USDA Forest Service
Research Paper INT-81
1970

VERTICAL DISTRIBUTION OF FUEL IN SPRUCE-FIR LOGGING SLASH

James K. Brown

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Ogden, Utah 84401

THE AUTHOR

JAMES K. BROWN received his bachelor's degree from the University of Minnesota in 1960, his master's from Yale University in 1961, and his Ph. D. from the University of Michigan in 1968, all in forestry. From 1961 to 1965 he did research on field measurement of fuel properties and fire-danger rating systems while with the Lake States Forest Experiment Station. In 1965 he transferred to the Northern Forest Fire Laboratory, Missoula, Montana, where he is responsible for research on the physical properties of fuel.

ACKNOWLEDGMENT

The help of David Bunnell who performed much of the fieldwork and analysis is greatly appreciated.

USDA Forest Service
Research Paper INT-81
December 1970

VERTICAL DISTRIBUTION OF FUEL IN SPRUCE-FIR LOGGING SLASH

James K. Brown

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

CONTENTS

ABSTRACT

About 70 percent of the volume and surface area of spruce-fir logging slash lies below the mid-depth of the slash. Material 0 to 1 centimeter in diameter was distributed vertically in the same proportions as all other material. Old slash in the first 20 centimeters above the ground contained a higher proportion of large material than new slash. Quantity of slash averaged 26.5 kg./$m.^2$ (118 tons/acre) dry weight with 0.57 kg./$m.^2$ composed of material 0 to 1 centimeter in diameter. Bulk density of slash decreased vertically and averaged 0.030 g./cc. for new slash and 0.053 for old slash. Needle mats suspended in the slash occurred with a 40 percent frequency.

INTRODUCTION

The flammability of logging slash depends largely on its physical properties such as fuel volume, surface area, weight, porosity, and size distribution of particles. Quantitative knowledge of these properties will aid in understanding and predicting fire behavior in slash. However, quantitative information describing many of the physical properties of slash is lacking, especially in regard to vertical distribution of volume and surface area.

Presented in this paper are results of a study that quantitatively determined fuel volume, surface area, bulk density, and the ratio of void volume of fuel complex to fuel surface area (λ) at different vertical levels within logging slash. Also discussed are loading (weight per unit area), percent composition of slash by particle sizes, existence of suspended needle mats, and methods of measurement.

This study is part of a fire research effort to quantitatively describe the properties of fuels and develop a means of relating these fuel properties to fire behavior. As this knowledge accumulates it will be used to formulate and improve a system for quantitatively appraising forest and range fuels.

Major findings of the study were:

1. Volume, surface area, and bulk density decrease from the ground up. Slightly over two-thirds of the total volume and surface area was in the lower half of the slash.

2. The total material in small-sized slash is distributed vertically in approximately the same proportions as in all-sized slash.

3. Aging of slash for 6 months to 1 year greatly reduced the amount of needle volume and surface area.

4. An average of 80 percent of the total slash volume in the study was comprised of material over 10 centimeters in diameter; this material would probably contribute relatively little energy to rate of spread and intensity of a fire front.

5. Mats of needles frequently were suspended in the slash and probably contribute to the flammability of aged slash.

METHODS

The area[1] chosen for study had been clearcut and was located on the Tally Lake Ranger District, Flathead National Forest. Trees in the study area (marked off in 10-acre blocks) were mostly Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), Engelmann spruce (*Picea engelmannii* Parry), and western larch (*Larix occidentalis* Nutt.). Eight blocks were selected so that north, east, south, and west aspects were equally represented; the blocks were sampled in July 1968. Also, the blocks were selected to furnish two age classes of slash separated by 4 to 7 months (table 1). Slash on different aspects and of different ages was sampled to increase the range of conditions examined and not to isolate the effects of aspect and age on the fuel properties.

The physical fuel properties were determined separately (from ground to top of slash) for 20-centimeter thick horizontal strata. A planar intersect technique, a

---

[1]This area is the site of a cooperative study on the use of fire in silviculture; cooperating in the study are the USDA Forest Service, Northern Region and Intermountain Forest and Range Experiment Station.

Table 1.--*Age of slash at time of measurement*

Old slash			New slash		
Aspect and Block	Date slashing completed	Age	Aspect and Block	Date slashing completed	Age
		Months			*Months*
South-10	5/31/67	12½	South-11	10/25/67	8
North-13	7/16/67	11½	East-5	11/16/67	7½
West-11	7/11/67	11½	East-4	11/17/67	7½
			North-10	2/7/68	5
			West-13	2/14/68	5
	Average	12		Average	6½

modification of the line interception technique,[2] provided the basis for estimating fuel volume and surface area. In using the planar intersect technique, 15 sampling planes that were 30 centimeters wide and as high as the slash were systematically located along transects in each of the eight blocks. The sampling planes were established on the ground parallel to contours of the slope by delineating the sides with metal rods plumbed vertically and spaced 30 centimeters apart (figure 1).

Figure 1.-- Pairs of metal rods, sharpened at one end, were stuck in the ground, plumbed vertically and braced 30 centimeters apart to delineate the sampling planes. Extremes in the amount of slash encountered are shown.

[2]R. H. Canfield. Application of the line interception method in sampling range vegetation. J. Forestry 39: 388-394. 1941.

The bottoms of the sampling planes were delineated by the top of the forest floor and the tops of the planes by the highest particle passing between the sides of the planes. Depth of slash was measured to the nearest centimeter, but forest floor litter was excluded from measurements. The vertical sampling planes were divided into strata 20 centimeters deep and the number of branch particles intersecting the planes recorded by strata and the following particle diameter classes: 0-1, 1-3, 3-10, and over 10 centimeters. Intersections by species were kept separate for the 0-1 size class. Particle diameters appearing borderline between classes were checked with a go-no-go gage.

Calculations

Volume of branchwood was calculated from:

$$V = L\left(\frac{nd^2\pi^2}{8}\right)$$

where V = Volume, $cm.^3$

L = Length of fuel complex perpendicular to sampling plane--set at 1 cm.

n = Number of particle intercepts

d = Average diameter of size class, cm.

Derivation of the formulas and theory and application of the technique are discussed further by Brown,[3] Beaufait,[4] and Van Wagner.[5]

Average diameter of the 0-1 centimeter size class was determined for a large sample of branches randomly collected from the study area. Branch diameters were measured every 10 centimeters beginning at a point 1 centimeter in diameter and continuing to and including the tips of all branchlets. The average was weighted by distance between measurements which was usually less than 10 centimeters for the tip measurements. Average diameter for the 1-3 and 3-10 size classes was determined by running transects through slash on all exposures and measuring diameters of all branches between 1 and 10 centimeters in diameter falling under the transect. Where pieces of slash over 10 centimeters in diameter intersected the sampling planes, they were measured individually and handled separately in the volume equation; thus, determination of an average diameter for these larger pieces was unnecessary.

---

[3]J. K. Brown. A planar intersect method for sampling fuel volume and surface area. Forest Sci. (in press).

[4]W. R. Beaufait. Prescribed fire cooperative study--Region 1-INT. (Study Plan No. 2102-12 on file at Intermountain Forest & Range Exp. Sta., Northern Forest Fire Laboratory, USDA Forest Serv., Missoula, Mont.) 1967.

[5]C. E. Van Wagner. The line intersect method in forest fuel sampling. Forest Sci. 14(1): 20-26, illus. 1968.

Volume of needles was calculated by summing the following formula over all tree species:

$$Vn = (V_b \rho_b cp)/\rho n$$

where Vn = Needle volume, cm.^{3}

V_b = Volume of branchwood 0-1 cm. in diameter, cm.^{3}

ρ_b = Density of branchwood 0-1 cm. in diameter, g./cm.^{3}

c = Needle weight (g.) per gram branchwood 0-1 cm. in diameter

p = Proportion of foliage attached to slash

ρ_n = Density of needles, g./cm.^{3}.

This formula determines the amount of needle volume per unit of branchwood volume. The planar intersect method furnished values of branchwood volume for use in the formula. Weight of needles per gram of branchwood was estimated by stripping needles from samples of branchwood (under 1 centimeter in diameter) and weighing the needle and branch components. The proportion of foliage attached to branches was ocularly estimated by species as the percent of total possible needles assuming no needle-fall had occurred. A mercury pycnometer was used to obtain the density values.

Surface area of branchwood was calculated from:

$$S = L\left[\frac{8.238\ nd}{2}\right]$$

where S = Surface area, cm.^{2}.

Surface area of needles was determined by species from the product of needle volume and needle surface area-to-volume ratio.[6]

RESULTS AND DISCUSSION

Density of foliage must be known prior to calculation of fuel volume and surface area. Density of foliage for all species averaged 0.55 gram per cubic centimeter. Density of branchwood, determined from particles in the 0-1 size class for all species, averaged 0.50 gram per cubic centimeter. The proportion of foliage attached to branches averaged 9 percent for old slash and 38 percent for new slash. Other fuel characteristics required for the calculations are in table 2.

Volume and Surface Area

Fuel volume was concentrated in the lower portions of the slash. About 68 percent of the total volume was below the average mid-depth of the slash (figure 2). Generally, there seemed to be only minor differences in volume between the small- and large-size material and between the old and new slash sampled at various heights above ground (table 3). These results indicate that the small-size material is distributed vertically in about the same proportions as all slash material. However, volume of old slash in the first 20 centimeters above ground comprised 52 percent of the total volume, which is noticeably greater than the 34 percent for new slash. The large proportion of old slash volume in the first 20 centimeters above ground was due to the presence of material over 1 centimeter in diameter.

---

[6] J. K. Brown. Ratios of surface area to volume for common fire fuels. Forest Sci. 16(1): 101-105. 1970.

Table 2.--*Average diameters, needle weights per gram of 0-1 centimeter diameter branchwood, and needle surface area-to-volume ratios for the different species in the slash*[1]

Species	Diameters 0-1 cm.	Diameters 1-3 cm.	Diameters 3-10 cm.	Needle weight per gram branchwood	Needle surface area-to-volume ratio
	Cm.	*Cm.*	*Cm.*	*G./g.*	*Cm.²/cm.³*
Douglas-fir and subalpine fir	[2]0.219	1.63	5.27	[2]1.49	69.1
Spruce	[2].195	1.90	4.76	[2]1.38	54.2
Larch	[2].260	1.82	4.36	[2].19	184.0
Lodgepole pine	.432	1.76	4.88	1.43	64.7
Average[3]	.224	1.74	5.02		

[1]Averages were based on 20 to 250 observations.
[2]Data acquired by W. R. Beaufait as a part of the cooperative study.
[3]Averages were weighted by the total number of sampled intersections for each species.

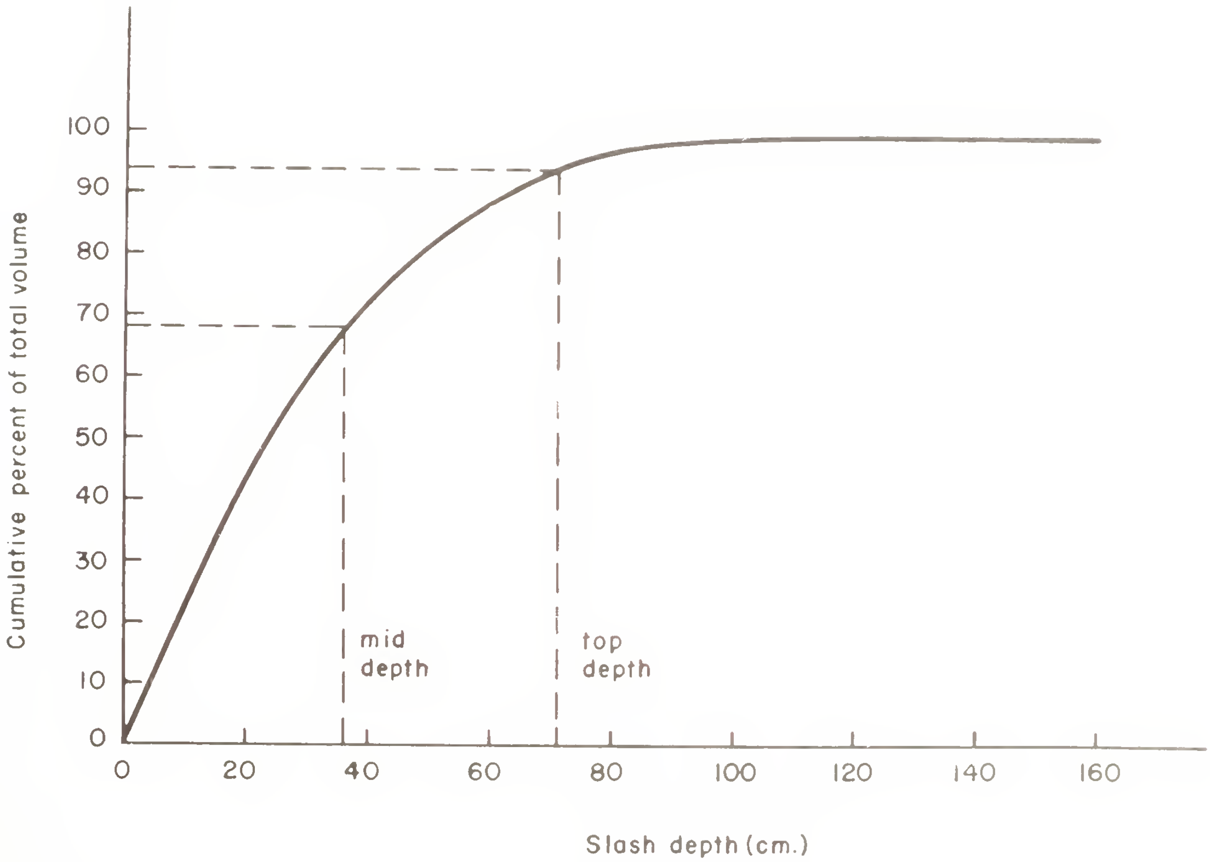


Figure 2.--Cumulative percent of total old and new slash volume at different slash depths. Top depth is the average of all depth measurements and mid-depth is one-half of the top depth.

Table 3.--*Percent of total slash volume by slash age, size, and height above ground*

Height of slash	All-size slash: Old	All-size slash: New	All-size slash: Old and new	0-1 cm.-size slash: Old	0-1 cm.-size slash: New	0-1 cm.-size slash: Old and new
Cm.			*Percent*			
0-19	52	34	43	47	48	48
20-39	23	38	30	32	28	29
40-59	13	19	16	12	14	14
60-79	12	5	9	4	3	3
80-99	<1	4	2	2	4	3
100-119	<1	<1	<1	2	1	1
120-139	<1	<1	<1	<1	<1	<1
140-159	<1	<1	<1	<1	<1	<1

Fuel surface area, like volume, was concentrated in the lower portions of the slash. About 68 percent of the total surface area was below the average mid-depth of the slash. The relationship between cumulative percent surface area and depth is almost identical to that in figure 2. Differences in the proportions of surface area, between small- and large-size material, and between new and old slash in the same strata, averaged a maximum of three percentage points.

Composition of Slash

The species composition of the slash based on the proportion of all particle intersections with all sampling planes was as follows:

Species	*Percent of total intersections*
Douglas-fir and subalpine fir	55.5
Spruce	32.1
Larch	8.1
Lodgepole pine	4.3
	100.0

The proportions of fuel volume and surface area by different-size material comprising the slash are shown in table 4. The new slash contained considerably larger proportions of volume and surface area in the 0-1 size class than old slash because a larger proportion of needles was attached to the branches in new slash. This is shown in the following tabulation of needle volume and surface area, for all of the plots expressed as a percent of the 0-1 size class volume and surface area:

Slash age	*Average needle volume (percent)*	*Average needle surface area (percent)*
Old	6.4	13.5
New	24.5	41.7

The 0-1 size class provided 79 percent of the fuel surface area in new slash but only 49 percent in the old slash. This large proportion of fine-particle surface area in new slash points out the higher potential flammability of new slash compared to old slash.

Table 4.--*Percent of total fuel volume and surface area comprising the slash by diameter classes*

Diameter size class	Volume		Surface area	
	Old slash	New slash	Old slash	New slash
Cm.	*Percent*	*Percent*	*Percent*	*Percent*
0-1	1.0	3.8	49.0	79.4
1-3	4.4	7.3	15.0	8.2
3-10	9.3	11.7	11.6	4.7
10+	85.3	77.2	24.4	7.7
	100.0	100.0	100.0	100.0

A practical fuel sampling technique is suggested by the observation that most of the slash volume (77 and 85 percent, table 4) was from material over 10 centimeters in diameter. If estimates of slash volume are desired, line intersect sampling of material over 10 centimeters in diameter probably would provide adequate fuel volume estimates. Aerial photographs might provide an effective, relatively inexpensive format for sampling with the line intersect method.

Loading

Loadings for the eight blocks examined are shown in the following tabulation:

Degree of loading	*All material*		*0-1 cm.-size class*	
	(kg./m.²)	*(Tons/acre)*	*(kg./m.²)*	*(Tons/acre)*
Highest	47.5	211	1.24	5.5
Lowest	5.1	23	.19	.8
Average	26.5	118	.57	2.6

Bulk Density

Bulk density, a measure of the porosity of a fuel complex, decreased from the ground up through the slash (figure 5). In the lower 20 centimeters of old slash, bulk density was quite high, averaging 0.10 gram per cubic centimeter. This was due to a large volume of material over 1 centimeter in diameter lying close to the ground. Average bulk densities for the entire depth of slash were as follows:

Slash age	*All material*	*0-1 cm.-size class*
	(g./cm.³)	*(g./cm.³)*
Old	0.053	0.00054
New	.030	.00104

The bulk density of old slash is almost twice that of new slash. This indicates that aging of slash permits compaction even within a few months. In a study of slash from nine conifer species, Fahnestock and Dieterich[7] found that slash depth was reduced by 20 percent in 1 year and 45 percent within 5 years. Bulk density also would be correspondingly reduced, although to a lesser extent than depth because loading would decrease due to decay, at least over a 5-year period.

[7] G. R. Fahnestock and J. H. Dieterich. Logging slash flammability after five years. USDA Forest Serv., Intermountain Forest & Range Exp. Sta. Res. Pap. 70, 15 p., illus. 1962.

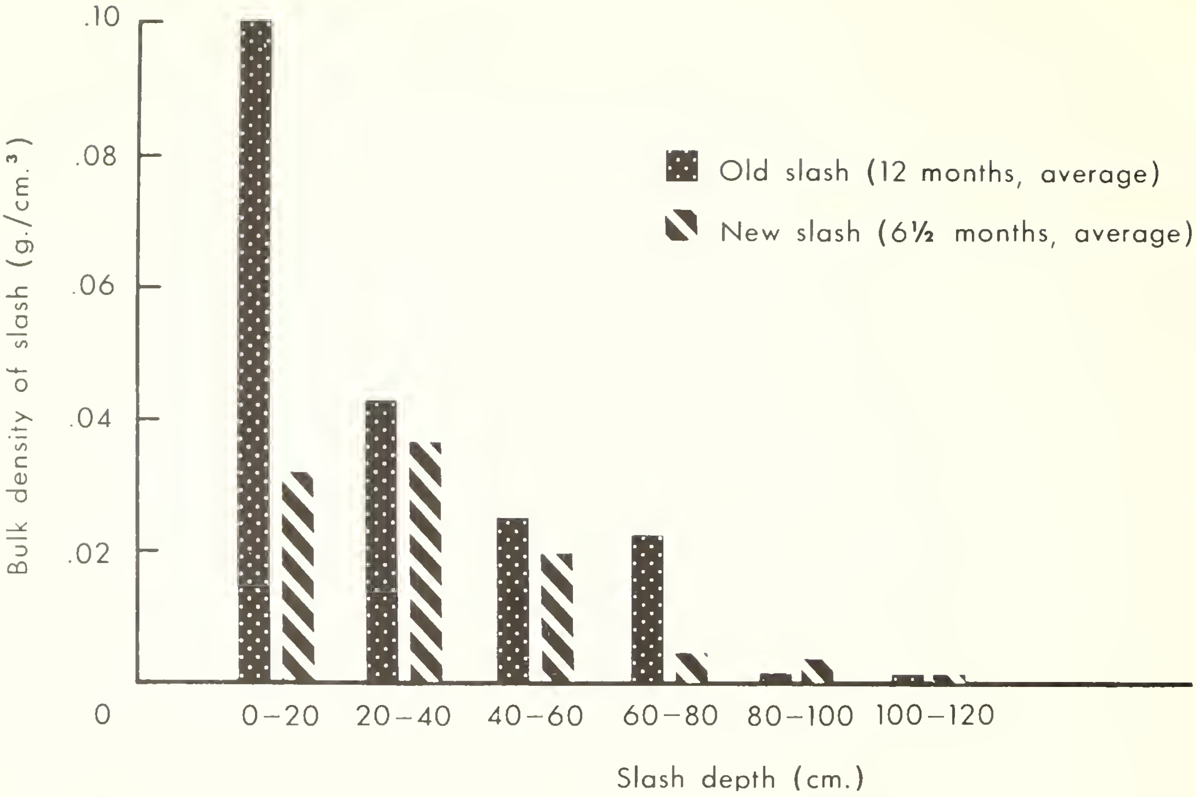


Figure 3.--Bulk density of old and new slash at 20-centimeter depth levels. The average depth was 73 centimeters for old slash and 68 centimeters for new slash.

Void Volume to Surface Area Ratio (λ)

The ratio λ is also a measure of the porosity of a fuel complex and expresses the amount of void space associated with a unit area of fuel surface. Generally, as λ increases, movement of air and other gases is freer because the space between particles is greater. But, at the same time, the distance radiant heat must travel between particles is greater.

In this study, λ increased vertically with old slash generally being more porous as shown in the tabulation below:

Slash depth	*Slash age*	
	Old	*New*
(cm.)	*(cm.³/cm.²)*	*(cm.³/cm.²)*
0-19	9	6
20-39	14	10
40-59	37	20
60-79	62	93
80-99	283	82
100-119	284	250
120-139	922	454
140-159	1,130	937

Suspended Needle Mats

Suspended needle mats are layers of dead needles formed when needles fall and catch on branches. The branches and trapped needles catch other needles, thus, forming mats. Mats of needles (some bark flakes are also present) may build up to a thickness of 2 or 3 centimeters and resemble small pieces of the forest-floor litter layer suspended within the slash.

Needle mats were recorded intersecting 40 percent of the sampling planes. This is a rather high occurrence of mats since each sampling plane is represented by a line transect 30 centimeters long. Thus, one or more mats were observed on almost every other 30-centimeter-long transect. The average length of mat material lying within a sampling plane was 21 centimeters. The number and size of needle mats did not vary significantly between old and new slash.

