thinning.

The proportion of saplings exhibiting epicormic branching in the sample was summarized by live crown classes. About 70 percent of all saplings with live crowns of 60 percent or less produced epicormic shoots. Incidence of shoots dropped to less than 25 percent for saplings with full crowns.

DISCUSSION AND CONCLUSIONS

The variables did not explain adequately the observed variation in growth of red fir advance regeneration after thinning. Even in the best equations, those for the initial 2-year period after thinning, the variables explained less than two-thirds of the variation in d.b.h. and height growth.

Explanations of growth increase in usefulness with time after release and thinning. Ideally, the land manager would wish to know the growth of saplings up to time of first commercial entry. But in the study reported here, the variance increased with length of period after thinning: for the 8-year period, the 95 percent confidence limit about the mean was 0.5 to 2.4 inches (1.3 to 6.1 cm) for diameter growth and 0.1 to 4.5 ft (0.03 to 1.37 m) for height growth. This range of values is of little use to the land manager. Growth of well-spaced, suppressed grand fir saplings after overstory removal in central Oregon also could not be reliably explained (Seidel 1980).

I found both tree age and precipitation to be strongly correlated with growth. But age of advance regeneration is difficult to measure in the field and precipitation cannot be known in advance.

The easily measured independent variables that were most strongly correlated with growth—pretreatment height growth and percent live crown—were found to be strongly correlated, either singly or in combination, with growth in similar studies of true fir in the West (Ferguson and Adams 1980, McCaughey and Schmidt 1982, Scharpf 1979, Helms and Standiford 1985). Although widely used, these variables may be too crude to identify the potential vigor and photosynthetic capacity of suppressed saplings in some situations. Further investigations will be necessary to develop adequate predictive equations.

Although the equations were unreliable, growth during the 8-year period averaged by percent live crown classes suggest that PLC may be a rough but useful guide for selecting leave trees when thinning. Minimum rates of growth for nonsuppressed red fir on sites of similar indices in northern California seem to be 0.15 inch (0.4 cm) in d.b.h. and 0.3 ft (0.01 m) in height, annually (Gordon 1973, Powers 1979).[1] Of the trees in this study with PLC of 30 or less, only 30 percent exceeded this minimum rate for d.b.h. growth and only 5 percent exceeded this minimum rate for height growth during the 8-year period. Deeper crowned sample trees (PLC of 40 and greater) grew more rapidly. Many sample trees reached or exceeded these minimum values for periodic annual increment (PAI): 56 percent for diameter and 41 percent for height. Growth rates found elsewhere may not apply to the trees in this study because slope direction and steepness as they affect depth and movement of snowpack may result in different growth rates for red fir saplings (Leaphart and others 1972, Williams 1966). These site differences are of less consequence to larger trees such as those measurable for site index. Nevertheless, these minimum PAI's provided rough target growth rates for evaluating the performance of the sample trees in this study.

Aside from growth, sample trees with larger live crowns withstood the sudden exposure resulting from thinning with less snow bending, and were sufficiently vigorous to heal more logging wounds during the study period than were sample trees with smaller live crowns. Nevertheless, many healed wounds—particularly at ground line—may be infected with rot fungi as were about half of the wounded grand fir and white fir examined in Washington and Oregon (Aho and Filip 1981). Sunscald was linearly related to PLC. In the study reported here, if only those trees with PLC of 40 or more had been chosen as potential crop trees, incidence of sunscald injury would have been 19 percent or less.

Saving advance regeneration for the next crop can shorten the rotation length compared with that required after establishing new trees. Observations of height growth of nonsuppressed saplings that originated in skid roads after overstory removal suggest that about 12 years may be saved by retaining the better advance regeneration as future crop trees. These saplings reached the same height—6.8 ft (2.1 m)—as the initial height of sample trees with PLC of 40 or more, in 12 years. Despite savings in rotation length, site preparation, and planting costs, advance regeneration requires costly precommercial thinning and poses the threat of future decay—especially if crop trees have been wounded. A final decision on whether to use advance regeneration for the next crop must consider both these advantages and disadvantages.