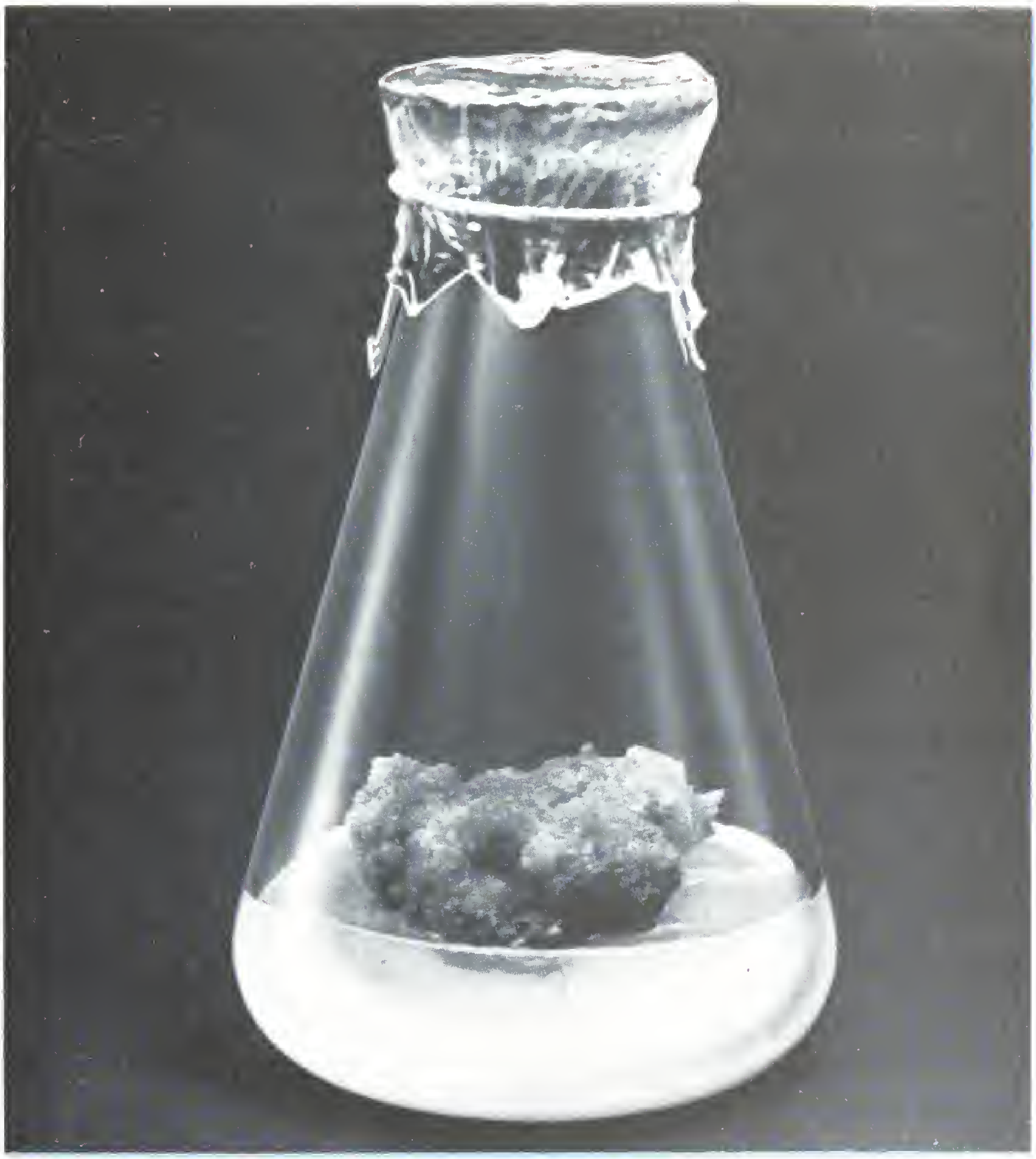
The significance of needle mats on the flammability of slash is unknown; however, these mats are probably highly flammable due to their fine particle composition. The formation of needle mats retains fallen dead needles within the slash and prevents their compaction on the ground.

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

PREPARATIVE TECHNIQUES AND TISSUE-SELECTION CRITERIA FOR *IN VITRO* CULTURE OF HEALTHY AND RUST-INFECTED CONIFER TISSUES

J. L. Grasham and A. E. Harvey



USDA Forest Service Research Paper INT-82, 1970

INTERMOUNTAIN FOREST AND RANGE
EXPERIMENT STATION
Ogden, Utah 84401

USDA Forest Service
Research Paper INT-82
1970

PREPARATIVE TECHNIQUES AND TISSUE-SELECTION CRITERIA FOR *IN VITRO* CULTURE OF HEALTHY AND RUST-INFECTED CONIFER TISSUES

J. L. Grasham and A. E. Harvey

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

THE AUTHORS

J. L. GRASHAM, Biological Research Technician, joined the Intermountain Station staff in January 1966 and is assigned to the Diseases of White Pine Forest Type Research Work Unit at the Forestry Sciences Laboratory, Moscow, Idaho. Previously, he was a Forestry Technician with the Insect and Disease Control Division, Clearwater National Forest, Pierce, Idaho. He attended the University of Arkansas 1957-1958, Connors Junior College 1958-1960, Northeastern State College 1960-1961. Presently, he is working towards a B.S. degree in Agriculture at the University of Idaho, majoring in Plant Sciences.

A. E. HARVEY, Research Plant Pathologist, is presently responsible for research investigations on the biology, host parasite physiology, and biochemistry of the white pine blister rust fungus and for developing methodology of screening and testing chemicals for its control. He is assigned to the Diseases of White Pine Forest Type Research Work Unit at the Forestry Sciences Laboratory, Moscow, Idaho. Dr. Harvey received the B.S. degree in Biology (1960), the M.S. degree in Plant Pathology (1962), and the Ph.D. degree in Plant Pathology (1968) from Washington State University. He joined the Intermountain Station staff in 1965.

CONTENTS

ABSTRACT

Selection of young stem sections free of external injury and the reduction of physical and/or chemical damage to tissues during their preparation, sterilization, and excision were the most important factors governing survival and growth of healthy and diseased conifer tissues *in vitro*. Most (75-98 percent) primary explants from properly selected stems, prepared as described, survived and produced subsequent growth on suitable media. Proliferation of the rust (*Cronartium ribicola* J. C. Fisch. ex Rabenh.) occurred in 75 percent of the surviving blister rust-infected primary explants from western white pine (*Pinus monticola* Dougl.).

INTRODUCTION

The tissue culture technique has long been used to study the physiology of specific plants, plant organs, and tissues. By employing this technique, one can control the environment, the substrate, and (if he uses clonal stock) the genetic composition of the tissues under observation. Thus, the effects of variables on such studies can be minimized or eliminated.

It is recognized that members of the order Coniferales are difficult to propagate vegetatively *in vitro* (Loewenberg and Skoog 1952; Reinert 1962). Researchers have reported excessive tissue damage and/or secondary contamination during the primary explanting stage (Gautheret 1959; Koenigs 1968). In the authors' opinion, failures to culture conifer tissues have been due to improper preparative techniques and tissue-selection criteria. Our success with several conifer species (Harvey 1967; Harvey and Grasham 1969a) and with rust-infected western white pine, *Pinus monticola* Dougl., (Harvey and Grasham 1969b) prompted us to prepare this paper detailing improved techniques.

TECHNIQUES

To be successful, our techniques require timing as well as treatment; so we have outlined them in order, from sample selection through explant incubation.

Preparation of Healthy Conifer Tissues

Tissue-selection criteria.--Optimum tissue culture proliferation was obtained by using primary explants from current-year stems of either vigorous nursery stock or field-grown trees. Satisfactory results were also obtained by using older material, but callus development and growth were not as rapid. Callus development was delayed when we cultured material collected in Idaho during the months of December, January, and February.

Contamination was kept minimal by using stem sections that had a smooth bark, free of insect or mechanical damage (figs. 1 and 2). Except for the fungi and bacteria indigenous to the cortex, subepidermal bark tissues were relatively free of contamination.

Cultures were prepared the day that material was collected. Although overnight refrigeration of material before preparation was acceptable, further delay allowed tissue oxidation and contamination buildup, both of which are severely detrimental to *in vitro* tissue growth.

Pre-sterilization preparation.--Needles were clipped flush with the bark surface before the stems were sterilized. Care was taken to avoid damage to bark tissues during this operation. Tears permitted the sterilizing fluids used during subsequent operations to penetrate and injure cortical tissues. Tissue damaged by excessive penetration of sterilizing fluids proliferated poorly *in vitro*.

Stems from which needles had been removed were sectioned into 2-3-cm. lengths by means of a high-speed, fine-bladed jigsaw (fig. 3). The fraying action of the reciprocating blade tended to seal the open ends, which prevented excessive penetration by sterilizing fluids. End pieces were extensively damaged at the time of collection and were always discarded.

Cut sections were washed for 1 hour under rapidly running tapwater to free them of dirt and other foreign matter. In our laboratory, a longer washing period resulted in contamination by bacteria commonly associated with the water supply. Water-saturated stem sections were not satisfactory to tissue culture for this reason.

Sterilization.--After being washed, the sections were gently shaken in 200-500 mℓ. of a 5.25% sodium hypochloride (NaOCl) solution contained in a 1-liter, screw-top flask. No more than 25 sections were treated at one time in order to minimize the total contaminant load and to assure proper sterilization. If stem sections were properly chosen, they required only 1 to 3 minutes of surface sterilization. Since the cortex is well-protected by the unbroken epidermis of current-year stems, it was relatively free of contamination and only surface sterilization was necessary. An alternate treatment, the use of a 3% hydrogen-peroxide (H_2O_2) solution for 24 hours, successfully controlled contamination of conifer species *(Pinus nigra, P. ponderosa, Larix occidentalis)* easily damaged by the NaOCl solution (Harvey and Grasham 1969a). Whenever cortical tissues had low levels of surface contamination, decreasing sterilization periods resulted in better tissue culture development, although for most tissues more time was needed to control contamination. An increase in sterilization delayed callus development. Immediately following sterilization with either NaOCl or H_2O_2, stem sections were rinsed three to five times in cool, sterile distilled water to remove all traces of the sterilant. (Complete removal of the sterilizing agent is necessary for normal callus development.)

Excision of primary explants.--Immediately after sterilization, cortical tissues were aseptically excised from the stem sections and transferred to the desired medium. These tissues constituted the primary explants.

During the excision process, all tools were kept cool (room temperature), extremely sharp, and free of the sterilizing agent. Razor blades and scalpels were changed frequently to prevent dull or damaged tools from tearing or bruising the tissue. Bruising or tearing of the cortical tissues during excision caused discoloration and abnormal development of the callus tissue. Similar effects were observed when tissues came in contact with hot instruments or with a sterilizing agent.

Each stem section was separately removed from the flask in a sterile room and placed on a sterile surface. Each section was held gently but firmly by sterile forceps. A sterile blade was then used to make a longitudinal slit through the bark and cambium (fig. 4). The Bard Parker surgical blade No. 11 was satisfactory. Forceps were then used to rotate the section while the cuticle and epidermis were surgically removed in thin, longitudinal strips (fig. 5). (Several fungi are associated with these tissues; so complete removal of these layers is essential.) Extreme care was taken not to bruise cortical tissues during this process. Cortical tissues were then undercut in the cambial zone (fig. 6) and carefully lifted from the woody cylinder (fig. 7). The wood was discarded. The damaged ends of the cortical tissues were trimmed, and the remaining tissues cut into 100-150-$mm.^2$ rectangular pieces. These pieces then were placed, cambium side down, on culture media. Optimum tissue culture growth and callus proliferation were obtained when large (100-150 $mm.^2$) primary explants were used. All working surfaces and tools were resterilized with alcohol, flame-dried, and air-cooled before the next section was prepared.

Incubation vessels.--Standard flare-mouth culture tubes (25 X 100 mm.) covered with a single layer of plastic food wrap were used successfully as incubation vessels. The tubes contained 15 mℓ. of medium and proved to be satisfactory for tests of 90 days' duration. Similarly covered, 125-mℓ., wide-mouthed Erlenmeyer flasks, containing 50 mℓ. of medium, produced superior growth when cultures were maintained more than 90 days.

The plastic film closures replaced Dispo foam plugs that were used during preparation of the media and as closures until all primary explants had been placed on a culture medium.

Closures were prepared by pressing large sheets of plastic food wrap on an alcohol-dampened surface for sterilization. Sheets then were cut in place with a razor blade into 6-cm. squares and placed, sterile side down, over the mouth of the vessel. A tight-fitting rubber band secured the closure.

Plastic film closures were superior to other types of closures tested. Tissue cultures grown in tubes that had cork or screw-cap tops showed erratic growth. Bacteriological stoppers or cotton plugs permitted media to dry too rapidly for our needs.

Incubation environment.--Explants were incubated at 20° C. ±2° with light for 16 hours and then at 5° C. ±2° without light for 8 hours (Harvey and Grasham 1969b). Cool, white fluorescent light at an intensity of 400 ft.-c. was satisfactory. Tissue cultures grown in darkness or semidarkness lacked vigor compared to those grown under light. Optimum results were obtained by beginning incubation of the explants at the start of the cool, dark period of the incubation cycle.

Medium.--Good proliferation was obtained with many conifer species (Harvey 1967; Harvey and Grasham 1969a) by using a simple medium consisting of the essential auxins, indoleacetic acid (IAA), napthaleneacetic acid (NAA) or 2,4-dichlorophenoxyacetic acid (2,4-D), at concentrations between .01 and 5 mg./ℓ.

Addition to the medium of certain amino acids, vitamins, and other growth factors further enhanced growth and development of many species (Harvey and Grasham 1969a). Tissue cultures benefited most when such compounds were used in microgram quantities (10, 100, 1,000 µg./ℓ.).

All *heat-sensitive organic* compounds were sterilized by *filtration* and added to the autoclaved, basal salt medium (Harvey and Grasham 1969a) after it had cooled to 50° C.

The pH of the medium played an important role in the initial growth of the cambium layer. Our work indicated that a pH range of 4.0 to 6.0 was suitable for the initial growth of most cambium explants (Harvey and Grasham 1969a).

Preparation of Blister Rust-Infected Western White Pine Tissues

Save for minor modifications, these same techniques were used for the *in vitro* culture of rust-infected western white pine (Harvey and Grasham 1969b). The proper selection of stem sections is critical to the culture of infected material. Material chosen must be 2 to 3 years older than that used in healthy tissue studies to assure rust infection and ramification. Nonfruiting rust cankers from 2- to 3-year-old growth segments of 6- to 10-year-old seedlings have been the best source of infected material.

After the needles were removed in the laboratory, the stems were sectioned as previously described. Only the outer edge of the infection was used. Stem sections were cut so that they were one-eighth infected and seven-eighths healthy tissue (fig. 3).

A sterilization period of 5-10 minutes using 5.25% NaOCl solution was necessary to adequately control contamination. Again, all traces of the sterilant were removed by rinsing the sections three to five times in cool, sterile distilled water.

Bark sections were excised according to the procedure outlined for healthy tissue, except that cortical tissues were divided into rectangular pieces (100-150 mm.^{2}). One-eighth of each rectangle was infected tissue, seven-eighths of each piece, healthy tissue (fig. 7).

Seventy-five to 98 percent survival and subsequent growth of healthy and blister rust-infected white pine (Harvey 1967; Harvey and Grasham 1969b) and a minimum of 75 percent survival and growth of other species (Harvey and Grasham 1969a) were obtained on artificial media by following these techniques.

DISCUSSION

The delay in tissue development experienced during the winter months appeared to be related to dormancy. The dormancy requirement apparently had not been satisfied. As a result, the physiological condition of this tissue was less receptive to auxin-induced growth and an adjustment period (not required by active tissue) was necessary.

The reduced surface oxidation and subsequent increase in growth noted when cultures were started at the beginning of the cool period were apparently related to the effects of temperature on the rate of chemical oxidation. The lower temperature may also have permitted the tissue to neutralize the effects of oxidation.

The use of large primary explants assures: (1) substantial food reserves necessary to maintain the explants until proliferation begins; and (2) reduction of the injured:uninjured tissue ratio to minimize the effects of damages incurred during tissue preparation.

The one-eighth infected to seven-eighths healthy tissue ratio used to culture rust-infected tissue allowed for good host development and adequate inoculum potential for rust proliferation. This ratio is important to successful culture of this host-parasite system and produces optimum results.

The increase of growth experienced when plastic vessel closures were used was apparently related to: (1) increased light transmission; (2) the conservation of moisture in the vessel; and (3) an adequate exchange of gases. The requirement for a balanced system of gaseous exchange and moisture conservation was effectively demonstrated when closures permitted either excessive moisture loss (cotton) or no gas exchange (screw caps or corks).

Since all other cultural conditions were identical, the increased growth obtained in 125-mℓ. flasks over that in 25 X 100 mm. tubes was due to the amount of medium and/or gas volume available to the tissues.

In our experience, failures of primary explants to proliferate into callus tissues were usually related to one or more of the following procedural errors:

1.--Improper selection of plant materials;
2.--Delay in excision of tissues after collection of materials;
3.--Improper length of time for sterilization;
4.--Inadequate removal of a sterilizing agent;
5.--Incomplete removal of the epidermis;
6.--Damage to cortical tissues from hot or dull excision blades;
7.--Bruising or tearing of the excised tissues;
8.--Delay in transferring excised tissues to a culture medium;
9.--Improper incubation conditions;
10.--Incorrect selection or concentration of auxin; and
11.--Improper pH of the medium.

CONCLUSIONS

The techniques described herein increase the efficiency of culturing a wide variety of conifer tissues. These techniques may also be beneficial to the *in vitro* establishment of many obligate parasites of cultured species. These techniques should not only improve results obtained in culturing conifer species, but may be applicable to the culture of other members of the plant kingdom.

LITERATURE CITED

Gautheret, R. J.
1959. La culture des tissus végétaux: techniques et réalisations. Masson et Cie, Paris. 863 p.

Harvey, A. E.
1967. Tissue culture of *Pinus monticola* on a chemically defined medium. Can. J. Bot. 45: 1783-1787.

________, and J. L. Grasham.
1969a. Procedures and media for obtaining tissue cultures of 12 conifer species. Can. J. Bot. 47: 547-549.

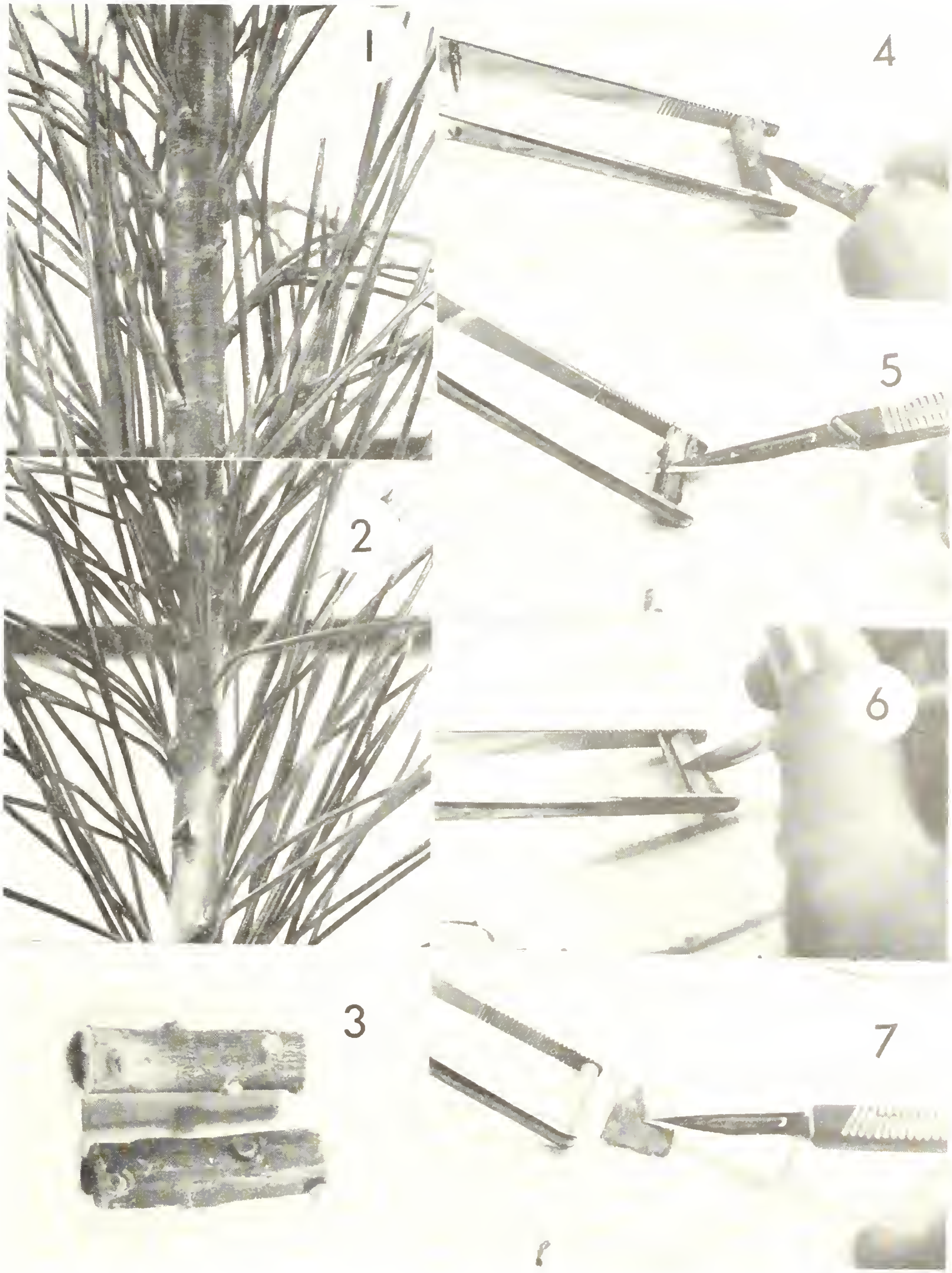
________, and J. L. Grasham.
1969b. Growth of the rust fungus *Cronartium ribicola* in tissue cultures of *Pinus monticola*. Can. J. Bot. 47: 663-666.

Koenigs, J. W.
1968. Culturing the white pine blister rust fungus in callus of western white pine. Phytopathology 58: 46-48.

Loewenberg, J., and F. Skoog.
1952. Pine tissue cultures. Physiol. Plant. 5: 33-36.

Reinert, J.
1962. Morphogenesis in plant tissue cultures. Endeavour 21: 85-90.

Figures 1-7. The selection and preparation of healthy and parasitized conifer explants for tissue culture. Figures 1 and 2, the type of stems found most suitable for tissue culture explants of healthy and infected western white pine and other conifer species. Arrow denotes the discolored edge of the rust-infected zone in figure 2 (2.5X). Figure 3, 2- to 3-cm. sections of healthy (lower) and rust-infected (upper) current-year stems of western white pine prepared for sterilization (2X). Figures 4, 5, 6, and 7, stepwise removal of an infected cambium strip from western white pine, after surface sterilization (3/4X).


1
2
3
4
5
6
7

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

ESTIMATING SEED STORED IN SEROTINOUS CONES OF LODGEPOLE PINE

James E. Lotan and Chester E. Jensen

USDA Forest Service Research Paper INT-83, 1970
Intermountain Forest and Range Experiment Station
Ogden, Utah 84401

THE AUTHORS

JAMES E. LOTAN has been Project Leader of the Intermountain Station's Lodgepole Pine Silviculture research work unit, located in Bozeman, Montana, since 1965. He has been a member of this unit since 1961 and has published a number of articles on lodgepole pine management.

CHESTER E. JENSEN is Principal Statistician for the Intermountain Forest and Range Experiment Station. Previously, he held the same position at the Northeastern and Central States Forest Experiment Stations. Mr. Jensen, who holds a master of forestry degree from Michigan State University, received his training in graduate statistics at Iowa State University.

USDA Forest Service
Research Paper INT-83
1970

ESTIMATING SEED STORED IN SEROTINOUS CONES OF LODGEPOLE PINE

James E. Lotan and Chester E. Jensen

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

CONTENTS

ABSTRACT

Two interim formulas for estimating the number of serotinous eones in lodgepole pine stands are presented. One formula requires a 25-limb sample count of serotinous eones on felled trees for which total tree estimates are desired together with tree d.b.h., erown ratio, and age; although this formula is more dependable, it is also more eostly in applieation. The seeond formula requires only a eount of trees bearing serotinous eones on eaeh plot plus average d.b.h. and average age for trees on eaeh plot.

Methods are also presented for expanding these estimates to number of viable seeds per aere, for the area of interest.

INTRODUCTION

Many stands of Rocky Mountain lodgepole pine (*Pinus contorta* Dougl.) bear an abundance of serotinous cones containing viable seed. These unopened cones remain on the trees up to 40 years and may provide most of the seed for regenerating burned or logged areas. However, the number of serotinous cones differs considerably from tree to tree within stands; also, the same is true for the proportion of closed-cone-type trees between stands (Crossley 1956; Lotan 1967, 1968).

When the closed-cone habit prevails, the species has the ability to store seed from year to year, accumulating literally millions of seed per acre, and if the forest manager is aware of the seed potential, he can secure natural regeneration through appropriate scheduling of cultural treatments.

It is equally important that the forest manager recognize a lack of stored seed in areas to be clearcut so that he can plan for artificial regeneration well in advance of cutting. Seed dispersed annually from surrounding uncut stands cannot be expected to reach more than 200 feet into cutover areas (Boe 1956; Tackle 1964).

It is clear that in lodgepole pine management there is need for evaluation of seed potential for both ecological and silvicultural purposes. The first step is to estimate the biotic potential for restocking, using an estimate of the number of viable seed per acre (as shown in this paper) as a base.

Previously, Lotan (1963) published a simple linear formula using a 25-limb count of serotinous cones on felled sample trees as the basis for estimating the total number of serotinous cones per tree. Since then, these data have been supplemented and more dependable multivariable formulas have been developed for use in the application of two estimating methods, one involving measurements on felled trees and the other on standing trees.

ESTIMATING THE NUMBER OF VIABLE SEED FOR THE AREA OF INTEREST

This process is described below in three steps.

A. Number of Serotinous Cones Per Acre

Method I

The first method for estimating the number of serotinous cones is likely to be the most dependable of the two considered here, but is costly to apply because of the need to fell plot trees. This method would perhaps be most appropriate for research applications in the area from which the study data originated and where higher estimating precision is required. It includes use of an equation (shown below) to estimate number of cones per tree for trees on sample plots. Plot totals are then converted to per-acre values and are averaged.

$$Y = (0.0807 \text{ d.b.h.}^2 + 60.3 \text{ cr} - 58.7 \text{ cr}^2 - 0.0754 \text{ age} + 0.1585 \text{ count} - 3.45)^2 \quad (1)$$

where Y = Total serotinous cones per tree,
D.b.h. = Diameter at breast height in inches,
Cr = Live crown ratio,
Age = Age of tree at stump height in years,
Count = Total number of serotinous cones on the 25-branch segments.

The coefficient of multiple determination, or R^2, was 0.834; i.e., these variables account for 83 percent of the variance in Y. The standard error of the estimate is 40 cones per tree, with an average of 965. The half-confidence interval is approximately 120 cones.

How to collect data:--Assuming the application of conventional sampling techniques, plot size should be large enough to include at least 4 to 6 trees of cone-producing size. The required data include:

1. D.b.h. in inches,
2. Total height in feet,
3. Crown length in feet,
4. Tree age at stump height in years,
5. The 25-limb sample count of serotinous cones.

For the 25-limb sample, all trees of cone-producing size must be felled prior to sampling. Count the serotinous cones on 25 outer-one-foot segments of main branches only. Start sampling at the top and work downward around the tree until 25 samples are collected. Record the total number of cones on the 25-limb samples. Use equation (1) and compute the estimated number of serotinous cones per tree. The cones-per-tree values can then be summed for each plot, expanded to per-acre values, and these averaged over plots.

A preliminary sample of plots can be used to determine the coefficient of variation of plot values. These in turn can be used to determine sample size, as is done for other sampling problems. Our samples had means from about 60,000 to 200,000 cones per acre and coefficients of variation that varied from 148 percent for the lower means to 77 percent for the higher means. The standard deviation will usually be about one-quarter to one-third of the range of data.

Method 2

This second method has a potential for rough estimates only, but all required measurements are relatively easy to make and it seems to be the most reasonable alternative available for obtaining stored-cone information.

The equation is:

$$Y = (1.925 \text{ d.b.h.}^2 - 1.371 \text{ age} + 3.411 \text{ tpa} - 0.00615 \text{ tpa}^2 + 46.2)^2 \quad (2)$$

where Y = Serotinous cones per acre,
D.b.h. = Mean plot d.b.h. in inches,
Age = Mean plot age in years,
Tpa = The number of serotinous-cone-type trees per acre.

Figure 1.--On a tree classified as "serotinous," 90 percent or more of the cones it bears are closed. Note the characteristic fusiform shape of the cones indicated by the arrows.

The R^2 for equation (2) is 0.703. But the "Y" values used as input for this equation were, themselves, derived from "smoothed" tree estimates using equation (1) so that the R^2 of 0.703 contains upward bias and the standard error of estimate (13.4 thousand cones per acre) is biased downward. These two biases are thought to be relatively small.

How to collect data:--The plot data required for Method 2 are little more than normally obtained for inventory purposes, and trees do not have to be felled. The data required are:

1. Mean plot d.b.h. in inches (merchantable trees only),
2. Mean plot age in years (merchantable trees only),
3. Number of serotinous-cone types of trees per acre.

Compute the average plot d.b.h. and age. Examine each tree in the plot to determine if it is of the serotinous-cone type. Use good quality binoculars of 6 or 7 power and determine the tree's cone habit. Trees included in the formula should definitely bear 90 percent, or more, serotinous cones (figure 1). Current-year, immature cones are not to be included. Trees not counted are those having 90 percent, or more, open cones (classified as "open-coned," figure 2), and those having between 10 and 90 percent serotinous cones (classified as "intermediate," figure 3). These data should not be collected in wet weather when open cones are closed by hygroscopic swelling (figures 4, 5, and 6). However, observations can be made in the winter when snow is on the ground if relative humidities are low. Field crews should be supervised for accuracy concerning cone determination.

Using equation (2), compute the estimated number of serotinous cones per acre for each plot. Then the average across all plots will be the estimated number of cones per acre. Values from preliminary samples can be used to determine the coefficient of variation and required sampling intensity as mentioned in Method 1.

Figure 2.--On a tree classified as "open-coned," 90 percent or more of the cones it bears are open. Note the characteristic globose shape of the cones indicated by the arrows.

Figure 3.--On a tree classified as "intermediate," between about 10 and 90 percent of its cones are serotinous. It is intermediate in cone habit.

Figure 4.--Serotinous cones.

Figure 5.--Open cones.

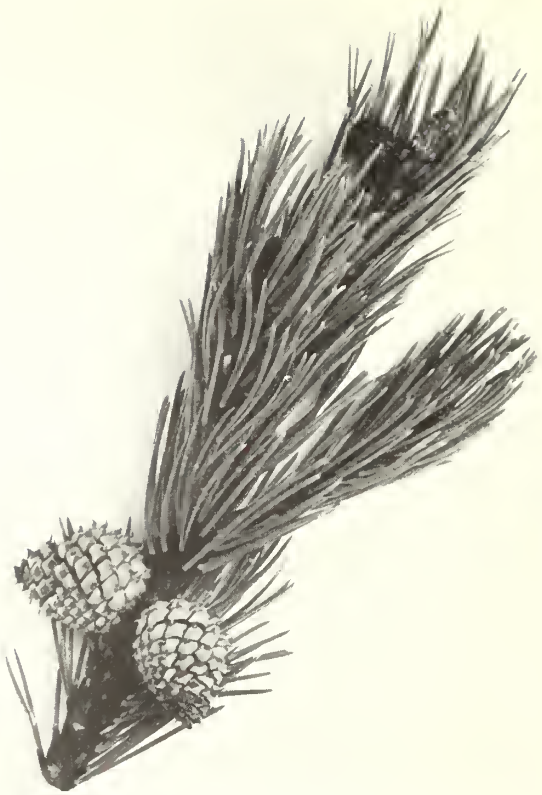


Figure 6.--Open cones closed due to moisture and hygroscopic swelling.

B. Number of Seed Per Acre

The number of cones per acre can be multiplied by an estimated number of seed per cone to arrive at number of seed per acre for the area of interest. A direct seed count from sample cones collected on or near the study plots is recommended.

Although direct seed counts are apt to be more reliable, average cone length can be used as a basis for estimating number of seed per cone. See Thompson's formula (1969) presented below:

$$Y = 10.3X - 25.3 \tag{3}$$

where Y = Number of seed per cone,
X = Cone length in cm. and $X \geq 2.5$ cm.

But the r^2 value (0.38) in Thompson's data was rather low, and there is no guarantee against bias in application.

C. Number of Viable Seed Per Acre

Either cutting or germination tests should be conducted on seed from the sample cones to obtain the percentage of viable seed; this value can then be multiplied by the total seed estimated for the area to arrive at total viable seed.

The viability of seed from serotinous cones varies substantially between areas and from year to year (from 10 to 90 percent, in our experience).

SAMPLE APPLICATION–NUMBER OF VIABLE SEED FOR THE AREA OF INTEREST

Assume that we have a 1,000-acre area for which we are estimating number of viable seed.

A. Number of Serotinous Cones Per Acre

Method 1

Assume the following measurements of three felled trees on a 1/50-acre plot:

Table 1.--*Measurements of three felled trees*

Tree number	D.b.h.	Total height	Crown length	Age	Serotinous cones on 25 limbs
	Inches	*Feet*	*Feet*	*Years*	*Number*
1	9	90	85	100	250
2	10	80	70	100	210
3	11	90	90	102	230

Table 2.--*Values of variables to be entered in equation (1)*

Tree number	D.b.h.^{2}	Cr	Cr^2	Age	Serotinous cones on 25 limbs
1	81	0.944	0.891	100	250
2	100	.875	.766	100	210
3	121	1.000	1.000	102	230

Multiplying each of these by the appropriate coefficient (from page 2) and adding the constant (-3.45), we have:

Table 3.--*Computations using equation (1)*

Tree number	0.0807 (d.b.h.)	60.3 (Cr)	-58.7 (Cr)^2	-0.0754 (age)	0.1585 (count)	Constant	Sum	(Sum)^2 or cones per tree
1	6.54	56.92	-52.30	-7.54	39.62	-3.45	39.79	1,583
2	8.07	52.76	-44.96	-7.54	33.28	-3.45	38.16	1,456
3	9.76	60.30	-58.70	-7.69	36.46	-3.45	36.68	1,345
Plot sum								4,384

Therefore, the estimate for this 1/50-acre plot is 4,384 serotinous cones. Assume that we had estimates totalling approximately 110,000 cones from twenty-five such plots distributed over the 1,000-acre tract. Then, since our total acres sampled would be 25 (1/50 acre) = 0.5 acre, we can convert the 110,000 cones to a per-acre figure and we have:

110,000 (1.0 acre/0.5 acre) = 220,000 cones per acre.

Method 2

Assuming existence of the following data:

1. Mean plot d.b.h. in inches = 10,
2. Mean plot age in years = 100,
3. Number of serotinous-cone type of trees per acre = 150.

Then using the proper formula (see page 2) we would have:

$$1.925(10)^2 - 1.371(100) + 3.411(150) - 0.00615(150)^2 + 46.2 = 474.9$$

The square of 474.9 or 225,530 is the estimate of number of cones per acre, or approximately 226,000.

B. Number of Seed Per Acre

Either make a direct seed count per cone or obtain length measurements and use Thompson's formula. Then, assume a sample cone estimate of 10 seed per cone. Using Method 1 we would estimate:

220,000 x 10 = 2,200,000 seed/acre.

Using Method 2 we would estimate:

226,000 x 10 = 2,260,000 seed/acre.

C. Number of Viable Seed Per Acre

Assume that either cutting or germination tests on seed from sample cones resulted in viability estimates of 80 percent. Then we would estimate viable seed per acre as being:

2,200,000(0.8) = 1,760,000, using Method 1
or, 2,260,000(0.8) = 1,808,000, using Method 2.

LIMITATIONS OF EQUATIONS (1) AND (2)

Equations (1) and (2) are interim and are most applicable to the largely mature and overmature stands sampled in this study near West Yellowstone, Montana, and Island Park, Idaho (Lotan 1967, 1968). The characteristics of these stands are shown in table 4. It is believed that these two equations will also be representative for the vast acreages of these types of stands in the northern Rocky Mountain and Intermountain Regions (Idaho, Montana, Wyoming, and Utah) not sampled here.

A positive coefficient might be expected for age in equations (1) and (2) for stands up to about 60 years old. However, in older stands such as those studied here, the trees gradually, with increased age, lose their capacity for cone production. Thus, we have a negative coefficient for age.

Table 4.--*Characteristics of stands in serotinous cone survey, Gallatin National Forest, 1963, and Targhee National Forest, 1964*

Study area	Average age	Average d.b.h.	Average total height
	Years	*Inches*	*Feet*
West Yellowstone Flat	111	8.3	49.2
Madison Plateau Front (old burn)	88	6.7	53.0
Island Park Flat	117	10.0	66.0
Moose Creek Plateau	191	12.5	61.0

SIGNIFICANCE OF STORED SEED PER ACRE

Seed per acre, stored in closed cones, give an estimate of the biotic potential of the previous stand to regenerate the disturbed area. If one knows the probability of a seedling becoming established (probable seed-seedling ratio) at a specific age (1 year old, 3 years old, etc.) for a given seedbed condition, habitat type, climate, and aspect, he can then estimate the number of seedlings per acre that can be expected at the age specified.

Throughout its range, lodgepole pine regeneration tends to vary. Stored seed per acre can vary from a few thousand to a few million and considering this wide range an estimator need only be concerned with large differences in stocking potential; that is, whether one might expect stocking on the order of a few hundred stems per acre or tens of thousands per acre.

After harvesting lodgepole pine in central Montana foresters can expect 20,000 seedlings per acre. Elsewhere, as in some parts of Wyoming, an absence of the serotinous cone habit in lodgepole pine requires an artificial means of regenerating the stand. However, in many areas, regeneration by natural means is variable. One of the important factors in this variability is the number of seed stored in serotinous cones of the species. An estimate of seed per acre is the first factor to consider in predicting success or failure of the natural regeneration process in lodgepole pine.

We can now see a number of opportunities to regulate stocking through manipulation of either the estimated seed supply or the environment. It is possible to secure adequate stocking on areas where experience-based seed-seedling ratios and stored seed estimates indicate probable understocking. This can be accomplished by any one of the following: intensifying site preparation; treating slash to assure maximum seed release; treating the area to reduce seed loss to rodents; or by using a combination of these treatments to gain maximum benefits from stored seed. Conversely, expected overstocking may be reduced by: limiting site preparation; reducing disturbance of the soil surface during logging; or by treating the slash to destroy a portion of the stored seed. During preparation of cutting plans, it is important to fully realize the potential for natural regeneration. This information will be useful in preparing stand prescriptions for future treatments; these treatments may involve major thinning operations or the gathering of seed and growing of seedlings at a nursery.

REFERENCES

Boe, Kenneth N.
1956. Regeneration and slash disposal in lodgepole pine cuttings. Northwest Sci. 30(1): 1-11, illus.

Crossley, D. I.
1956. Fruiting habits of lodgepole pine. Can. Dep. Northern Aff. and Nat. Resources, Forest Res. Div. Tech. Note 35, 32 p., illus.

Lotan, James E.
1963. Sampling serotinous cones in lodgepole pine. Mont. Acad. Sci. Proc. 23: 20-24, illus.

_______ 1967. Cone serotiny of lodgepole pine near West Yellowstone, Montana. Forest Sci. 13(1): 55-59, illus.

_______ 1968. Cone serotiny of lodgepole pine near Island Park, Idaho. U.S. Forest Serv. Res. Pap. INT-52, 6 p., illus.

Tackle, David
1964. Regenerating lodgepole pine in central Montana following clear cutting. U.S. Forest Serv. Res. Note INT-17, 7 p., illus.

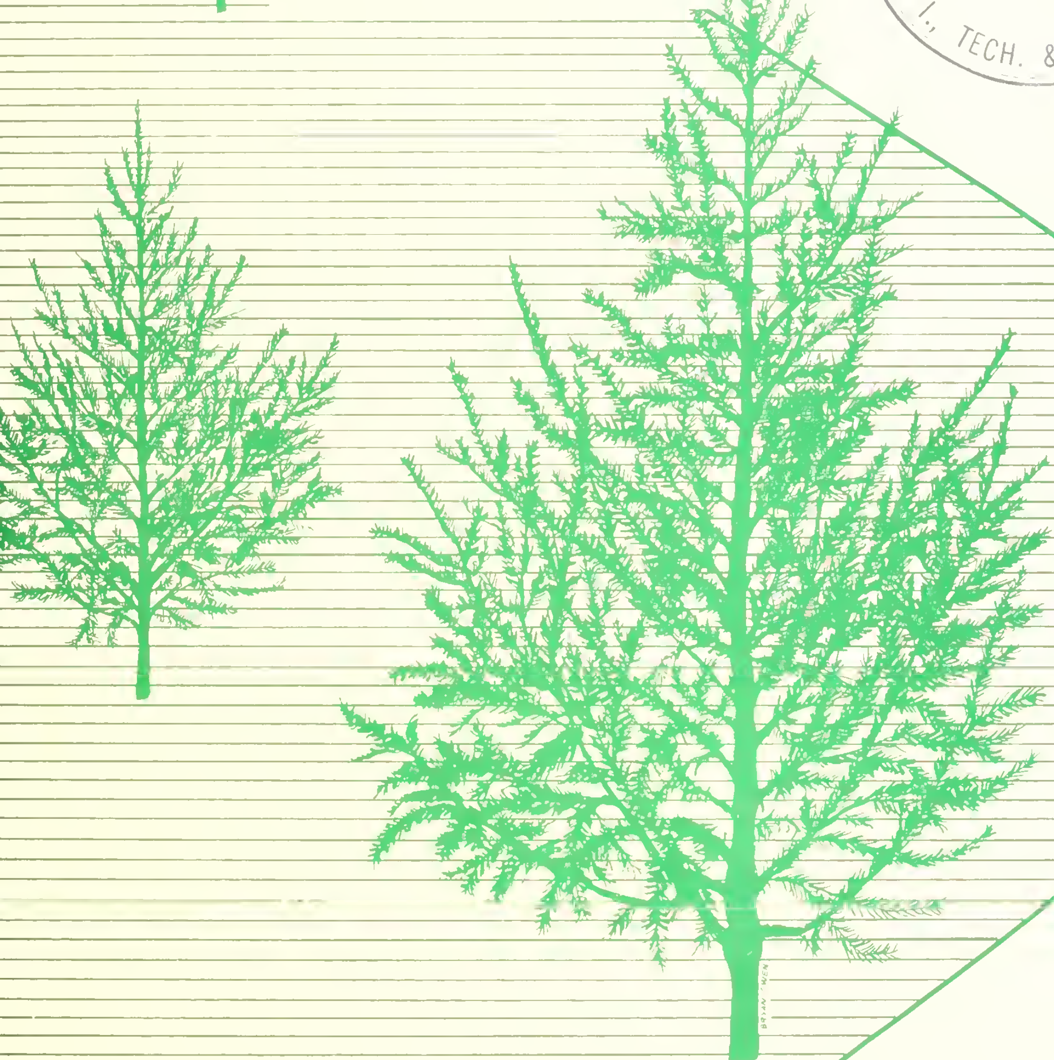
Thompson, Ronald E.
1969. Relationship of seed yield and viability to the age of cones of lodgepole pine. Unpub. master's thesis, Univ. of Mass., Amherst.

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

Christmas Tree Culture In Natural Stands Of Douglas-Fir In Montana

BY WYMAN C. SCHMIDT



U S D A FOREST SERVICE
RESEARCH PAPER INT 84
1970

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
OGDEN, UTAH 84401

THE AUTHOR

WYMAN C. SCHMIDT is Associate Silviculturist and Leader of the Silviculture of Western Larch and Engelmann Spruce research work unit at the Forestry Sciences Laboratory in Missoula, Montana. After 1 year with the National Forest Administration in the Black Hills, he joined the Intermountain Station in 1960 and since then has worked primarily in research of young coniferous forests. He holds B.S. and M.S. degrees in Forest Management and is currently completing requirements for the Ph.D. in Forest Ecology at the University of Montana.

The author acknowledges the work of B. M. Huey, A. L. Roe, K. N. Boe, and R. C. Shearer in designing, establishing, and collecting field data for this study and the cooperation of Gilbert Kries, Don and Winton Weydemeyer, as well as the Anaconda Forest Products, Northern Pacific Railroad, Montana State Forester, and the Flathead, Kootenai, and Lolo National Forests in the use of their lands.

USDA Forest Service
Research Paper INT-84
December 1970

CHRISTMAS TREE CULTURE IN NATURAL STANDS OF DOUGLAS-FIR IN MONTANA

Wyman C. Schmidt

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

CONTENTS

ABSTRACT

A 10-year study of three commonly used Christmas tree culture methods--stump culture, basal pruning, and thicket thinning--in natural stands of Douglas-fir in Montana showed that quantity and quality of trees can be increased. Stump culture, featuring upturned branches or adventitious shoots, produced large high quality trees rapidly. Trees originating from branch turnups reached larger sizes earlier than those from shoots. Basal pruning reduced height growth in direct proportion to the amount of crown removal for 5 to 10 years but demonstrated no corresponding increase in quantity or quality of the trees produced on the relatively low quality sites represented in the study. Douglas-fir thickets produced many Christmas trees in the initial thinnings and subsequent harvests, but they were small medium quality trees. Light to moderate thinnings maintained the stand in better condition for future production than heavy thinning.

INTRODUCTION

Douglas-fir *(Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco) still reigns as king of the Christmas tree industry in the northern Rockies, accounting for over 80 percent of the Christmas trees harvested. Montana alone supplied over 80 million Christmas trees in the last three decades--practically all of them Douglas-fir (Benson 1967). Its harvests increased rapidly during the 1930's and 1940's, reaching a peak in 1956 when 4.2 million trees were exported from the State (Wilson 1957); since then, harvests have declined to 2 million trees annually (Benson 1965). However, Montana still accounts for about 5 percent of the trees sold in the United States, but this amounts to less than half of its share of the market during the 1940's when it supplied over 10 percent of the Nation's wants.

Several factors probably account for this decline. Disease and insects, such as needlecast disease *(Rhabdocline pseudotsugae* Syd.), needle midge insects *(Cecidomyia* sp.), and Cooley's gall louse *(Adelges cooleyi* Gill.), periodically flare up and reduce tree quality (Roe 1948). Spruce budworm *(Choristoneura* sp.) populations built up in the 1950's and still continue to defoliate extensive areas of Douglas-fir. All of these pests reduce the number of good quality trees available for the increasingly competitive Christmas tree market. Artificial Christmas trees have increased nationwide and may also be a factor involved in the decline of Montana tree sales.

Douglas-fir trees have many inherent desirable Christmas tree qualities--soft short needles, deep green color, pleasant aroma, a "natural" look, good needle retention after cutting, and good shipping characteristics. As a result, the demand for Douglas-fir trees has always been strong and they command a good price, sometimes twice as much as similar quality pine trees (Wright 1965). However, an increasing number of buyers are demanding trees with crowns that are denser than crowns of trees commonly found in wild stands. As a result, cultured trees are commanding an increasing share of the market--uncultured trees from natural, wild stands dropped from 57 percent of the total shipments from the Pacific Northwest in 1959 to 24 percent in 1964 (Douglass 1965).

Christmas tree producers in the Northern Rockies seek to promote both the area and the species in the eyes of the buyer by increasing the quality of trees reaching the market. To do this, they are using numerous cultural methods in their natural stands.

However, many growers are uncertain whether they are benefiting from using such methods or which methods yield the greatest number of marketable trees on their site conditions. This study was designed to determine if these commonly used cultural treatments actually do increase the total production as well as the quality of Christmas trees in natural Douglas-fir stands.

CULTURAL METHODS TESTED

Three types of cultural methods--stump culture, basal pruning, and thicket thinning--were tested over a 10-year period starting in the late 1940's. Five study plots in western Montana near Eureka, Kalispell, Greenough, Plains, and Lolo (fig. 1) provided a cross section of stand and site conditions. Tree quality and size, based on Hutchison's and Huey's (1949) standards for Montana,[1] and growth data were collected 5 and 10 years after the treatments.

---

[1]The Christmas tree grades used in this study--premium, standard, utility, and cull--are very similar to the present grades (U.S. Dep. Agr. 1962)--premium, choice, standard, and cull--respectively.