REFERENCES

Aho, Paul E.; Filip, Gregory M. **Decay in grand and white firs**. In: Proceedings of the 29th annual western international forest disease work conference; 1981 September 15–18; Vernon, BC. Juneau, AK: Alaska Region, Forest Service, U.S. Department of Agriculture; 1981: 40–42.

Cosens, Richard D. **Epicormic branching on pruned white fir**. J. For. 50(12): 939–940; 1952.

Ferguson, Dennis E.; Adams, David L. **Response of advance grand fir regeneration to overstory removal in northern Idaho** Forest Sci. 26(4): 537–545; 1980.

Fowells, H. A. **The period of seasonal growth of ponderosa pine and associated species**. J. For. 39(7): 601–608; 1941.

Gordon, Donald T. **Released advance reproduction of white and red fir . . . growth, damage, mortality**. Res. Paper PSW-95. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1973. 12 p.

Helms, John A.; Standiford, Richard B. **Predicting release of advance reproduction of mixed conifer species in California following overstory removal**. Forest Sci. 31(1): 3–15; 1985.

Kozlowski, T. T. **Growth and development of trees. Volume I. Seed germination, ontogeny, and shoot growth.** New York: Academic Press; 1971. 443 p.

Leaphart, Charles D.; Hungerford, R. D.; Johnson, H. E. **Stem deformities in young trees caused by snow pack and its movement**. Res. Note INT-158. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1972. 10 p.

Levitt, J. **Responses of plants to environmental stresses. Vol. 1. Chilling, freezing, and high temperature stresses.** 2d ed. New York: Academic Press; 1980. 497 p.

McCaughey, Ward W.; Schmidt, Wyman C. **Understory tree release following harvest cutting in spruce-fir forests of the Intermountain West**. Res. Paper INT-285. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 19 p.

Powers, Robert F. **Response of California true fir to fertilization**. In: Proceedings, forest fertilization conference; 1979 September 25–27; Union, WA. Forest Resour. Contrib. 40. Seattle: Univ. Wash. Coll. Forest Resour. Inst.; 1979: 95–101.

Scharpf, Robert F. **Dwarf mistletoe-infected red fir: growth after release**. Res. Paper PSW-143. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1979. 9 p.

Schumacher, Francis X. **Yield, stand and volume tables for red fir in California**. Bull. 456. Berkeley, CA: Univ. Calif. Coll. Agric. Exp. Stn.; 1928. 29 p.

Seidel, K. W. **Diameter and height growth of suppressed grand fir saplings after overstory removal**. Res. Paper PNW-275. Portland, OR: Pacific Northwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1980. 9 p.

Williams, Carroll B., Jr. **Snow damage to coniferous seedlings and saplings**. Res. Note PNW-40. Portland, OR: Pacific Northwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1966. 10 p.

The Forest Service, U.S. Department of Agriculture, is responsible for Federal leadership in forestry. It carries out this role through four main activities:

- Protection and management of resources on 191 million acres of National Forest System lands.
- Cooperation with State and local governments, forest industries, and private landowners to help protect and manage non-Federal forest and associated range and watershed lands.
- Participation with other agencies in human resource and community assistance programs to improve living conditions in rural areas.
- Research on all aspects of forestry, rangeland management, and forest resources utilization.

The Pacific Southwest Forest and Range Experiment Station

- Represents the research branch of the Forest Service in California, Hawaii, and the western Pacific.

Oliver, William W. **Growth of California red fir advance regeneration after overstory removal and thinning**. Res. Paper PSW-180. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1985. 6 p.

Overstory removal and thinning can reduce competition and increase growth of advance regeneration under old-growth California red fir (*Abies magnifica* A. Murr.). To guide selection of leave trees, land managers need to know which tree characteristics are associated with growth after release and thinning. Periodic growth in diameter and height was tested for its relationship to stem and crown characteristics of about 200 red fir saplings in a stand in northeastern California. Strongest correlations were between growth and the independent variables percent live crown and 3-year pretreatment height growth. Although the correlations were statistically significant ($p < 0.01$), unexplained variation was too high for reliable predictions. Lacking a more precise guide, virgorous, well-formed dominants and codominants with a percent live crown of 40 or greater are suggested for potential crop trees in similar stands.

Retrieval Terms: California red fir, *Abies magnifica*, advance regeneration, tree growth, damage, mortality