Figure 1.--Location of test plots used in study.

Stump Culture

Stump culture is an intriguing practice that likely developed more by chance than by design. If live branches are left on the stumps of small Douglas-fir trees after cutting, the stumps often remain alive and produce new trees from adventitious shoots or branch turnups. Using proper culture treatment, these have potential value as Christmas trees. This study phase had two primary objectives: (1) to determine if stump culture treatments favoring either branch turnups or adventitious shoots were equally effective in producing Christmas trees, and (2) to determine when stumps could be cultured most effectively; 0, 1, 2, or 3 years after the original tree was cut.

The original trees, which averaged 12 to 16 feet in height, were cut with a handsaw about 3 to 4 feet above ground and 3 to 4 inches above a good branch whorl. Stumps treated to favor branch turnups were trimmed to feature one large vigorous branch in the top whorl leaving 5 to 7 vigorous, alternate branches in the lower whorls. Stumps treated to favor adventitious shoots were trimmed so that all the branches on the upper 18 inches, and all but 5 to 7 vigorous, alternate branches in the lower whorls were removed (fig. 2).

Five to 7 years later, most of the featured branches had turned up, or adventitious shoots had formed and whorls were developing. At that time, excess branches,

Figure 2.--Two stumps were cultured to produce Christmas trees: left stump was treated to favor adventitious shoots; right stump was treated to favor a branch turnup.

which were competing for space with the featured turnups and shoots, were removed. In addition, about half of the lower branches of the new turnups were pruned to reduce excessive height growth.

A paired-tree design method was used: stumps treated to favor branch turnups were matched with those treated to favor adventitious shoots. This same pairing method was used in each of 4 successive years following the cutting of the original trees. Included were 6 pairs of trees in each of 4 years at 5 locations--making a total of 120 pairs of trees. All treatments were randomly assigned.

Basal Pruning

Low-density crown, due to excessive distances between whorls, was felt to be responsible for reducing the quality of many trees. Five different basal pruning methods applied once at the start of this study were tested to determine if height growth, and as a result, distance between whorls could be reduced and if higher quality trees would result. The treatments were:

1. Remove lower two-thirds of the green crown

2. Remove lower one-half of the green crown

3. Remove one-half of the green crown from midtree, leaving lower branches for future stump culture (fig. 3)

4. Remove crown along two-thirds of one side of the green crown and strip off one inch or more of the bark

5. Shear buds from leaders and laterals

A paired-tree design, with one of the pair randomly chosen for pruning and the other used as a check, was used to determine pruning effects (fig. 4). Six pairs of trees for each of the five treatments at five locations--a total of 150 pairs--comprised the sample. When treated, the trees averaged 12 feet in height, ranging from 10 feet on the plot near Eureka to 14 feet on the plot near Lolo.

Figure 3.--Shown above is a natural Douglas-fir tree before and after one-half of the live crown was pruned from midtree. Lower branches were retained for future stump culture.

Thicket Thinning

Douglas-fir often grows in thickets dense enough to severely restrict crown development on individual trees. Consequently, their marketability as Christmas trees is reduced. We sought to determine how three different levels of thinning affect the quantity and quality of trees that could be harvested in these thickets, both initially and subsequently. The three thinning levels were based primarily on ocular estimates of light, medium, and heavy, using the following criteria:

1. Light.--Badly deformed Douglas-fir and all other species removed plus a few merchantable Christmas trees. Residual stand was still crowded with an average spacing of less than 2 feet between trees.

2. Medium.--Badly deformed Douglas-fir and all other species removed plus some merchantable Christmas trees. Residual stand was less crowded than above but there was still some side shading.

3. Heavy.--Badly deformed Douglas-fir and all other species removed plus many merchantable Christmas trees. Residual stand was moderately open with very little side shading.

Figure 4.--Paired trees were used to determine effects of basal pruning on Christmas tree production: the lower two-thirds of the green crown was removed on the tree on the left; the tree on the right served as a check.

All three thinning treatments were installed at each of five locations, making a total of 15 plots. All plots were 1/100 acre in size and were surrounded with a 15- to 20-foot wide isolation zone. Treatments were randomly chosen. Dominant and codominant trees in the thickets averaged 15- to 19-feet tall when the study was started.

STUDY RESULTS

Stump culture was the most successful treatment tested in this study, producing large numbers of trees that were above average in both quality and size. None of the pruning methods significantly (t-test, 1 percent confidence level) increased total Christmas tree production. Heavy thinnings produced the most trees initially, but 10 years later the light and moderately thinned areas still had three times as many trees capable of producing Christmas trees.

Stump Culture

A comparison of the two types of stump tree origins--branch turnups and adventitious shoots--demonstrated that over three times (significant at the 1 percent level by t-test) as many turnups developed into Christmas trees as shoots. As shown in table 1, 59 percent of the stumps treated to favor branch turnups produced Christmas trees. Meanwhile, 17 percent of the stumps treated to favor adventitious shoots produced Christmas trees.

Year of stump treatment had no apparent effect on tree production because the number of trees produced from branch turnups varied only slightly by years (table 1). Production from adventitious shoots was slightly more erratic, but no pattern was apparent.

Table 1.--*Percentile Christmas tree production from branch turnups and adventitious shoots by year of treatment and tree grade*[1]

Year treated[2]	Christmas tree grade: Premium	Standard	Utility	Total
		BRANCH TURNUPS		
0	7	27	23	57
1	17	13	30	60
2	7	23	33	63
3	10	20	27	57
Average	10	21	28	59
		ADVENTITIOUS SHOOTS		
0	0	3	20	23
1	0	3	4	7
2	0	0	13	13
3	10	10	3	23
Average	3	4	10	17

[1]Expressed as a percent of total possible.
[2]Number of years after the original tree was cut.

The relation of tree grades to the actual number of Christmas trees produced was nearly the same for branch turnups and adventitious shoots. However, there was a tendency toward better grades being produced from branch turnups, as reflected in this tabulation:

Grade	*Branch turnups* (*Percent*)	*Adventitious shoots* (*Percent*)
Premium	17	15
Standard	35	25
Utility	48	60
Total	100	100

Tree production was best on the Eureka and Kalispell areas but the differences, by areas, were not too pronounced, as shown in the following tabulation:

Location	*Branch turnups* (*Percent*)	*Adventitious shoots* (*Percent*)
Eureka	71	21
Kalispell	62	29
Greenough	62	17
Plains	50	17
Lolo	50	0
Average	59	17

Figure 5.--Douglas-fir stump 1 year after a Christmas tree was harvested from the top portion. The branch on the left has already turned up and all but five vigorous branches in the lower whorls have been removed to give the turnup room to develop into another Christmas tree.

The lack of Christmas trees produced from shoots on the Lolo site was due primarily to the severe competition branch turnups offered the shoots on this area. In addition, those shoots that did not have turnup competition grew too fast for satisfactory Christmas tree development.

Year of treatment had no apparent effect on the sizes of trees produced from either turnups or shoots. The data are somewhat erratic, but the distribution in the different size classes was similar from year to year (table 2).

Branch turnups produced large trees rapidly (fig. 5). Over a third of the merchantable trees produced from turnups were in the 10- and 12-foot classes (table 2). Trees from adventitious shoots were smaller than those from turnups. Nearly three-fourths of the shoot trees were in the 2- and 4-foot classes.

Nearly three-fourths of the stumps produced at least one adventitious shoot--the average was $3\frac{1}{2}$ per stump. Stump treatments delayed the longest produced the most shoots, ranging from a low of 46 percent of the stumps treated in the first year to a high of 90 percent of those treated 3 years later (table 3). This apparently reflected the extra vigor in stumps that still had their full branch complement. Trees in most of the areas responded similarly except for those in the Eureka area where less than half as many of the stumps produced shoots.

Excessive growth, particularly on the Greenough, Plains, and Lolo plots, caused many of the shoot and turnup trees to be classed as culls. Insufficient development, crowding of shoots by turnups, competition from adjacent trees, lack of symmetry, and needle blight accounted for most of the other culls.

Basal Pruning

All of the pruning treatments significantly (t-test, 1 percent confidence level) reduced height and diameter growth for at least the first 5 years after pruning and three of the five treatments reduced such growth during the 5- to 10-year period (table 4). Height growth reduction was directly proportional to the amount of live crown removed.

Table 2.--*Percentile Christmas tree production from branch turnups and adventitious shoots by year of treatment and size*[1]

Year treated[2]	Size classes: 2- and 4-ft.	6- and 8-ft.	10- and 12-ft.	Total
	BRANCH TURNUPS			
0	14	17	26	57
1	20	23	17	60
2	10	33	20	63
3	20	17	20	57
Average	16	22	21	59
	ADVENTITIOUS SHOOTS			
0	17	6	0	23
1	7	0	0	7
2	7	6	0	13
3	17	6	0	23
Average	12	5	0	17

[1]Expressed as a percent of total possible.
[2]Number of years after the original tree was cut.

Table 3.--*Percent of stumps with adventitious shoots by area and year of stump culture treatment*

Area	Year treated[1]: 0	1	2	3	Average
Eureka	17	33	33	50	33
Kalispell	66	66	100	100	83
Greenough	66	50	100	100	79
Plains	66	66	100	100	83
Lolo	17	83	100	100	75
Average	46	60	87	90	71

[1]Number of years after the original tree was cut.

Table 4.--*Growth of sample trees in the first and second 5-year periods after pruning*

Treatment[1]	Height: Average annual growth of unpruned trees	Height: Pruned trees[2]		Diameter: Average annual growth of unpruned trees	Diameter: Pruned trees[2]	
	0-10 years	0-5 years	5-10 years	0-10 years	0-5 years	5-10 years
	Feet	*Percent*		*Inches*	*Percent*	
1	1.2	48**	76**	0.21	50**	69**
2	1.2	67**	88**	.22	69**	81**
3	1.2	76**	88**	.21	74**	78**
4	1.1	82**	97	.20	86**	105
5	.9	86**	114	.17	84**	109

[1]For description of treatments, see page 3.

[2]Expressed as a percent of the unpruned tree growth.

**Significantly different than the unpruned paired trees as determined by "t" tests (1 percent confidence level).

The most severe pruning treatment--where the lower two-thirds of the green crown was removed--reduced height growth in the first 5 years to about half of its previous rate. The other pruning treatments demonstrated similar but proportionately less reduction. Diameter growth responded the same as height.

The trees gradually recuperated from the effects of pruning. Although all treatments reduced growth considerably the first 5 years after pruning, only the more severe pruning had any significant (t-test, 1 percent confidence level) effect during the second 5-year period. Even the most severely pruned trees gradually regained their normal height growth--from about 50 percent of normal in the first 5 years to 76 percent in the second 5-year period. Diameter growth rates returned to normal more slowly than did height growth rates.

Production was nearly identical on pruned and unpruned trees (table 5). The two treatments in which half of the crown was removed appeared to increase production during the first 5 years after treatment, but these differences were not statistically significant because of considerable variation in response. About one-third of the sample trees produced Christmas trees during the first 5-year period after treatment and another third during the succeeding 5 years.

No differences in tree grade could be detected between pruned and unpruned trees using any of the pruning methods. Approximately one-third of the merchantable Christmas trees produced were standard-grade trees and the other two-thirds were utility-grade trees (table 6). Only a few premium trees were produced in all of the paired samples.

About one-third of all the trees were classed as culls. The following accounted for about 90 percent of the culling: crowns were too open, 70 percent; and trees damaged by Christmas tree blight, 20 percent. Suppression, deformities, and poor balance caused the remainder of the culling. Mortality was light in both pruned and unpruned trees. Only 4 percent of the pruned trees and 1 percent of the unpruned trees died during 10 years following treatment.

About two-thirds of the merchantable trees produced were in the 6- and 8-foot classes (table 7). Most of the others were in the 2- and 4-foot classes; 10- and 12-foot trees were rare.

Table 5.--*Percentile Christmas tree production on pruned and unpruned trees during the first and second 5-year periods after treatment*[1]

Pruning treatment[2]	First 5 years		Second 5 years	
	Pruned	Unpruned	Pruned	Unpruned
1	33	33	71	71
2	50	33	71	67
3	50	17	75	62
4	20	20	50	50
5	27	43	38	58
Average	36	29	61	62

[1]Expressed as a percent of total possible.
[2]For description of treatments, see page 3.

Table 6.--*Percentile Christmas tree production by grade and treatment during the 10 years after treatment*[1]

Pruning treatment[2]	Christmas tree grade							
	Premium		Standard		Utility		Cull or dead	
	Pruned	Unpruned	Pruned	Unpruned	Pruned	Unpruned	Pruned	Unpruned
1	4	0	12	29	54	42	30	29
2	0	0	25	21	46	46	29	33
3	0	0	33	21	42	42	25	37
4	4	0	17	12	29	38	50	50
5	0	0	21	17	17	42	62	41
Average	2	0	22	20	37	42	39	38

[1]Expressed as a percent of total possible.
[2]For description of treatments, see page 3.

Table 7.--*Percentile Christmas tree production by size and treatment during the 10 years after treatment*[1]

Pruning treatment[2]	Christmas tree size classes					
	2- and 4-ft.		6- and 8-ft.		10- and 12-ft.	
	Pruned	Unpruned	Pruned	Unpruned	Pruned	Unpruned
1	21	4	50	58	0	8
2	29	17	42	46	0	4
3	29	12	38	50	8	0
4	17	12	33	38	0	0
5	17	29	21	29	0	0
Average	22	15	37	44	2	3

[1]Expressed as a percent of total possible.
[2]For description of treatments, see page 3.

Table 8.--*Percentile Christmas tree production by grade and size at different locations*[1]

Location[2]	Total	Grade			Size classes		
		Premium	Standard	Utility	2- and 4-ft.	6- and 8-ft.	10- and 12-ft.
Eureka	70	2	30	38	37	33	0
Kalispell	75	2	23	50	18	55	2
Greenough	55	0	20	35	12	38	5
Plains	45	0	10	35	8	35	2
Average	61	1	21	39	19	40	2

[1]Expressed as a percent of total possible.
[2]Ten-year production records for the Lolo area are not complete.

The height growth reduction caused by the pruning apparently resulted in smaller merchantable tree sizes (table 7). The total number of merchantable trees that fell in the 2- through 8-foot classes were identical on pruned and unpruned trees. However, more of the pruned trees fell in the 2- and 4-foot classes and fewer in 6- and 8-foot classes than the unpruned.

Eureka and Kalispell, the two northernmost study areas, produced the most Christmas trees. Nearly three-fourths of the total number of potential Christmas trees on these two areas reached merchantability during the 10-year study period compared to about one-half of the potential trees at Greenough and Plains (table 8). In addition, tree quality was also best at these two northern areas. About twice as many standard- or premium-grade trees were produced there as at Greenough and Plains. Production of utility-grade trees was about the same on all of the areas.

Thicket Thinning

Total Christmas tree production from the thicket thinnings was directly proportional to the number of trees per acre in the original stand. Between 7 and 8 percent of the original stands, regardless of thinning treatment, produced merchantable Christmas trees sometime during the 10-year study period, either in the initial or subsequent harvests (table 9). Thus, the thickets that had the most trees per acre initially produced the greatest total number of Christmas trees.

Production from subsequent harvests was directly related to the number of trees left after thinning. About 8 percent of the reserve stand produced Christmas trees in the 10-year period following thinning (table 9).

During the first 10 years, the most pronounced effect of different thinning intensities was the shift in the time of harvest (table 9). Most of the Christmas trees on the heavily thinned plots came from the initial thinning, while in the lightly thinned plots, nearly all of them came from subsequent harvests. Production on the medium thinnings was more evenly distributed during the study period.

No differences in tree grade or size could be detected between the three thinning treatments or on the different areas. Over half of the trees were standard grade, and most of the remainder were utility grade. Only 4 percent were premium-grade trees. Over three-fourths of the trees were in the 2- and 4-foot classes (table 10).

Table 9.--*Christmas tree production (per acre) from initial thinnings and subsequent harvests*

Thinning level	Stand density: Before thinning	Stand density: After thinning	Christmas tree production: From initial thinning	Christmas tree production: From subsequent harvests	Christmas tree production: Total
Light	15,100	12,300	80	980	1,060
Medium	12,920	9,600	200	820	1,020
Heavy	17,160	6,800	880	440	1,320
Average	15,060	9,567	386	747	1,133

Table 10.--*Percentile Christmas trees produced in thickets thinned to three different levels according to grade and size*

Thinning treatment	Tree grade: Premium	Tree grade: Standard	Tree grade: Utility	Height classes: 2-ft.	Height classes: 4-ft.	Height classes: 6-ft.	Height classes: 8-ft.
Light	8	59	33	31	43	18	8
Medium	0	46	54	27	55	16	2
Heavy	5	77	18	14	63	23	0
Average	4	61	35	24	54	19	3

Nearly all of the Christmas tree production came from dominant or codominant trees of good and fair vigor--96 percent of the merchantable Christmas trees were classified either dominant or codominant, while 70 percent were of good vigor and 29 percent of fair vigor when the study was initiated. These figures were essentially the same for all three thinning intensities.

Stand vigor declined under all three thinning intensities. During the first 6 years after thinning, 28 percent of the trees dropped at least one vigor class; i.e., from good to fair or fair to poor, while only 5 percent of the trees increased in vigor. The remaining high percentage (67 percent) of trees showing "no change" is somewhat deceiving. Most of these trees were of poor vigor at the start of the study; thus, there was no way for them to drop into a lower vigor class. In general, good vigor trees maintained their vigor; fair vigor trees declined; and poor vigor trees died or barely stayed alive. Differences between thinning treatments were minor.

Crown classes showed the same trend as vigor. Over a third of the trees dropped into lower crown classes; i.e., from dominant to codominant, codominant to intermediate, or intermediate to suppressed. Only 1 percent increased their crown position. Most of the trees that did not change crown class were suppressed trees that could not drop into a lower classification.

Records are not complete for the last remeasurement; but where recorded, vigor and crown class continued to decline.

Mortality started early and continued throughout the entire study period. Approximately one-fourth of all the "leave" trees in each thinning treatment died during the 10-year period after thinning (table 11).

Table 11.--*Accumulative mortality on thicket thinning treatments 3, 5, and 10 years after thinning*[1] [2]

Thinning treatment	3 years	5 years	10 years
Light	3	13	26
Medium	1	17	28
Heavy	4	17	23
Average	3	15	26

[1]Expressed as a percent of the reserve stand.
[2]The number of years is only approximate because of different measurement schedules.

Suppressed, poor vigor trees accounted for nearly all of the mortality. Dominant trees of good vigor made up only a small portion of the mortality during the study period, as shown in the following tabulations.

Crown class	*Mortality* (*Percent of total*)
Dominant	1
Codominant	5
Intermediate	26
Suppressed	68
Total	100

Vigor class	*Mortality* (*Percent of total*)
Good	4
Fair	14
Poor	82
Total	100

Although heavy thinnings produced more Christmas trees in the first 10 years, the possibilities of future production were better on the medium and lightly thinned areas. They still had about three times as many dominant and codominant trees and twice as many trees of good or fair vigor as did the heavily thinned areas (table 12).

Table 12.--[illegible]

Thinning treatment	Total residual stand	Crown class				Vigor class		
		Dominant	Codominant	Intermediate	Suppressed	Good	Fair	Poor
Light	7,820	220	1,160	[illegible]	[illegible]	460	3,140	4,220
Medium	5,920	240	920	1,760	3,000	600	2,200	3,120
Heavy	4,720	60	380	[illegible]	[illegible]	180	1,240	3,300
Average	6,153	173	820	[illegible]	[illegible]	413	[illegible]	[illegible]

CONCLUSIONS AND RECOMMENDATIONS

Cultural treatments can increase Christmas tree production in natural stands of Douglas-fir. The results from this study should encourage the use of stump culture treatments, discount the value of single pruning treatments on many Christmas tree sites, but encourage frequent, light to moderate thinnings in thickets.

Stump culture produced large, high quality Christmas trees rapidly. In this study, a higher percentage of premium quality trees were produced from stump culture than from any other treatment. Of the stumps treated to feature branch turnups, 60 percent produced merchantable trees within the 10-year period after the original tree was cut. Treatment to favor adventitious shoots also produced Christmas trees, but treatment to favor branch turnups outproduced them 3 1/2 to 1. This contrasts with the coast form of Douglas-fir in the Pacific Northwest where adventitious shoots appear to be more productive than branch turnups.[2]

Treatments favoring either turnups or shoots produce Christmas trees of nearly equal quality, but trees from turnups reach larger sizes earlier than do trees from shoots. About half of the merchantable trees from the stump treatments in this study were premium- or standard-grade, but one-third of the turnup trees reached the 10- and 12-foot class while none of the shoot trees reached these sizes.

The manager apparently has a fair amount of latitude in choosing the time to treat stumps. No differences could be detected in this study between stumps treated the same time as the original tree was cut or stumps treated as much as 3 years later. However, to assure that stump vigor is maintained, some growers feel that treatment should be delayed a year or more.

The logic behind stump treatment is sound. The inherent genetic characteristics that determined the quality of the original tree--for example, branch angle and needle color and density--can be relied upon to provide the same qualities in the turnups or shoots. Thus, the stumps not only produce Christmas trees sooner than could be grown from planted stock, but their quality is also predictable.

Stumps from open-grown trees should be treated for branch turnups. Such a stump can produce a Christmas tree, and in many cases, several trees before any comparable trees could be grown from natural or planted seedlings. The following can be recommended as guidelines:

1. Treat stumps of trees that have demonstrated desirable Christmas tree characteristics.

2. Cut the original tree above the second or third whorl of vigorous live branches.

3. Reserve as many as six or seven major branches to sustain the vigor of the stump. Favor two or more of these branches on alternate sides of the stump for turnup trees by removing branches that are competing with them for space. By favoring more than one turnup tree at a time, excessive leader growth can be more easily controlled.

4. Turnup trees may be basal pruned to maintain satisfactory internode length because they often grow too fast.

---

[2]Personal communication with Bernard S. Douglass, State and Private Forestry, Region 6, USDA Forest Service.

Basal pruning has been one of the most controversial Christmas tree culture methods, and results of this study illustrate why. Even though all five of the different prunings substantially reduced the height growth (which presumably makes the crown appear denser), there appeared to be no corresponding overall increase in number, quality, or size of merchantable Christmas trees during the 10-year period. However, there did appear to be a trend toward increased production during the first 5-year period on trees that had been moderately pruned.

Douglass (1963) also found that height growth could be reduced by pruning. However, he cautioned that pruning is frequently overdone on lower-quality sites and results only in increasing the time required to grow a merchantable size tree.

Height growth and the corresponding internode length are generally not excessive on most sites suitable for Christmas trees in Montana. Areas where annual growth of most of the trees exceeds 16 inches are probably better suited for growing timber than they are for Christmas trees. However, pruning can be used to reduce the length of the internodes where height growth is excessive on areas dedicated to Christmas tree production.

Where pruning is needed:

1. Prune from the middle of the green crown, leaving two or three good whorls of lower branches for subsequent stump culture.

2. Prune at the following rates:

If Actual growth exceeds desired growth by (Percent)	*Then* Remove the following amounts of green crown (Percent)
25	33
50	50
75	60
100	66

3. Prune as often as necessary to maintain the desired internode length.

4. Shear to shape and increase the density of the crown. Kintigh (1965) found that shearing was one of the best cultural methods to use for increasing the quality of Douglas-fir Christmas trees.

5. Harvest cultured areas annually to assure maximum utilization of trees when they are ready.

6. After harvesting, culture the stump for branch turnup development.

Douglas-fir thickets provide an extensive source of small, medium-quality Christmas trees in Montana. For example, about 8 percent[3] of the trees in the original stand used for this study produced merchantable trees during the initial thinning or during the following 10-year period. However, over 95 percent of the trees were 2- to 4-feet tall and of standard quality or less.

---

[3]This is equivalent to about 1,000 trees per acre in the thickets but because the thickets are clumpy, the average per acre for an area as a whole would be considerably less.

Dominant and codominant trees of good and fair vigor are the source of nearly all the Christmas trees in thickets. Crown deterioration in the intermediate and suppressed trees is apparently severe enough to preclude their use for Christmas trees initially or in any reasonable period of time after that.

The Christmas tree grower's objectives largely dictate his choice of thinning. Heavy thinnings produce the most Christmas trees initially but light to moderate frequent thinnings produce more trees in subsequent harvests as well as maintain stands with a greater potential for future production. In thinning, badly deformed Douglas-fir trees, as well as trees of all other species, should be removed. All merchantable trees that appear to have reached their maximum development in quality and size should be harvested annually.

In summary, Christmas tree growers utilizing natural stands of Douglas-fir must recognize that they deal with extremely heterogeneous tree populations. Prescriptions must be based upon sound biological and economic principles applicable to each stand and individual tree. Culture techniques for Douglas-fir have been fairly well described (Wellner and Roe 1947, Burlison and Pitkin 1962, Douglass 1967), but the "professional touch" still will be needed to successfully prescribe the best combination of these techniques for optimizing Christmas tree production.

LITERATURE CITED

Benson, Robert E.
1965. Export of Christmas trees from Montana in 1964. U.S. Forest Serv. Res. Note INT-38, 4 p.

______ 1967. Montana Christmas trees: over 80 million in three decades. Amer Christmas Tree Growers J. 11(3): 21-22.

Burlison, Vernon H., and Franklin H. Pitkin.
1962. Christmas tree growing in Idaho. University of Idaho, Forest Wildlife and Range Exp. Sta., Res. Note 20, 25 p.

Douglass, Bernard S.
1963. Leader growth control for Douglas-fir. Amer. Christmas Tree Growers J. 7(2): 13-14, 55-56.

______ 1965. Growing Christmas trees in western United States. J. Forest. 63(11): 862-864.

______ 1967. Development of high quality sheared Douglas-fir Christmas trees. U.S.D.A. Forest Serv., Pacific Northwest Region, State and Private Forestry, Managing Your Woodland, How To Do It Guides, No. 12, 21 p.

Hutchison, S. Blair, and Ben M. Huey.
1949. Suggested Montana Douglas-fir Christmas tree standards. U.S.D.A. Forest Serv., Northern Rocky Mountain Forest and Range Exp. Sta., Sta. Pap. 18, 13 p.

Kintigh, Robert G.
1965. Some results of succulent shearing of Douglas-fir in western Oregon. Amer. Christmas Tree Growers J. 9(2): 25-26.

Roe, Arthur L.
1948. What caused "blight" on Christmas trees in the Northern Rockies in 1947. U.S.D.A. Forest Serv., Northern Rocky Mountain Forest and Range Exp. Sta. Res. Note 65, 5 p.

U.S. Department of Agriculture.
1962. United States standards for grades of Christmas trees. U.S.D.A. Agr. Marketing Serv., Washington, D.C., 12 p.

Wellner, C. A., and A. L. Roe.
1947. Management practices for Christmas tree production. U.S.D.A. Forest Serv., Northern Rocky Mountain Forest and Range Exp. Sta., Sta. Pap. 9, 21 p.

Wilson, Alvin K.
1957. A new high in Montana Christmas tree shipments. U.S.D.A. Forest Serv., Intermountain Forest and Range Exp. Sta. Res. Note 44, 4 p.

Wright, Jonathan W.
1965. Choice of species for Christmas tree plantations. J. Forest. 63(11): 844-846.

AFLC/HAFB, Ogden

USDA Forest Service
Research Paper INT-85
1970

SHEET EROSION ON INTERMOUNTAIN SUMMER RANGES

Richard O. Meeuwig

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Ogden, Utah 84401

THE AUTHOR

RICHARD O. MEEUWIG, Principal Soil Physicist in the Watershed Protection and Rehabilitation work unit, joined the staff of the Intermountain Station in 1956. He holds B.S. and M.S. degrees in Forestry from the University of California, Berkeley; and a Ph.D. in Soil Physics from Utah State University. He is stationed at the Renewable Resources Center, University of Nevada, Reno.

USDA Forest Service
Research Paper INT-85
December 1970

SHEET EROSION ON INTERMOUNTAIN SUMMER RANGES

Richard O. Meeuwig

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

CONTENTS

ABSTRACT

Simulated rain was applied to small plots on seven mountain rangeland sites in Utah, Idaho, and Montana. Multiple regression equations were developed for each site relating the resultant erosion to cover characteristics, soil properties, and slope gradient. The magnitude of erosion was found to depend primarily on the proportion of the soil surface protected from direct raindrop impact by plants, litter, and (in some cases) stone. Soil organic matter favored stability of fine-textured soils, but apparently increased erodibility of sandy soils. The regression equations are presented in tabular and nomographic form to aid the land manager in the assessment of potential sheet erosion on sites similar to those studied.

INTRODUCTION

Early detection of incipient erosion is necessary for efficient management of range-watersheds. The early stages of sheet erosion are much more difficult to recognize than the pedestals, rills, and gullies typical of advanced erosion. Yet, sheet erosion profoundly affects the range; productivity declines as fertile topsoil and humus are gradually lost. This loss can proceed undetected for years until its adverse effects on plant growth and infiltration capacity lead to the more obvious stages of erosion. Once the advanced stages are reached, regaining control of erosion is much more difficult than preventing excessive sheet erosion at the incipient stage.

Sheet erosion is usually caused by convectional rainstorms. These storms are characterized by many large raindrops falling at velocities ranging up to more than 20 miles per hour (Laws 1941). Upon striking bare soil these large drops detach particles from the soil mass and the resulting splash carries them as far as 2 or 3 feet from their original site. Since the rainsplash tends to move farther downhill than uphill, the net effect of rainsplash is downhill soil movement even in the absence of overland flow. If rivulets of overland flow are present, soil particles splashed into such rivulets are carried even farther downhill.

Soils vary in their susceptibility to erosion. Clays, particularly those that are tightly bound into large aggregates, tend to be difficult to detach. However, once detached, clays are easily transported and can be suspended and carried in overland flow for great distances. Sands are less cohesive and are easily detached but because of larger size are less easily transported and are not carried as far by overland flow unless it is rapid and turbulent.

Vegetative cover is the best practical protection against excessive sheet erosion because it breaks raindrop impact and favorably influences infiltration capacity. However, the amount of vegetative cover needed to achieve a given level of control of sheet erosion will vary with slope and soil properties because susceptibility to detachment and transportation vary with these factors.

To obtain maximum use of forage without risking excessive erosion, and to recognize potential erosion hazard, the range manager needs to know quantitative relations between vegetative cover and potential sheet erosion under diverse climatic, soil, and topographical conditions. At present, quantitative information on this subject is limited to a few geographical areas.

Osborn (1956) studied the effects of vegetative cover and soil on splash erosion on rangeland in Texas and Oklahoma and developed vegetative cover requirements to control splash erosion on various soil textures and plant species compositions in that area.

On the basis of simulated rain experiments on granitic soils in southern Idaho, Packer (1951) concluded that adequate control of summer storm runoff and erosion on wheatgrass (*Agropyron inerme*) range requires at least 70 percent ground cover of plants and litter and that bare openings should be no larger than 4 inches. Ground cover consists of plant basal area plus surface litter. On cheatgrass (*Bromus tectorum*) range, 70 percent ground cover is required also, but bare openings should be no larger than 2 inches. The effects of slope gradient, soil depth, soil porosity, and root abundance in the soil were also investigated but these effects were not great enough at this location to warrant their inclusion in the protection requirements.

On an aspen site in northern Utah, Marston (1952) found that ground cover of 65 percent or more was required for effective control of overland flow and erosion caused by storms having rainfall intensities in excess of 3 inches per hour.

Packer (1963) prescribed ground cover densities of at least 70 percent and soil bulk densities no greater than 1.04 g./cc. as necessary to maintain soil stability on the Gallatin elk winter range in south-central Montana.

Using a rainfall simulator on a subalpine cattle range in central Utah, Meeuwig (1965) found that soil erosion was more closely correlated with the proportion of soil surface protected from direct raindrop impact by plants, litter, and stone than any other measured variable. However, this relation between protective cover and soil erosion is strongly influenced by soil bulk density; the influence of cover is greatest at high bulk density and is least at low bulk density. If protective cover exceeds 85 percent, the amount of soil eroded is small, irrespective of bulk density.

The results of a study on the sheet erosional behavior of seven diverse summer range sites in Idaho, Montana, and Utah are presented in the following sections of this paper. This study was designed to augment the previously reported studies and to provide means for predicting sheet erosion potential under a variety of slope, soil, and cover conditions. Soil eroded from small plots (20 by 30.5 inches, or about 0.1 milacre in size) under simulated high-intensity rain was measured and related to slope gradient, weight and areal cover of vegetation and litter, and several soil properties.

STUDY AREAS

The study areas are located on middle-to-high-elevation herbaceous rangelands (fig. 1). All such areas are grazed by livestock during the summer except Area 2 on the Davis County Experimental Watershed from which grazing has been excluded for more than 30 years. Following are details of each area:

1. *Great Basin Experimental Area* (GBEA), Manti-LaSal National Forest, central Utah. This is sheep range with a wide variety of grass and forb species. Soils are mostly silty clay loams and clay loams derived from sedimentary rock, predominantly limestone but containing some shale and sandstone. Elevations of study plots ranged from 7,000 to 10,000 feet; most were about 9,000 feet.

2. *Davis County Experimental Watershed* (DCEW), Wasatch National Forest, northern Utah. This area was the source of serious floods during the period 1923 to 1933. Much of this watershed was contour trenched and seeded to grass during the period 1933 through 1936. Grazing has been excluded since 1933. Soils are mostly silt loam and loam. Parent materials vary from metamorphic gneisses and schists to conglomerates, sandstone, and shales. Elevations of study plots were between 8,000 and 9,000 feet.

3. *Vigilante Experimental Range and Monument Ridge* in the Gravelly Range, Beaverhead National Forest, southwestern Montana. This is cattle and sheep range dominated by Idaho fescue (*Festuca idahoensis*) in many parts and by native forbs or seeded grasses such as crested wheatgrass (*Agropyron desertorum*) in others. Soils are mostly silt loam and silty clay loam derived from red shales, siltstone-shales, and glacial till. Elevations of study plots were between 7,000 and 9,500 feet.

4. *Diamond Mountain Cattle Allotment* near Flaming Gorge, Ashley National Forest, eastern Utah. This is an experimental grazing area where much of the native sagebrush-grass vegetation has been replaced with introduced grass species. Soils are loams and sandy loams derived from sedimentary rocks. Plots were at about 8,000 feet.

5. *Basalt* range north of Seven-Devils, Nezperce National Forest, central Idaho. Study plots in this area were located in grassy openings in open ponderosa pine stands. Soils are loams and silt loams derived from basalt. Most plots were near 5,000 feet.

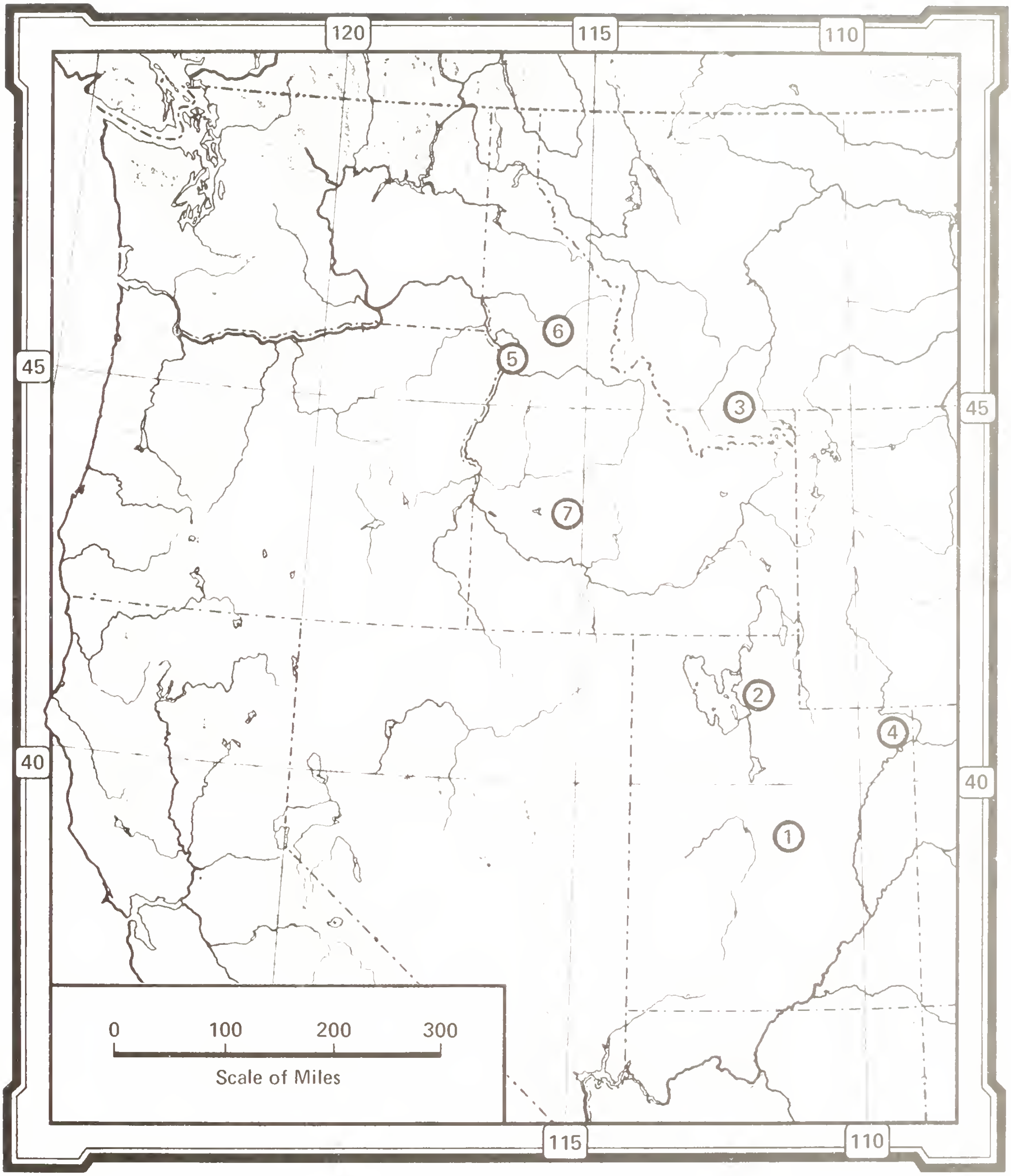


Figure 1.--Locations of the seven study areas.

6. *Coolwater Ridge*, Nezperce National Forest, central Idaho. Vegetation on this deteriorated subalpine range is predominantly low-value forbs. The granite-derived soils are sandy loam and loam. Plots were at about 6,000 feet.

7. *Trinity Mountains*, Boise National Forest, southern Idaho. Study plots were located in large and small openings in coniferous forest. The granitic soils, typical of much of the Idaho batholith, are sandy loams and loamy sands. Average elevation of plots was about 7,000 feet.

MEASUREMENTS

Sheet erosion.--Simulated rain was applied to the 20- by 30.5-inch plots at a constant intensity of 5 inches per hour for 30 minutes, using the rainfall simulator described by Dortignac (1951). The raindrops produced by this simulator tend to be larger than those of natural high-intensity storms but possess less impact energy than natural rain because of their lower impact velocity. All water running off each plot was collected and the suspended sediment allowed to settle. This sediment, plus that deposited in the runoff-collecting trough at the bottom of the plot frame, was ovendried and weighed.

Initial soil moisture content.--Immediately prior to the application of simulated rain, two 240 cc. soil samples were obtained adjacent to each plot in the surface 2 inches of soil. These samples were ovendried to determine moisture content. To obtain a wider range of initial moisture conditions, half of the plots at each study site were prewet the day before the simulated rain test by applying 0.5 inch of simulated rain during a 15-minute period.

Protective cover.--Density and composition of cover on each plot were measured with a point frame (Levy and Madden 1933), using first strikes of 100 mechanically spaced pins to determine the proportions of the soil surface protected from direct raindrop impact by plant species, litter, or stone. One or 2 days after the application of simulated rain, all vegetation and litter were removed from the plot, allowed to air-dry at least 2 weeks, and then weighed.

Soil properties.--Two days after application of the simulated rain, soil core samples were taken at the following depths: 0 to 1 inch, 1 to 2 inches, 2 to 4 inches, and 4 to 6 inches. Capillary porosity and bulk density of these soil cores were measured by the tension table method and subsequent ovendrying (Leamer and Shaw 1941). Soil organic matter contents at 0- to 1-inch and 1- to 2-inch depths were determined by the dichromate method (Peech, Alexander, Dean, and Reed 1947). Particle size distribution of the surface 1 inch of soil was measured by the hydrometer method (Bouyoucos 1962). Soil aggregation in the surface inch was measured by Middleton's (1930) method. In addition, Yoder's (1936) wet-sieving method was used to determine size distribution of water-stable aggregates in the surface inch of soil on the Davis County and Montana plots.

ANALYSES

The data of this study were analyzed by multiple regression techniques. In all cases, the dependent variable ($\hat{y}$) was the common logarithm of ovendry weight (pounds per milacre) of soil and organic material washed from the plot, including that deposited in the collector trough at the bottom of the plot frame. Logarithms were used because the erosion data were not normally distributed but were skewed to the right, that is, a large majority of the values were less than the mean. The logarithmically transformed data approached a normal distribution.

For each of the seven study areas, all measured site factors were evaluated for their contribution to explained variance by stepwise multiple regression analyses.

Many variables were found to be highly correlated with erosion but intercorrelation among most of these was also quite high. For each area, the most promising variables were chosen. In these analyses, the general objective was to reduce standard error to a minimum using, as much as possible, those variables most easily measured or estimated.

These analyses produced seven regression equations, one for each study area. Each of the following variables appears in at least one equation:

A - Proportion of the soil surface protected from direct raindrop impact by vegetation and litter.

B - Proportion of soil surface protected from direct raindrop impact by vegetation, litter, *and* stone.

D - Sand content of the surface inch of soil (proportion by weight).

E - Organic matter content of the surface inch of soil (proportion by weight).

F - Organic matter content of the surface 2 inches of soil (proportion by weight).

G - Slope gradient in percent.

H - Bulk density of the surface 4 inches of soil (g./cc.).

L - Air-dry weight of litter (pounds per milacre).

Of course, these are not the only variables that affect erosion. Most of the other measured variables had some effect on erosion but they did not explain sufficient additional variance to merit their inclusion in any multiple regression equations. For example, erosion was closely correlated with soil aggregation characteristics in some areas but the relations are rather complex and variable. Large water-stable aggregates resist erosion but stable aggregates smaller than 0.5-mm. diameter seemed to be more easily eroded than unaggregated material. Organic matter content served to explain as much, or more, variance as aggregation. When organic matter content was included in the equations, the additional variance explained by aggregation was small. Erosion was also affected by soil moisture content but these relations were also complex and variable. Some soils are more erodible when wet and some are more erodible when dry. Since surface soil moisture content was so variable, changed so rapidly, and generally had minor effects, it was not included in any of the final equations.

RESULTS AND DISCUSSION

Without exception, protection of the soil surface from direct raindrop impact proved to be the most important means of controlling erosion on the study areas. On four of the study areas, the logarithm of soil eroded was more closely correlated with proportion of soil surface protected from raindrop impact by vegetation and litter than with any other measured variable. On the other three, the highest correlation was obtained with proportion of the soil surface protected by plants, litter, *and* stone. On these study areas, the presence of stone on soil surface not otherwise protected contributed significantly to protection against erosion. It is probable that stone had a protective influence in all cases but its effects were negligible on four of the seven areas, possibly because stone was not very prevalent on those areas or did not provide protection that was as effective as plants and litter.

The effects of plot slope gradient are important on all seven study areas and appear in all but one regression equation. This exception is the equation for an area where there were few observations and little variation in slope. The direct relation between erosion and slope tends to be greatest on the sandy soils.

Soil organic matter content appears in five of the equations. The favorable effects of organic matter in promoting aggregation of clay are well documented. However, the equations for the Diamond Mountain, Basalt, and Trinity study areas imply definitely adverse effects of organic matter on the stability of sandy soils; and it is expected that more intensive sampling would have revealed similar effects on Coolwater Ridge. It appears that while organic matter binds clay and silt particles into aggregates that resist erosion, it has an adverse effect on aggregation of sand particles. It is hypothesized that this adverse effect results from the hydrophobic character of organic coatings on sand particles, which causes the particles to resist wetting and, possibly, to possess mutual electrostatic repulsion, thus making the sand particles more easily detached and transported. No report of this phenomenon has been found in the literature but its occurrence in widely separated areas, as found in this study, indicates that it is not a mere coincidence, but an actual effect that should be recognized and investigated further.

The effects of cover, slope, organic matter content, and other site factors are discussed in detail for each study area in the following sections. Results on two of the study areas appear in other papers (Meeuwig 1969, 1970), but they are also presented here in a revised form to serve the purposes of this paper.

Great Basin Experimental Area.--In this area of calcareous fine-textured soils, bulk density was found to be the most important secondary factor affecting soil erosion. The proportion of soil surface protected from direct raindrop impact explains 52 percent of the variance of the log of soil eroded. Bulk density of the surface 4 inches of soil in combination with cover explains 62 percent of the variance. Plot slope gradient accounts for an additional 4 percent of the variance.

The regression equation for sheet erosion on this study area is:

$$\hat{y} = -3.12 - 0.618B - 2.50B^2 + 5.92H - 2.53H^2 + 1.44BH + 0.0221G$$

in which B, H, and G are: protective cover (plant, litter, and stone); bulk density; and slope, as defined previously. This equation is based on 162 plots and has a coefficient of determination (R^2) of 0.66. Its standard error of estimate is 0.38. Since the dependent variable is a logarithm, the standard error of estimate is also a logarithm and not easily interpreted. To overcome this difficulty, erosion as estimated by this equation is plotted logarithmically in figure 2 against erosion as actually measured.

The relation of erosion to protective cover and bulk density, as defined by this equation, is shown graphically in figure 3. Slope gradient was held constant at its average of 18 percent for the calculation of curves presented in figure 3. While cover percentage exerts the major controlling influence on the weight of soil eroded, soil bulk density has an important influence. At any fixed cover percentage the amount of soil eroded is about twice as great at a bulk density of 1.1 g./cc. as it is at 0.9 g./cc. Bulk density influences erosion because aggregation and porosity are inversely related to bulk density. Well-aggregated soils tend to have low bulk densities and they also tend to resist erosion. Soils of high porosity have good infiltration characteristics and, consequently, produce less overland flow and erosion.

Correction factors for deviations of slope gradients from an average of 18 percent are tabulated in table 1. Weights of soil eroded in figure 3 should be multiplied by the appropriate factor in table 1 to correct for slope effects. At any given cover percentage and bulk density, the amount of erosion is about 3 times greater on 40 percent slopes than on 18 percent slopes.

Figure 2.--Estimated versus actual soil erosion on the Great Basin Experimental Area.

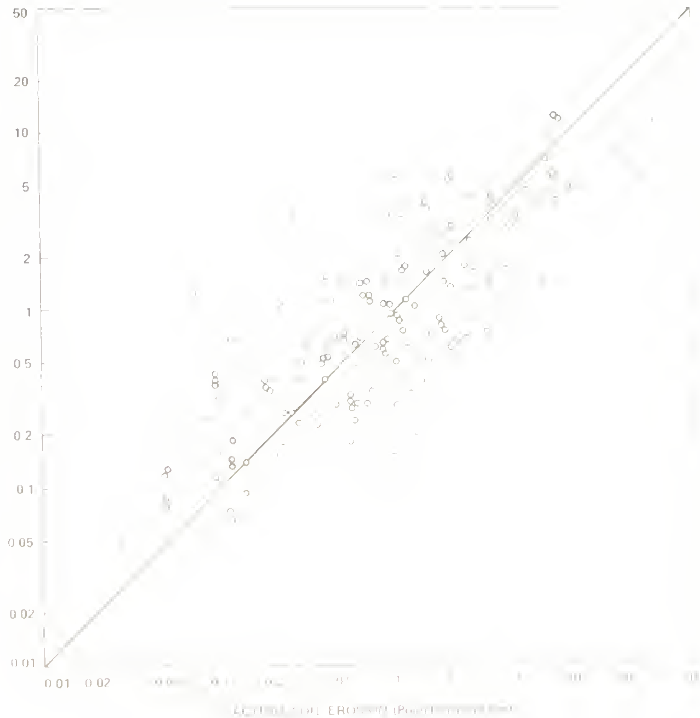


Figure 3.--Soil erosion on the Great Basin Experimental Area in relation to percent of soil surface protected from direct raindrop impact at bulk densities of 0.9, 1.1, and 1.3 g./cc.

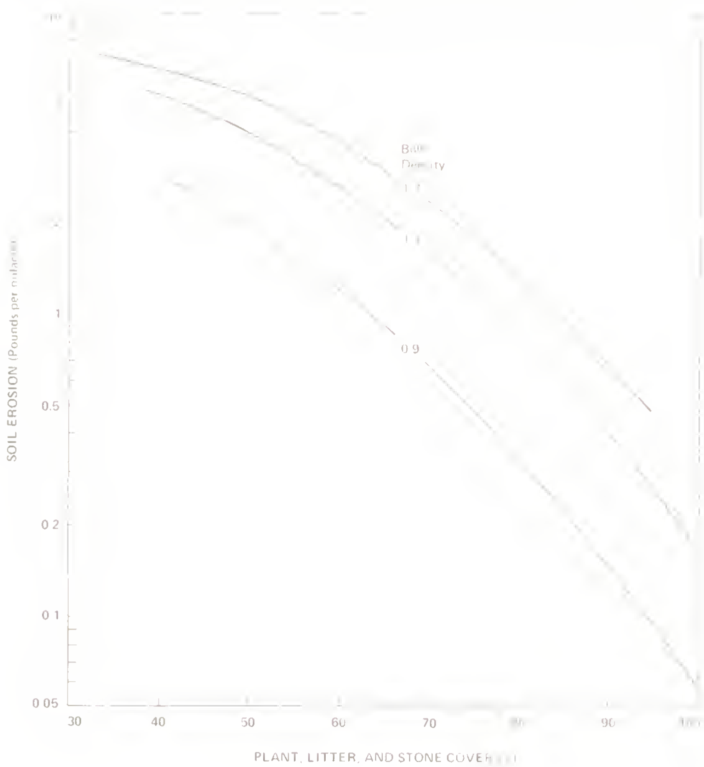


Table 1.--*Correction factors for slope gradient*

Study area	Slope gradient (%) 5	10	15	20	25	30	35	40
GBEA	0.52	0.66	0.86	1.11	1.43	1.84	2.37	3.06
DCEW	.51	.64	.80	1.00	1.25	1.56	1.95	2.44
Montana	.69	.81	.94	1.10	1.28	1.49	1.73	2.02
Diamond	.64	1.00	1.55	2.41	3.75	--	--	--
Basalt	.57	.70	.88	1.09	1.35	1.69	2.10	2.61
Trinity	.38	.49	.65	.86	1.11	1.46	1.91	2.51

Davis County Experimental Watershed.--Protective cover provided by plants and litter explains 76 percent of the variance in the log of soil eroded from study plots on this area. Three other site factors about equal in secondary importance are: slope gradient; litter weight; and soil organic matter. These, in combination with cover density, account for 83 percent of the variance.

The regression equation for sheet erosion on this study area is:

$$\hat{y} = 0.858 - 0.176A - 1.81A^2 - 0.117L + 0.0511AL - 5.89F + 0.0193G$$

in which A, L, F, and G are: plant and litter cover; litter weight; soil organic matter content; and slope gradient defined in the analyses section of this paper. This equation is based on 79 plots and has a standard error of estimate of 0.44 (fig. 4).

Sheet erosion as a function of plant and litter cover and litter weight is shown in figure 5. The amount of erosion is governed primarily by the proportion of soil surface protected by plants and litter but the actual weight of litter has an additional favorable influence in retarding erosion.

The curves of figure 5 are based on the above equation with organic matter content at its average of 6 percent and slope gradient at its average of 20 percent. Correction factors for variation of organic matter content of the surface 2 inches of soil are given in table 2. To correct for organic matter content variation, the soil erosion values in figure 5 should be multiplied by these factors. At an organic matter content of 11 percent, the amount of erosion is about one-half that indicated by figure 5; but if organic matter content is only 1 percent, erosion is almost twice that shown in figure 5. In like manner, corrections for slope can be obtained from table 1.

Table 2.--*Correction factors for organic matter content in the surface 2 inches of soil on the Davis County Experimental Watershed*

Organic matter (% by weight)	Correction factor	Organic matter (% by weight)	Correction factor
1	1.97	7	.87
2	1.72	8	.76
3	1.50	9	.67
4	1.31	10	.58
5	1.15	11	.51
6	1.00	12	.44

Figure 4.--Estimated versus actual soil erosion on the Davis County Experimental Watershed.

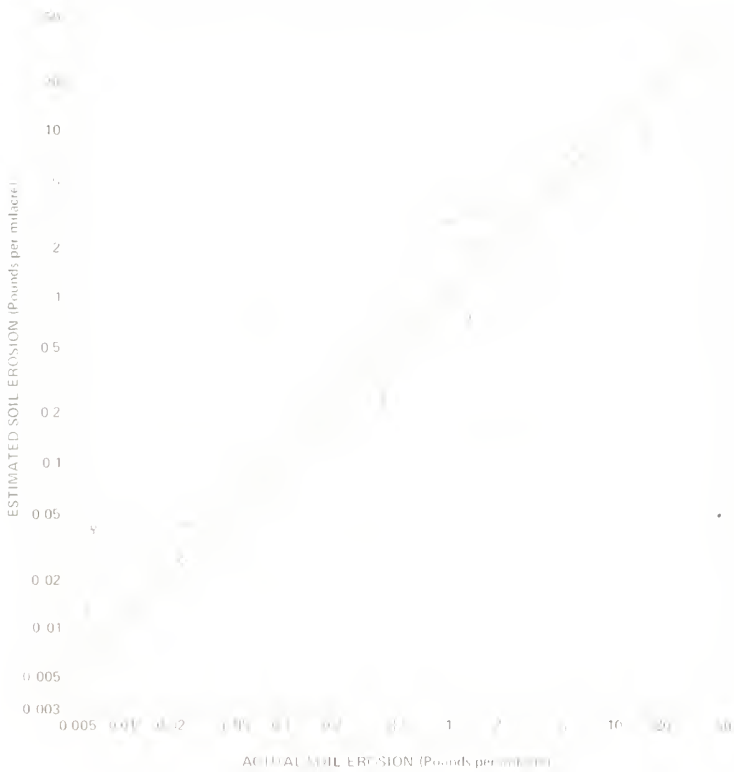
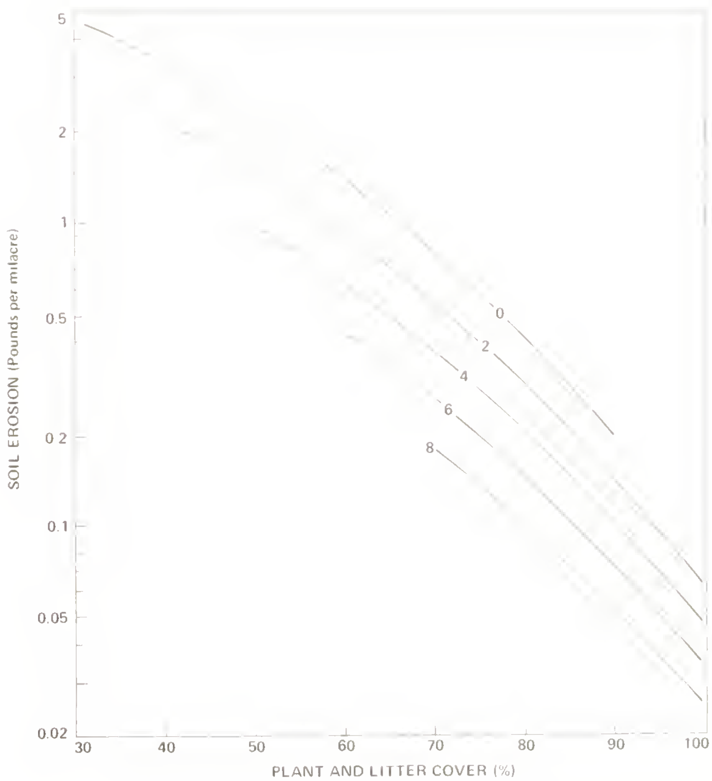


Figure 5.--Soil erosion on the Davis County Experimental Watershed in relation to percentage of soil surface protected from direct raindrop impact by plants and litter at litter weights of 0, 2, 4, 6, and 8 pounds per milacre.



Vigilante Experiment Range and Monument Ridge, Montana.--Plant and litter cover explains 80 percent of the variance of the log of soil eroded from plots on this study area. Organic matter content of the surface inch of soil also favors resistance to erosion, probably through aggregation of soil particles, and explains an additional 4 percent of the variance. Slope gradient explains an additional 2 percent of the varian

The regression equation for this study area is:

$$\hat{y} = 1.563 - 0.629A - 1.86A^2 - 26.0F + 13.2F^2 + 19.0AF + 0.0133G$$

This equation is based on 86 plots and has a standard error of estimate of 0.33 an a coefficient of determination of 0.86 (fig. 6). Sheet erosion as a function of plant and litter cover and organic matter content of the surface 2 inches of soil is shown in figure 7. Correction factors for deviation of slope gradient from its average of 17 percent are in table 1.

Diamond Mountain.--The three most important site variables on this study area are: plant and litter cover; organic matter content of the surface inch of soil; and slope gradient. The effects of cover are similar to those found on the other study areas, but the effect of slope is greater than on the other study areas. Unlike the previous three areas, organic matter content is positively correlated with erosion. The regression equation for sheet erosion developed from Diamond Mountain data is:

$$\hat{y} = -1.015 + 1.31A - 2.08A^2 - 5.87AE + 8.13E + 0.0383G$$

This equation is based on 34 observations. Its standard error of estimate is 0.32 and its R^2 is 0.71 (fig. 8). With slope gradient fixed at its average of 10 percent, this equation is presented graphically in figure 9.

Figure 6.--Estimated versus actual soil erosion on the Montana study area.

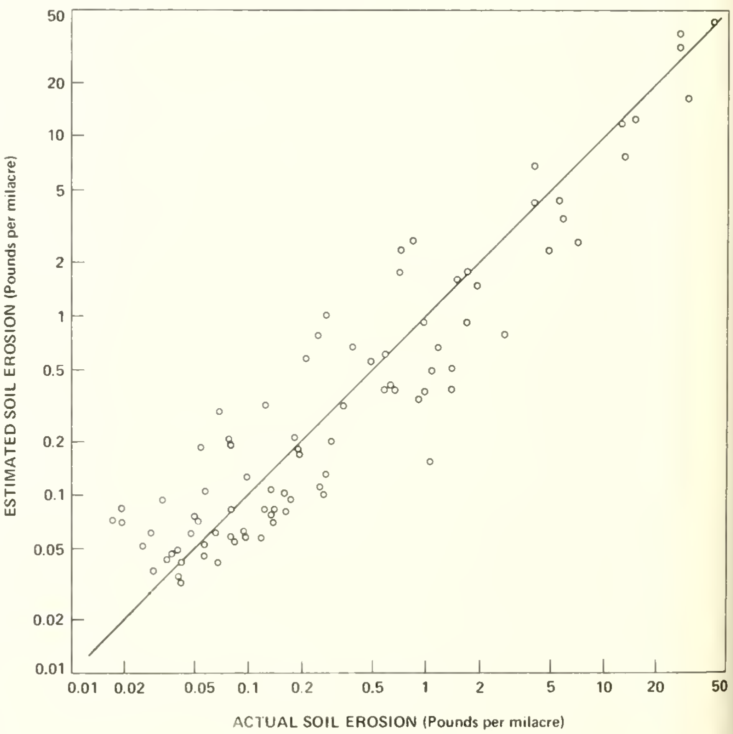


Figure 7.--Soil erosion on the Montana study area in relation to percentage of soil surface protected from direct raindrop impact by plants and litter at 2, 6, 10, and 14 percent organic matter in the surface 2 inches of soil.

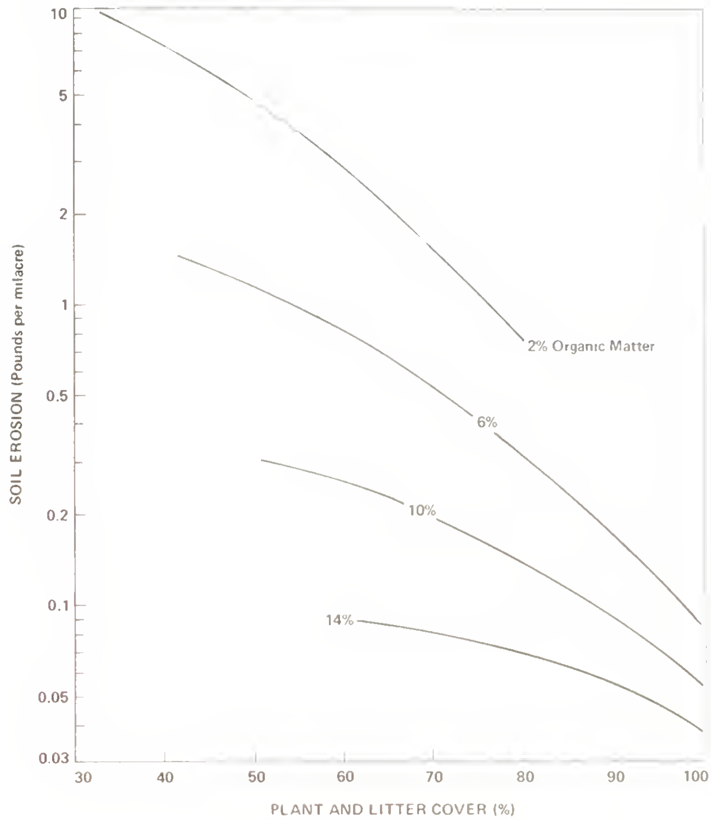


Figure 8.--Estimated versus actual soil erosion on the Diamond Mountain study area.

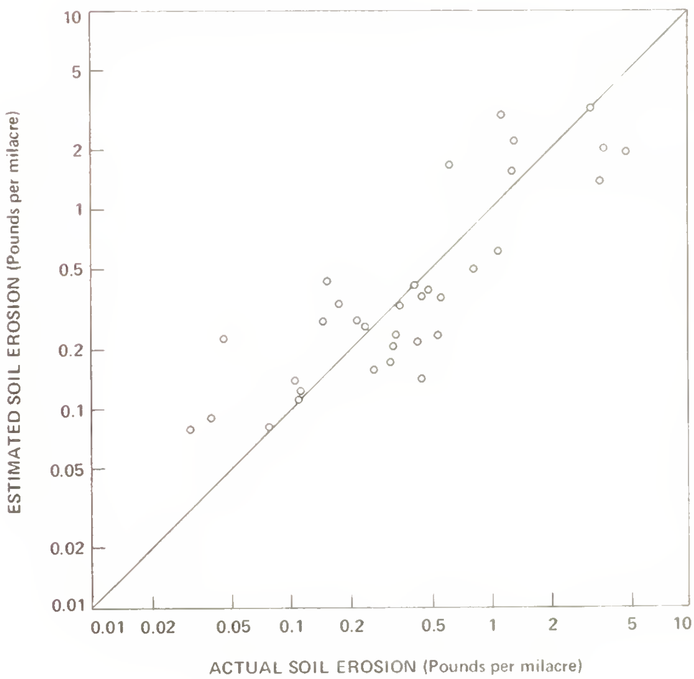
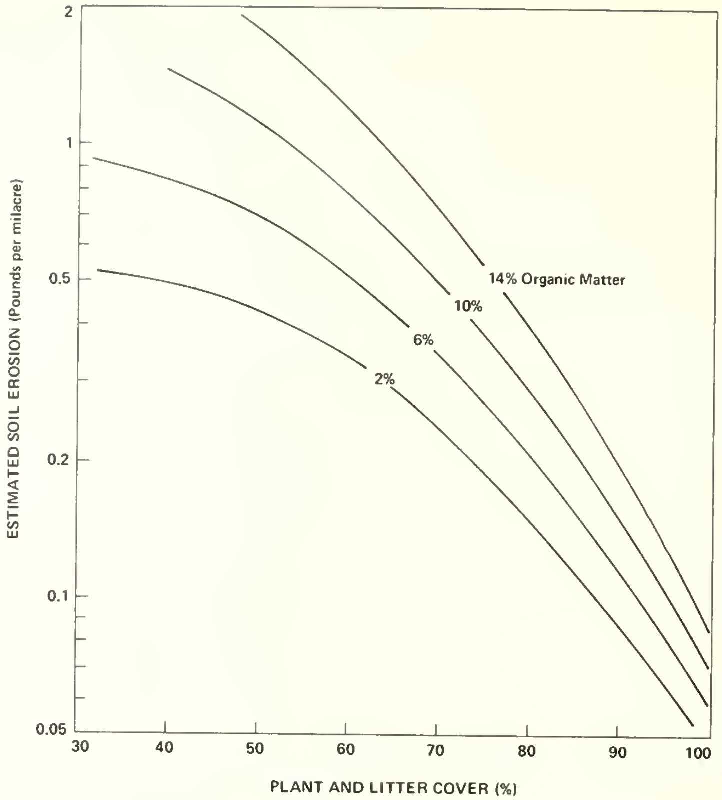


Figure 9.--Soil erosion on the Diamond Mountain study area in relation to percentage of soil surface protected from direct raindrop impact by plants and litter with 2, 6, 10, and 14 percent organic matter in the surface inch of soil.



The striking feature of this equation is that the amount of erosion increases as organic matter content increases. This is contrary to results of studies on finer textured soils where organic matter favors the formation of erosion-resistant aggregates. One would suspect spurious correlation if this positive relation between erosion and organic matter content were observed only on this study area. However, similar relations were observed on other coarse-textured soils in Idaho, up to 500 miles from this study area.

Basalt.--The strong interaction between sand content and organic matter content was quite apparent on this area. The regression equation for sheet erosion on this study area is:

$$\hat{y} = 6.615 - 3.58B + 1.50B^2 - 19.7D + 15.0D^2 - 41.4E + 92.7DE + 0.0189G$$

This equation is based on 44 plots and has a standard error of estimate of 0.39 and a coefficient of determination of 0.69 (fig. 10). Protective cover provided by plants, litter, and stone (fig. 11) is the most important variable and the effects of slope gradient (table 1) were similar to those on other study areas. The curve in figure 11 is based on average slope (18 percent), average sand content (38 percent), and average organic matter content (9 percent). The effects of variations of sand and organic matter are shown graphically in figure 12. Where sand contents are low, erosion decreases sharply as organic matter increases. But organic matter apparently had a reverse effect on erosion where sand contents are high, an effect similar to that observed at Diamond Mountain. In soil having a 45 percent sand content, organic matter has little influence on erosion, probably because its aggregating influence on clay is compensated by its unfavorable influence on erodibility of sand.

The net effect is that the fine-textured soils are more erodible if there is little organic matter in the surface soil but, when there is much organic matter, sheet erosion is greater on sandy soils.

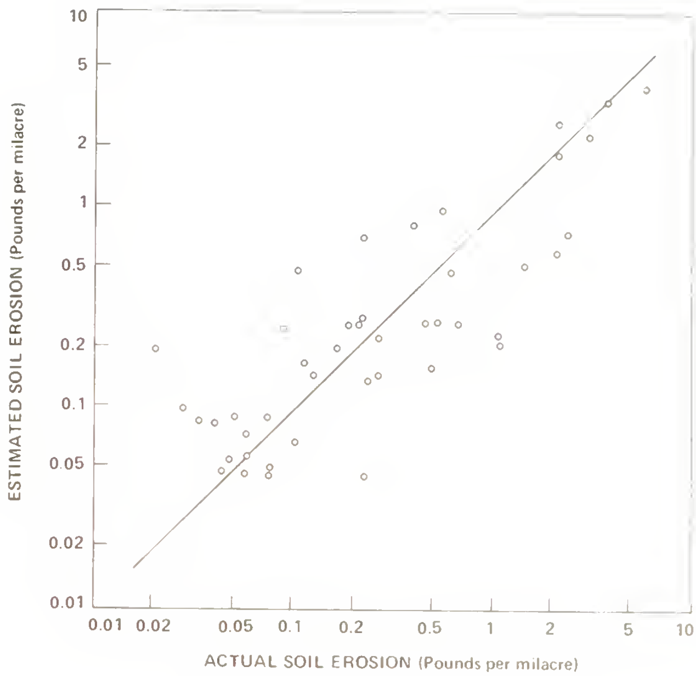


Figure 10.--Estimated versus actual erosion on the Basalt study area.

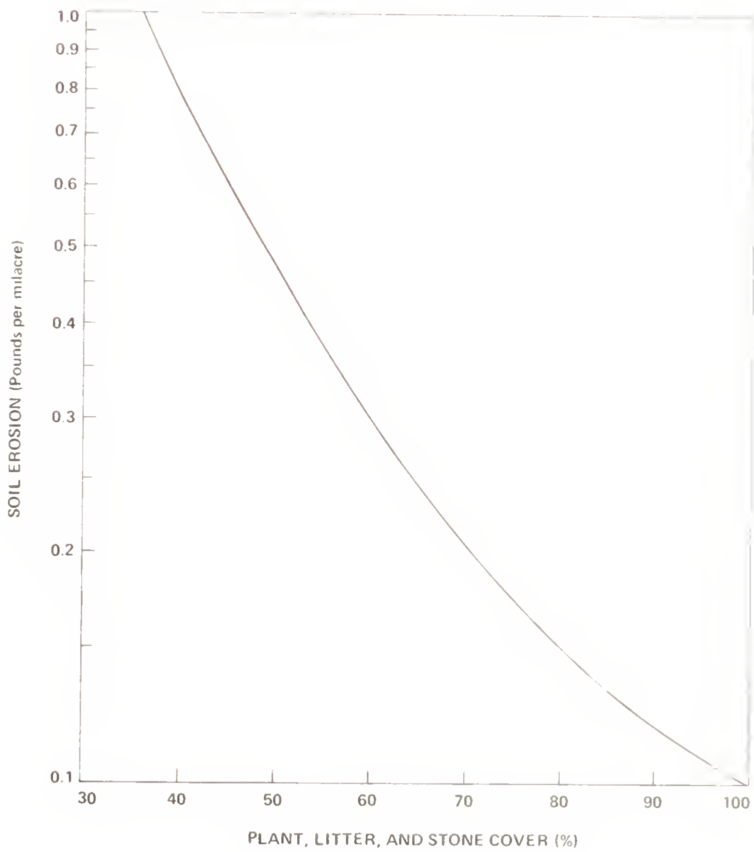
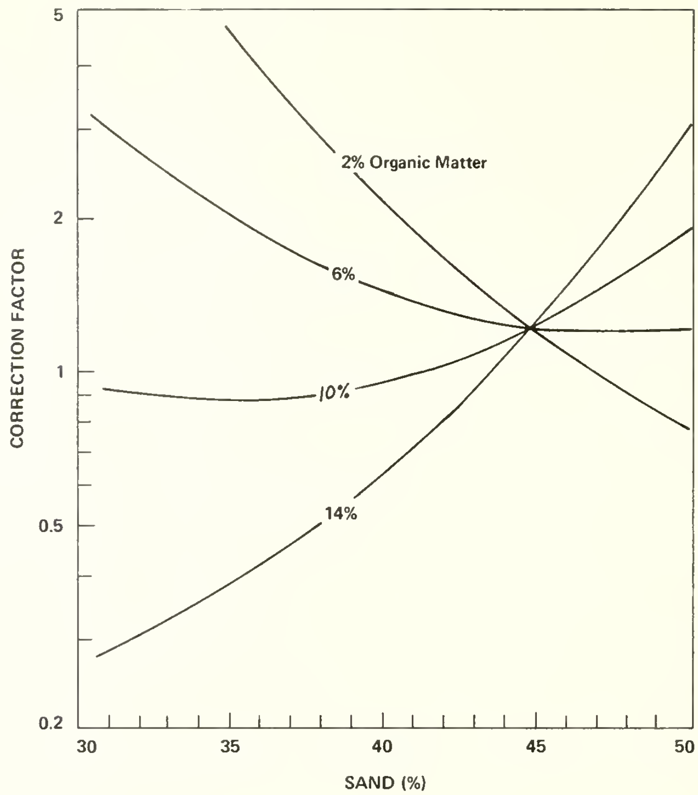


Figure 11.--Soil erosion on the Basalt study area in the relation to percent of soil surface protected from direct raindrop impact when the surface inch of soil contains 38 percent sand and 9 percent organic matter.

Figure 12.--Effects of changes in sand and organic matter content on amount of soil erosion on the Basalt study area. Soil erosion indicated in figure 11 should be multiplied by correction factor indicated in figure 12 to correct for variations in soil organic matter content and sand.



Coolwater Ridge.--Plant, litter, and stone cover explains 83 percent of the variance in the log of soil eroded. No significant additional variance was explained by any other variable, probably because of the few plots (15) and the limited variation in these other variables. The following equation has a standard error of 0.32:

$$\hat{y} = 1.293 + 0.105B - 2.04B^2$$

The curve defined by this equation is plotted in figure 13 along with the data. Erosion is generally greater at Coolwater Ridge than on the other study areas because of rather steep slopes (33 percent average) and a high sand content (57 percent average) combined with a rather high organic matter content (10 percent average). Observations on other study sites indicate that high organic matter content and steep slopes both operate to increase erosion on sandy soils. Another reason for greater erosion at Coolwater Ridge may be due to the character of the vegetation which consists mainly of low-value forbs such as polygonum. This type of vegetation, with its small basal area and low litter production, gives less protection against erosion than an equal areal coverage of grasses or mat-forming forbs.

Trinity Mountains.--The erosional behavior of these granitic soils is rather erratic. Only about 45 percent of the variance of the log of soil eroded is accounted for by plant and litter cover. The influence of cover on erosion is greatest on soils of high organic matter content. The multiple regression equation is:

$$\hat{y} = -0.666 + 1.71A - 1.82A^2 + 8.60E - 18.0AE + 0.0235G$$

This equation is based on 40 plots. The standard error of estimate for this equation is 0.40 but the coefficient of determination is only 0.57 (fig. 14). With plot slope gradient fixed at its average of 23 percent, this equation is presented

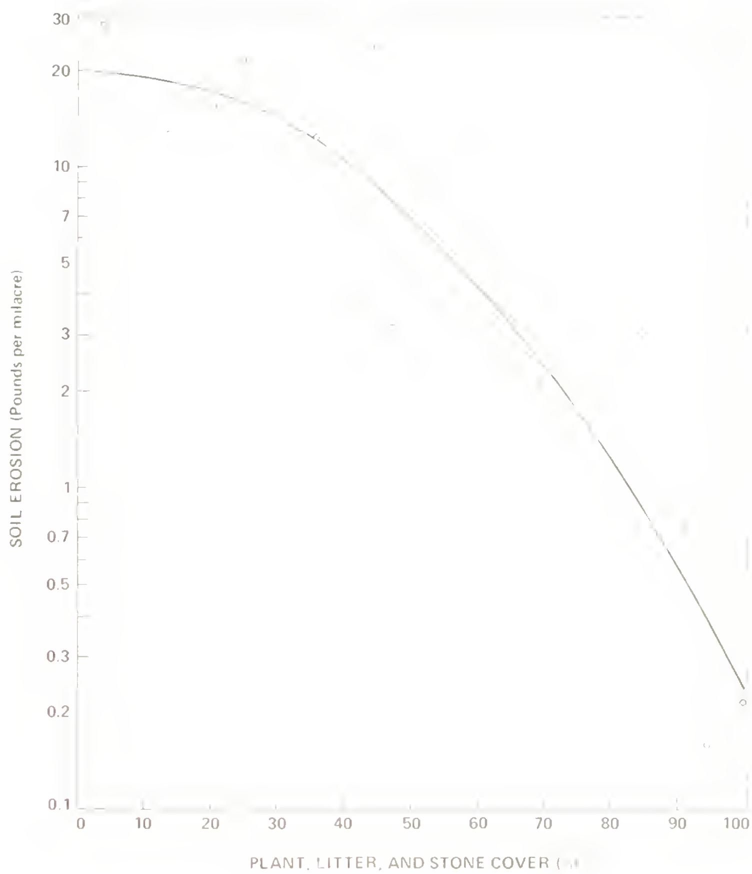


Figure 13.--Soil erosion on the Coolwater Ridge study area in relation to percent of soil surface protected from direct raindrop impact.

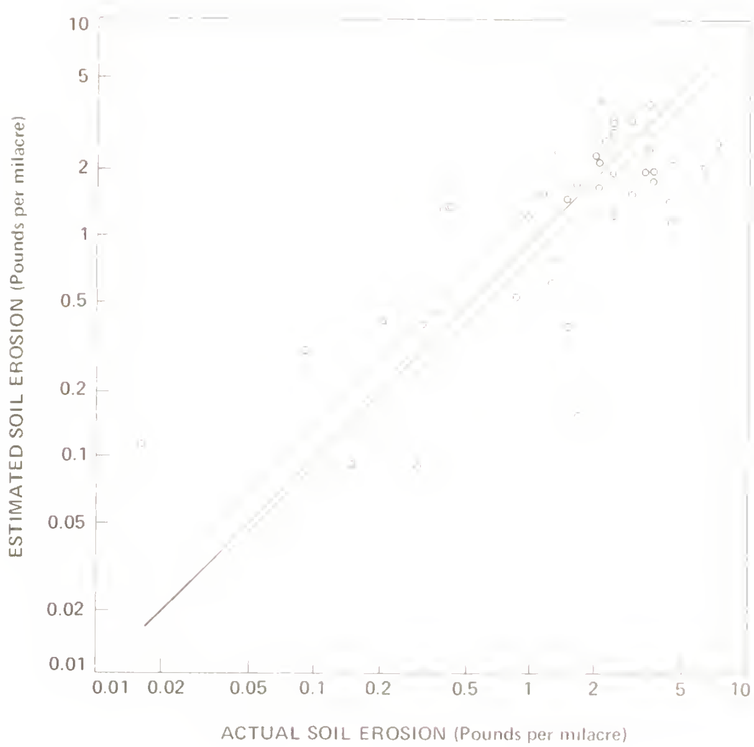
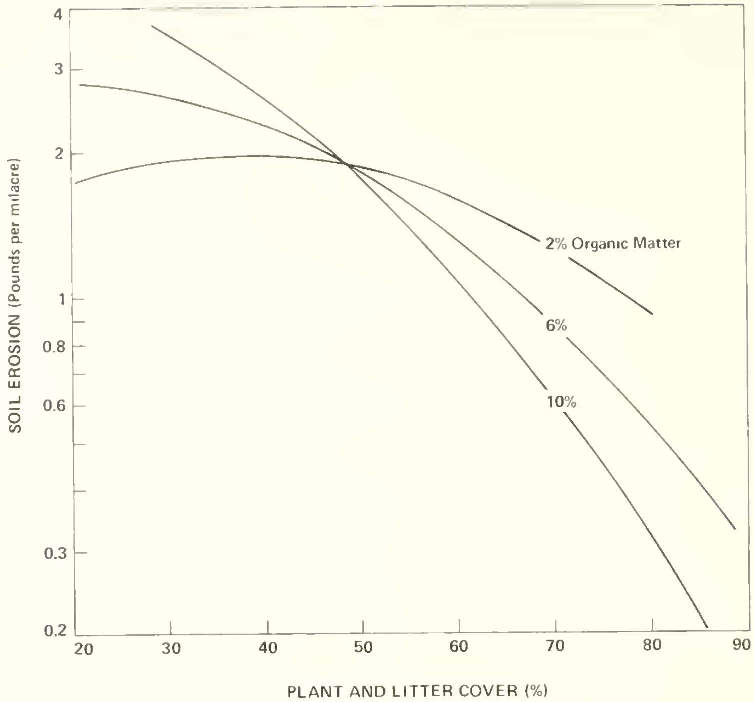


Figure 14.--Estimated versus actual soil erosion on the Trinity Mountains study area.

Figure 15.--Soil erosion on the Trinity Mountains study area in relation to percent cover of plant and litter at 2, 6, 10 percent organic matter in the surface inch of soil.



graphically in figure 15. When more than 50 percent of the soil surface is protected by vegetation and litter, organic matter favors resistance to erosion. At less than 50 percent cover, there is a reversal of this influence and a tendency for the more highly organic soils to be more erodible. This is an important consideration because the average plant and litter cover on the plots in this study area was only 52 percent and organic matter content averaged 6 percent, a high organic matter content for soils averaging 72 percent sand.

Since this equation accounts for only 57 percent of the variance, there are obviously other factors affecting erosion on this site. Further study is needed, particularly on inorganic bonding between sand particles and on the nature of the adverse effects of organic matter on stability of sandy soils.

APPLICATION

The regression equations presented in this paper may be used to estimate the amount of sheet erosion expected under design rainstorm conditions. These estimates are relative values to be used for comparisons among sites. The equations are derived from small plots with a fixed amount of simulated rain and cannot be expected to yield absolute estimates of erosion because variations in rainfall characteristics and plot size will influence the actual amount of erosion.

Since direct solution of the equations is tedious unless a computer is available, tables and nomograms are provided in the Appendix to facilitate calculations. Coolwater Ridge is not included because its equation is based on too few observations to be useful for estimation.

Estimates may be made for areas other than those studied only if there is reasonable assurance that the area in question closely resembles one of the study areas and the equation for that study area is used. Obviously, the uncertainty of the estimate increases as the difference between the area of application and the original study area increases.

The accuracy of the estimates can be improved by considering some site factors that do not appear in the equations but still may influence amount of erosion.

On most of the plots in this study, the cover was fairly uniform in distribution. If cover is not uniformly distributed, as on bunchgrass range, estimates of erosion will probably be low; the size of bare openings can affect erosion significantly (Packer 1951).

Basal area of vegetation is another factor that should be considered. Although protection from direct rainfall impact is likely the most important single function of vegetation, the amount of cover in direct contact with the ground is also important. At any given areal cover percentage, those species having a larger basal area will retard overland flow and erosion more than those with a smaller basal area. In this respect, grasses are superior to tall, single-stem forbs.

On finer textured soil, litter weight apparently exercises some restrictive influence on erosion in addition to that attributable to protection from direct raindrop impact. On sandy soils, litter appears to have no favorable influence beyond that of raindrop interception.

The erodibility of the litter itself must also be considered. It may be eroded if it consists of small, easily detached fragments. Erosion tends to be greater on sites with easily detached litter than on otherwise similar sites with firmly anchored litter.

Bulk density occasionally influences erosion but these effects are complex. There is an inverse relation between bulk density and infiltration because soil porosity is inversely related to bulk density; this means more runoff and, consequently, more erosion on denser soils. There is also an inverse relation between bulk density and organic matter content; and, as noted earlier in this paper, organic matter exercises a variable effect on erosion, depending on soil texture. Under some circumstances, and this was noted particularly on sandy soils, cohesiveness and resistance to detachment are positively related to bulk density; some light fluffy soils are highly erodible.

While it is obvious that soil erodibility depends on many factors, results of this study suggest that reliable estimates of erodibility may be made on the basis of a few of the most important ones. The equations in this paper give reasonable approximations of the amount of sheet erosion that will occur on any particular site under the impact of a half-hour simulated design rainstorm. These approximations, augmented by visual observations in the field, provide bases for estimating potential sheet erosion on sites similar to those studied.

LITERATURE CITED

Bouyoucos, G. J.
1962. Hydrometer method improved for making particle size analyses of soil. Agron. J. 54: 464-465.

Dortignac, E. J.
1951. Design and operation of Rocky Mountain infiltrometer. U.S. Forest Serv., Rocky Mountain Forest and Range Exp. Sta., Sta. Pap. 5, 68 p.

Laws, J. O.
1941. Measurements of the fall-velocity of waterdrops and raindrops. Amer. Geophys. Union Trans. 22: 709-721.

Leamer, R. W., and B. Shaw.
1941. A simple apparatus for measuring noncapillary porosity on an extensive scale. Amer. Soc. Agron. J. 33: 1003-1008.

Levy, E. B., and E. A. Madden.
1933. The point method of pasture analysis. New Zealand J. Agr. 46: 267-279.

Marston, R. B.
1952. Ground cover requirements for summer storm runoff control on aspen sites in northern Utah. J. Forestry 50: 303-307.

Meeuwig, R. O.
1965. Effects of seeding and grazing infiltration capacity and soil stability of a subalpine range in central Utah. J. Range Manage. 18: 173-180.

____
1969. Infiltration and soil erosion on Coolwater Ridge, Idaho. USDA Forest Serv. Res. Note INT-103, 5 p.

____
1970. Infiltration and soil erosion as influenced by vegetation and soil in northern Utah. J. Range Manage. 23: 185-188.

Middleton, H. E.
1930. Properties of soil which influence soil erosion. U.S. Dep. Agr. Tech. Bull. 178, 16 p.

Osborn, B.
1956. Cover requirements for the protection of range site and biota. J. Range Manage. 9: 75-80.

Packer, P. E.
1951. An approach to watershed protection criteria. J. Forestry 49: 639-644.

____
1963. Soil stability requirements for the Gallatin elk winter range. J. Wildlife Manage. 27: 401-410.

Peech, M., L. T. Alexander, L. A. Dean, and J. F. Reed.
1947. Methods of soil analysis for soil-fertility investigations. U.S. Dep. Agr. Circ. 757, 25 p.

Yoder, R. E.
1936. A direct method of aggregate analysis and a study of the physical nature of erosion losses. J. Amer. Soc. Agron. 28: 337-351.

APPENDIX

Great Basin Experimental Area.--Estimated sheet erosion on GBEA as a function of bulk density (surface 4 inches of soil) and total cover percentage (plants, litter, and stone) is listed in table 3. For example, if a site has 60 percent cover and bulk density is 1.05 g./cc., the estimate is 2.16 pounds per milacre, without slope correction. If the slope gradient of this site is 10 percent, the correction factor is 0.66 (from table 1). Estimated erosion, corrected for slope, is 2.16 X 0.66 = 1.4 pounds per milacre.

Davis County Experimental Watershed.--The nomogram (fig. 16) for DCEW is used as follows:

1. Start at plant and litter cover percentage on line A and draw a line to litter weight (lbs./milacre) on line B.

2. Draw a line from the intersection point on line C to slope percentage on line D.

3. Draw a line from the intersection point on line E to organic matter percent on line F.

4. The intersection on line G is estimated erosion in pounds per milacre.

For example, if a site has 80 percent cover of plants and litter, 4 pounds of litter per milacre, 36 percent slope, and 8.1 percent organic matter in the surface 2 inches of soil, its estimated sheet erosion is 0.30 pound per milacre according to figure 16.

Table 3.--*Sheet erosion on GBEA as affected by total cover (plants, litter, and stone) and soil bulk density (surface 4 inches)*

Cover	Bulk density (g./cc.)								
(%)	0.90	0.95	1.00	1.05	1.10	1.15	1.20	1.25	1.30
	Pounds per milacre								
30	3.40	4.11	4.84	5.53	6.14	6.62	6.93	7.05	6.96
35	3.05	3.72	4.42	4.98	5.69	6.20	6.53	6.71	6.68
40	2.65	3.27	3.91	4.54	5.12	5.62	5.98	6.18	6.21
45	2.25	2.79	3.36	3.95	4.48	4.96	5.32	5.54	5.62
50	1.85	2.31	2.81	3.32	3.81	4.25	4.60	4.83	4.93
55	1!48	1.87	2.28	2.72	3.15	3.56	3.86	4.09	4.21
60	1.14	1.46	1.80	2.16	2.52	2.86	3.15	3.36	3.49
65	.86	1.12	1.38	1.68	1.97	2.25	2.50	2.70	2.81
70	.63	.82	1.02	1.16	1.49	1.72	1.92	2.09	2.20
75	.45	.59	.74	.92	1.10	1.28	1.44	1.57	1.68
80	.31	.41	.52	.65	.78	.92	1.05	1.15	1.24
85	.21	.28	.36	.44	.55	.65	.75	.82	.89
90	.14	.18	.24	.30	.37	.44	.51	.57	.62
95	.09	.12	.15	.20	.24	.29	.34	.39	.43
100	.05	.07	.10	.12	.15	.19	.22	.25	.28

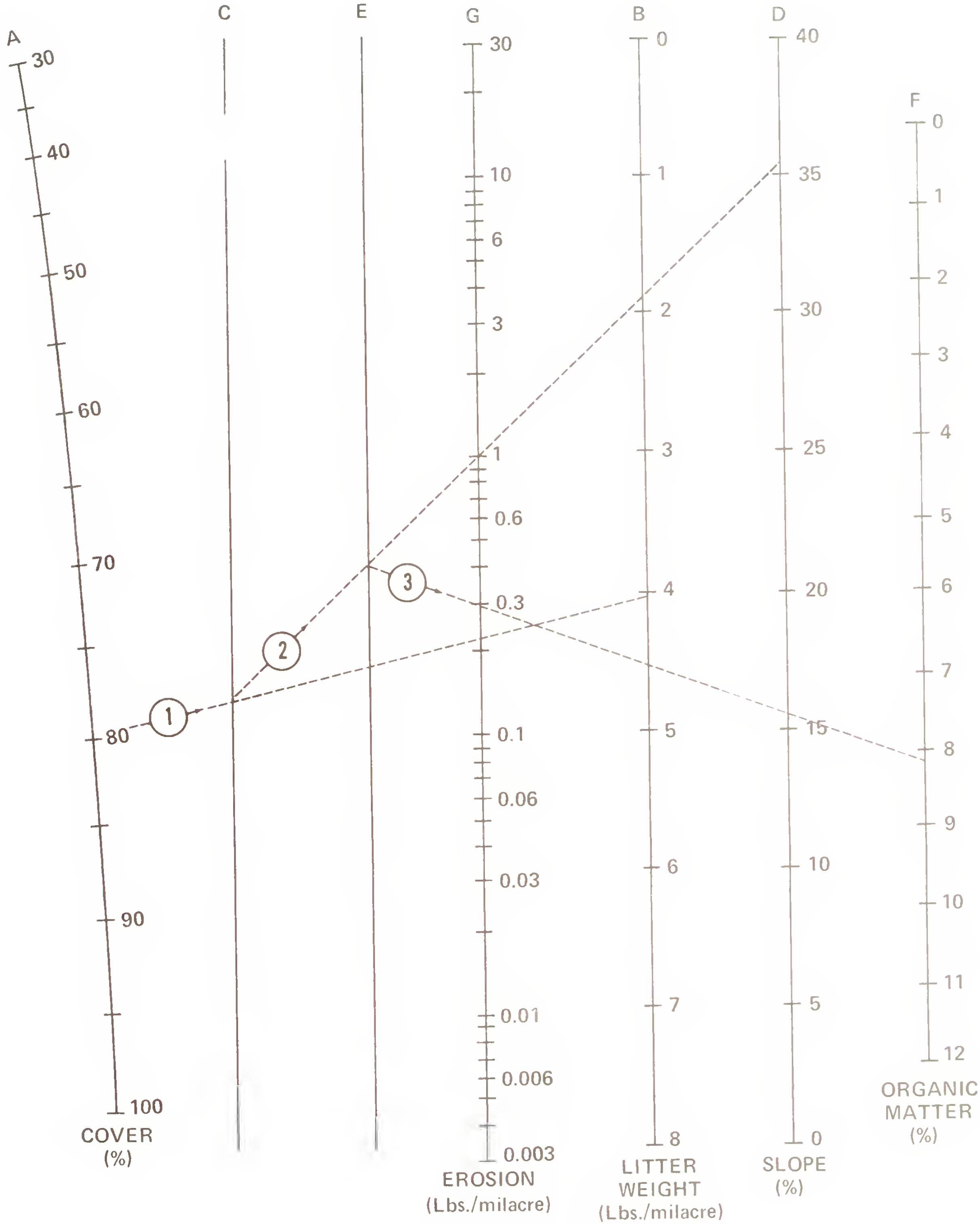


Figure 16.--Nomogram for estimating sheet erosion on the Davis County Experimental Watershed.

Table 4.--*Estimated sheet erosion on Monument Ridge and the Vigilante Experimental Range as a function of plant and litter cover and organic matter content of the surface 2 inches of soil*

Cover (%)	Organic matter content (% by weight) 2	4	6	8	10	12
	Pounds per milacre					
30	10.78	4.39	1.83	.78	--	--
35	9.11	3.88	1.69	.76	.35	--
40	7.53	3.35	1.53	.71	.34	--
45	6.10	2.83	1.35	.66	.33	--
50	4.83	2.35	1.17	.59	.31	.17
55	3.75	1.90	.99	.53	.29	.16
60	2.85	1.51	.82	.46	.26	.15
65	2.11	1.17	.66	.39	.23	.14
70	1.54	.89	.53	.32	.20	.13
75	1.09	.66	.41	.26	.17	.11
80	.76	.48	.31	.21	.14	.10
85	.52	.34	.23	.16	.11	.08
90	.35	.24	.17	.12	.09	.07
95	.23	.16	.12	.09	.07	.06
100	.14	.11	.08	.07	.05	.04

Monument Ridge and Vigilante Experimental Range.--Table 4 lists estimated sheet erosion as a function of plant and litter cover and organic matter content of the surface 2 inches of soil. These values should be multiplied by the appropriate correction factor in table 1 to correct for slope.

Diamond Mountain.--The nomogram (figure 17) for the Diamond Mountain Cattle Allotment is used as follows:

1. Draw a line from the plant and litter cover percentage on line A to the organic matter content of the surface inch of soil on line B.

2. Draw a line from the intercept on line C to the slope gradient on line D.

3. The intersection on line E is estimated sheet erosion.

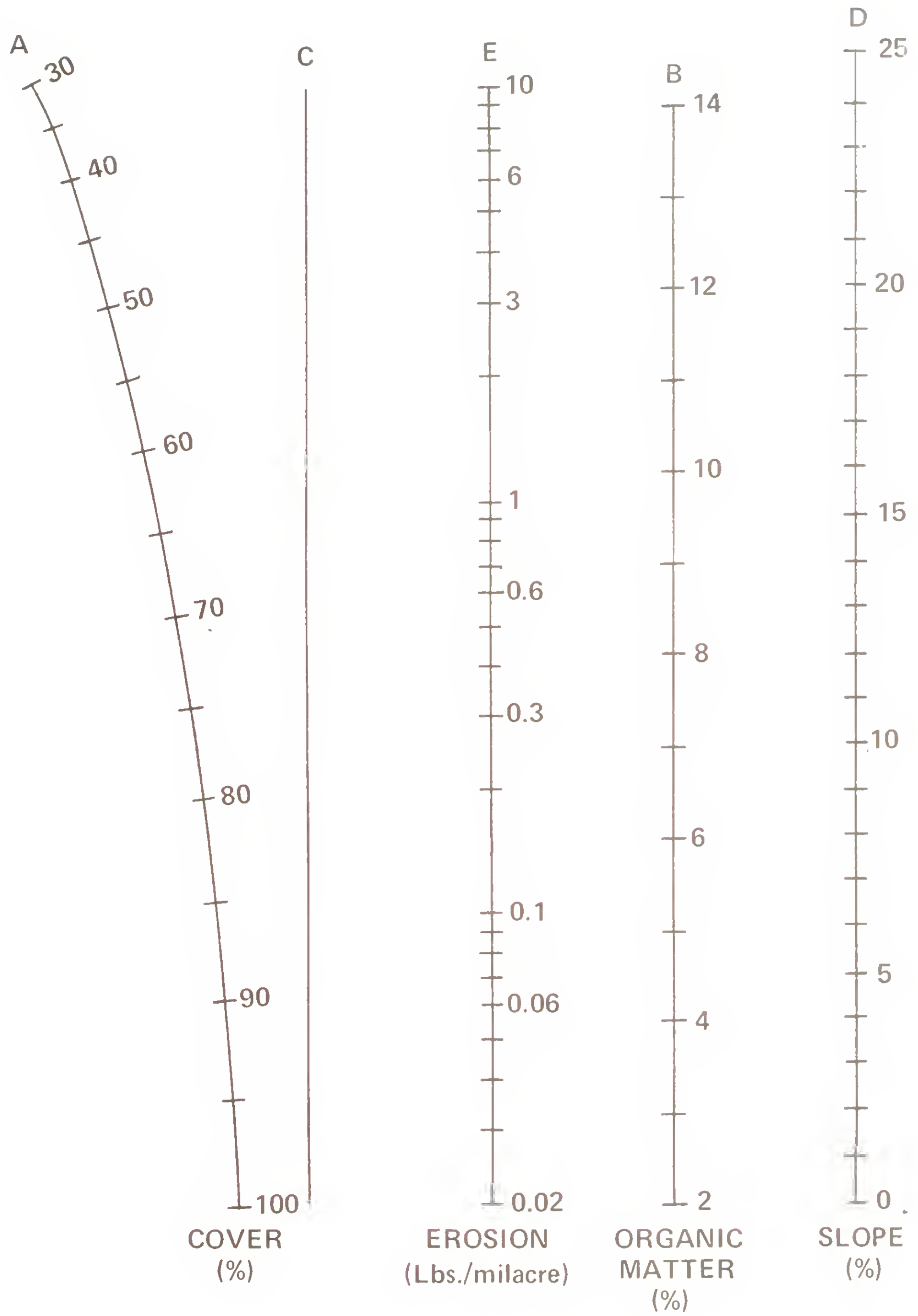


Figure 17.--Nomogram for estimating sheet erosion on the Diamond Mountain study area.

Basalt.--Three tables (1, 5, and 6) are required to calculate estimated erosion on the Basalt study area. Table 5 lists erosion as a function of plant, litter, and stone cover percent. Table 6 contains correction factors for sand and organic matter content of the surface inch of soil. For example, a site has 80 percent cover, 40 percent sand, 10 percent organic matter, and a 30 percent slope. Table 5 indicates sheet erosion to be 0.15 pound per milacre, uncorrected for slope or soil. Table 1 indicates a slope correction of 1.69. Table 6 indicates a soil correction of 0.92. Therefore, estimated sheet erosion is: 0.92 X 1.69 X 0.15 = 0.23 pound per milacre.

Trinity Mountains.--The nomogram (fig. 18) for this study area is used as follows:

1. Draw a line from the plant and litter cover percentage on line A to the organic matter content of the surface 1 inch of soil on line B.

2. Draw a line from the intercept on line C to the slope gradient on line D.

3. The intersection on line E is estimated sheet erosion.

Table 5.--*Estimated sheet erosion on the Basalt study area as related to protective cover provided by plants, litter, and stone*

Cover (%)	Erosion (lbs./milacre)	Cover (%)	Erosion (lbs./milacre)
30	1.36	70	.20
35	1.15	75	.17
40	.76	80	.15
45	.58	85	.13
50	.45	90	.12
55	.36	95	.11
60	.29	100	.10
65	.24		

Table 6.--*Correction factors for sand and organic matter content in the surface inch of soil on the Basalt study area*

Sand (%)	Organic matter content (% by weight)							
	2	4	6	8	10	12	14	16
30	--	--	3.17	1.69	0.91	0.49	0.26	0.14
32	--	4.34	2.53	1.48	.86	.50	.29	.17
34	5.15	3.27	2.08	1.32	.84	.53	.34	.22
36	3.67	2.54	1.76	1.22	.84	.58	.40	.28
38	2.68	2.02	1.53	1.15	.87	.65	.49	.37
40	2.02	1.66	1.36	1.12	.92	.75	.62	.51
42	1.56	1.40	1.25	1.12	1.00	.89	.80	.71
44	1.24	1.21	1.18	1.15	1.12	1.09	1.06	1.03
46	1.02	1.08	1.14	1.21	1.28	1.36	1.45	1.54
48	.85	.99	1.14	1.32	1.52	1.76	2.03	--
50	.74	.93	1.17	1.47	1.85	2.33	--	--

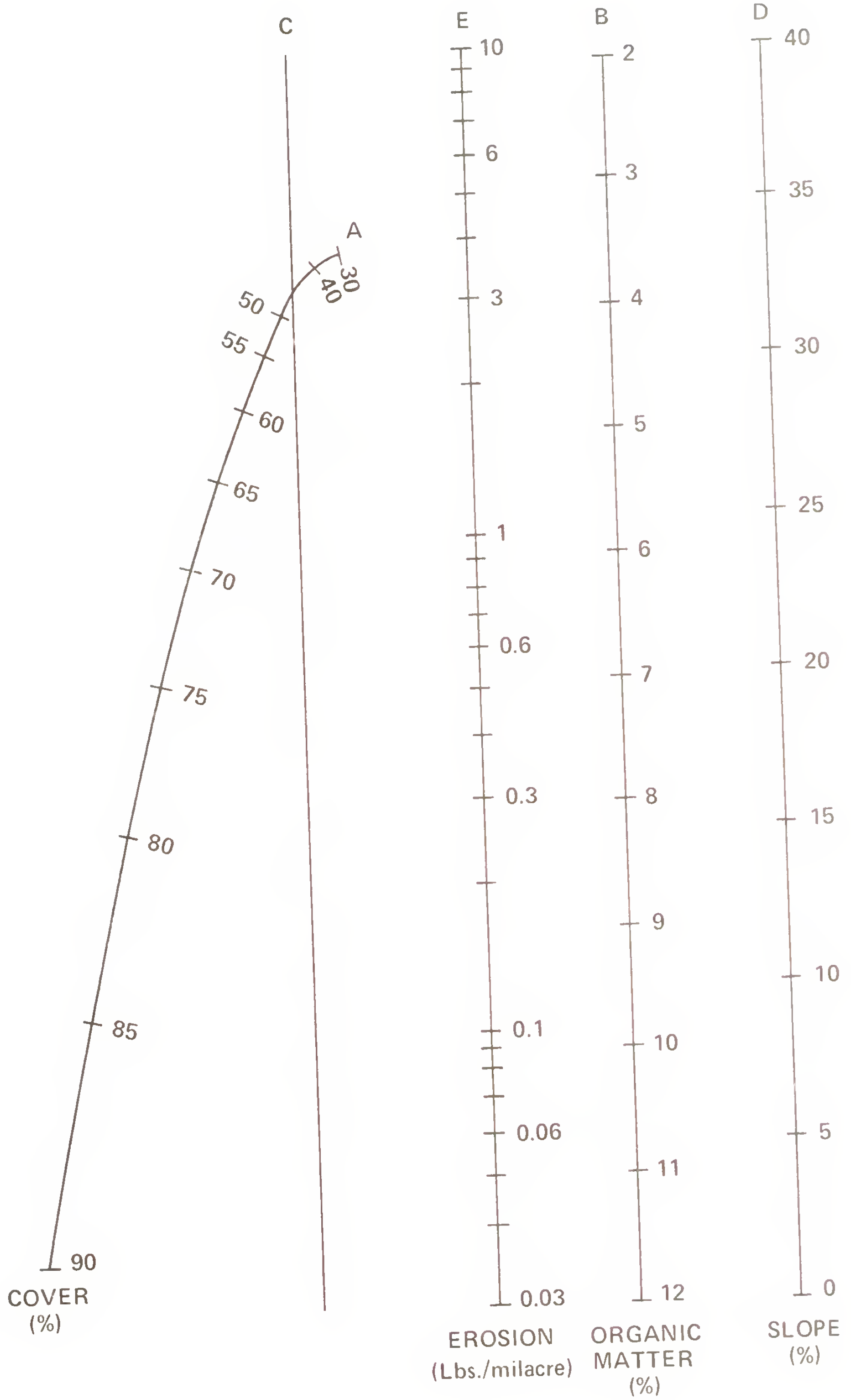
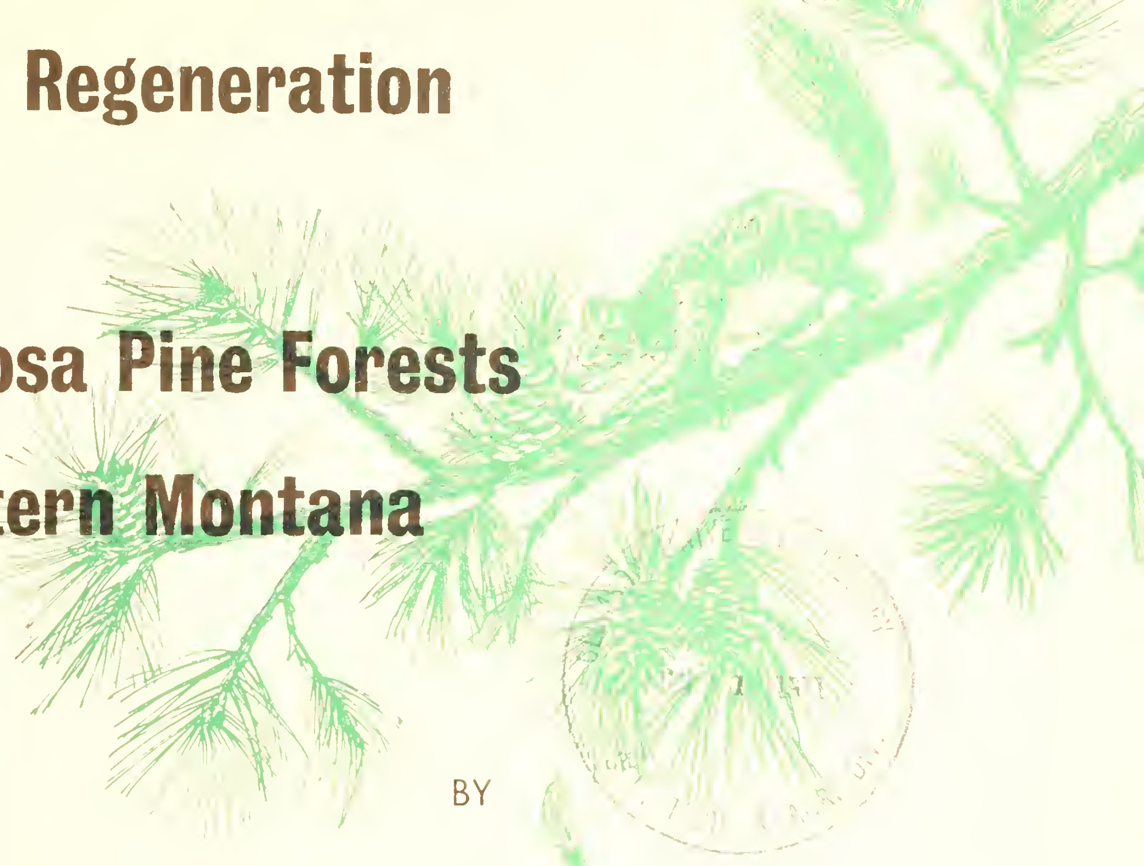


Figure 18.--Nomogram for estimating sheet erosion on the Trinity Mountains study area.

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

Natural Regeneration in Ponderosa Pine Forests of Western Montana



BY

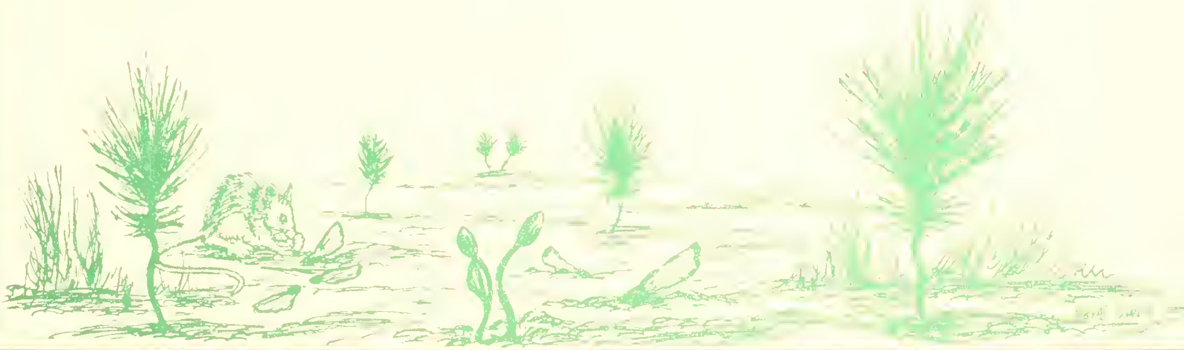
RAYMOND C. SHEARER

WYMAN C. SCHMIDT

U S D A FOREST SERVICE

RESEARCH PAPER INT-86

1970



INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION

Ogden, Utah 84401

THE AUTHORS

RAYMOND C. SHEARER received his B.S. degree in Timber Management from Utah State University in 1957 and his M.S. degree in Silviculture in 1959. Since 1957 he has been an Associate Silviculturist, assigned to the Station's Silviculture of Western Larch and Engelmann Spruce research work unit at the Forestry Sciences Laboratory at Missoula, Montana. His primary assignment has been the study of natural and artificial regeneration of western larch and associated species.

WYMAN C. SCHMIDT is Associate Silviculturist and Leader of the Silviculture of Western Larch and Engelmann Spruce research work unit at the Forestry Sciences Laboratory in Missoula, Montana. After 1 year with the National Forest Administration in the Black Hills, he joined the Intermountain Station in 1960 and since then has worked primarily in research of young coniferous forests. He holds B.S. and M.S. degrees in Forest Management and is currently completing requirements for the Ph. D. in Forest Ecology at the University of Montana.

The authors acknowledge with appreciation the work of K. N. Boe, R. K. LeBarron, A. L. Roe, A. E. Squillace, and D. Tackle for designing and establishing these studies and collecting much of the field data. We are indebted to the Bitterroot, Kootenai, and Lolo National Forests; St. Regis Paper Company; and the Anaconda Forest Products for their cooperation and use of their lands. On areas used for study of natural regeneration, R. D. Pfister described the plant communities and assigned habitat types and R. C. McConnell determined the general geology and soils information.

USDA Forest Service
Research Paper IN[illegible]
December [illegible]

NATURAL REGENERATION IN PONDEROSA PINE FORESTS OF WESTERN MONTANA

Raymond C. Shearer and Wyman C. Schmidt

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

ABSTRACT

At eight locations in western Montana some factors limiting the success of ponderosa pine natural regeneration were identified. During the 45-month period from ovulate bud formation until the seedlings were 1 year old, the potential decreased a thousandfold. Losses were attributed mainly to abortions and squirrel cutting during the 2-year cone development period and to mice and chipmunks during the 8-month period from seedfall to germination. Mineral soil seedbed enhanced the survival of young seedlings. These results showed that cone production in 50-year-old trees was temporarily stimulated by girdling, that squirrel losses can be eliminated by banding trees with metal strips, and that prospective cone crops can be detected early enough to permit the coordination of site preparation with an adequate seed crop.

CONTENTS

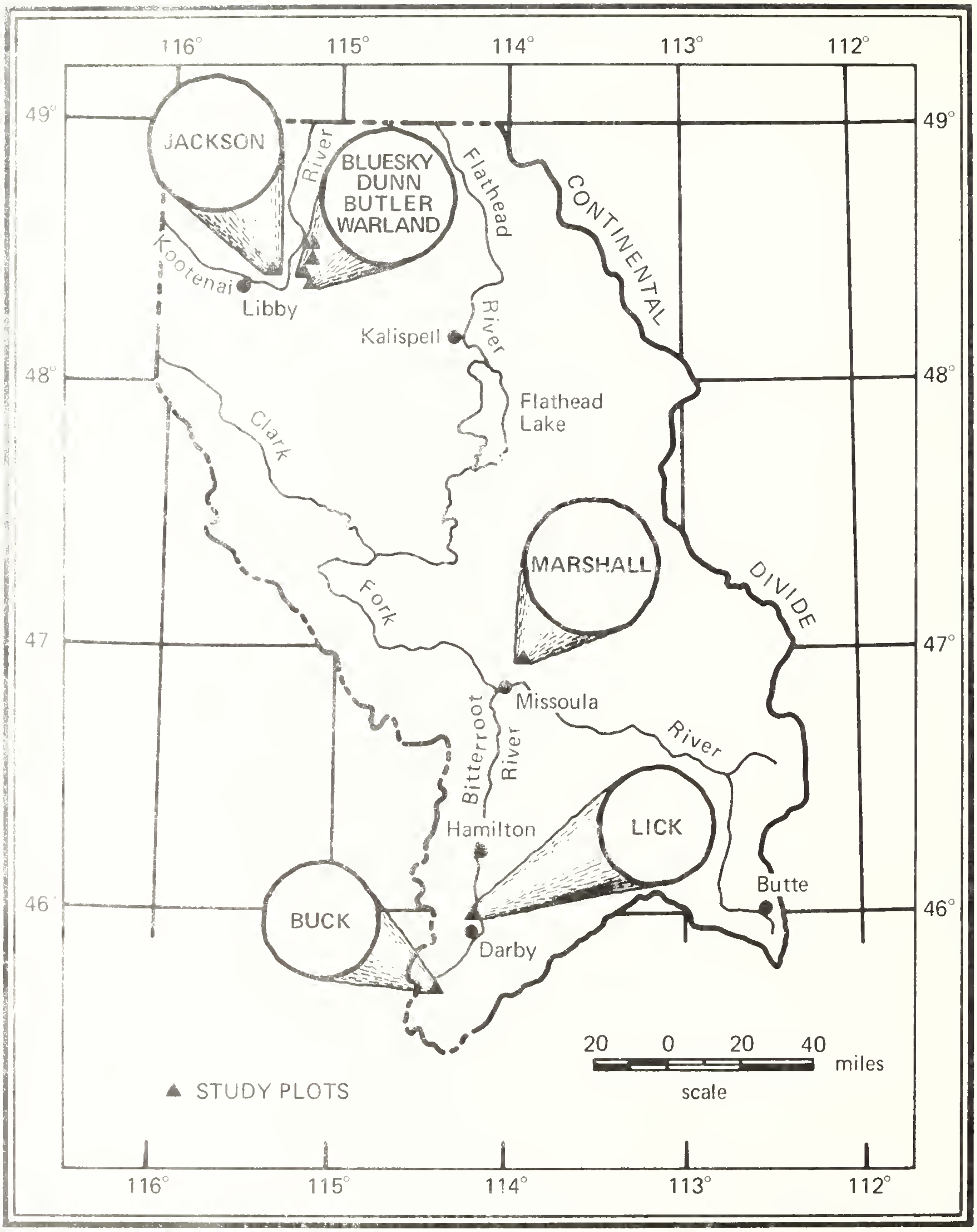


Figure 1.--Location of natural regeneration studies of ponderosa pine in western Montana.

INTRODUCTION

Following harvest cutting, natural regeneration of ponderosa pine (*Pinus ponderosa* Laws.) in western Montana usually is uncertain. Therefore, forest managers frequently rely on planting to promptly regenerate ponderosa pine and prevent future gaps in volume production. When the forester decides to restock an area by natural regeneration, he must effectively manipulate the factors under his control that influence seedling establishment.

Good ponderosa pine seed crops occur at irregular intervals (USDA Forest Service 1965); thus, timing of site preparation to coincide with seed production is a critical requirement for successful natural regeneration. Once cones are initiated, it is important to understand the factors influencing their survival. In addition, stimulation of cone production by girdling or release of seed trees would be a useful tool if ponderosa pine responds to either of these treatments.

Even when a sufficient seed crop is produced, the success of natural regeneration is further influenced by: (1) dissemination to a favorable seedbed; (2) seed loss to biotic agents; (3) germination of the remaining seed; and (4) survival of germinated seedlings.

All of these facets of natural regeneration were studied in western Montana from 1948 to 1962. Five studies were conducted at eight locations (fig. 1). The factors studied on each area are shown in table 1.

Table 1.--*Factors studied that influence natural regeneration of ponderosa pine in western Montana by study area*

Study area	Cooperators	Factors studied: Cone production	Cone stimulation	Seed dispersal	Seed survival	Seedling establishment
Northwestern Montana						
Bluesky Creek	Kootenai N.F.	[1]X		X	X	X
Butler Creek	St. Regis Paper Co.	[2]X		X	X	X
Dunn Creek	St. Regis Paper Co.	[2]X		X	X	X
Jackson Creek	Kootenai N.F.					X
Warland Creek	Kootenai N.F.					X
Southwestern Montana						
Buck Creek	Bitterroot N.F.		X	X		
Lick Creek	Bitterroot N.F.		X	X		
Marshall Creek	Anaconda Forest Products and Lolo N.F.		X	X		

[1]Complete evaluation of cone development and loss.
[2]Squirrel cutting.

The study plots, ranging from 5 to 50 percent in steepness, were located on south- or west-facing slopes lying between 3,000 and 3,900 feet elevation. Although ponderosa pine was dominant, Douglas-fir, its chief associate, was climax for these areas. The habitat types (Daubenmire and Daubenmire 1968) on each of the study plots were as follows (in order of decreasing moisture):

Bluesky - *Pseudotsuga menziesii* - *Physocarpos malvaceus* (moistest)
Warland - *Pseudotsuga menziesii* - *Calamagrostis rubescens, Arctostaphylos uva-ursi* phase (includes *Symphoricarpos albus* and *Spirea betulifolia*)
Jackson and Dunn - *Pseudotsuga menziesii* - *Calamagrostis rubescens, Arctostaphylos uva-ursi* phase (includes *Spirea betulifolia*)
Butler - *Pseudotsuga menziesii* - *Calamagrostis rubescens* (driest)

The soils developed in glacial till deposits. Silty volcanic ash mixed with local colluvial materials in the upper horizons while the horizons below 8 to 15 inches were of older colluvium. The soils were classified as Typic Cryandept at Bluesky and Warland, Mollic Cryandept at Jackson, and Typic Cryoboralf at Dunn and Butler. All were silty and loamy. Site quality class averaged IV or V for ponderosa pine by Meyer's (1938) classification.

Because there were studies on eight areas, the methods and results are presented in the natural sequence of events under the five main headings: (1) cone production; (2) cone stimulation; (3) seed dissemination; (4) seed survival; and (5) seedling establishment.

CONE PRODUCTION

Roeser (1941) studied ponderosa pine seed development, in central Colorado, from flowers to the mature cones. He found that an average of only about 1/4 of the pistillate flowers ultimately developed into mature cones; most of the mortality occurred in the first season of cone development. Further studies on development of ponderosa pine cones from the initial ovulate bud were made in western Montana to identify these factors that limit cone production and are reported here.

Methods

Eight sample trees, at least 16 inches d.b.h., were randomly selected for study in a partially cutover ponderosa pine stand at Bluesky (fig. 1). A total of 100 branches in the upper portion of the crowns of the trees (10 to 15 branches per tree) were systematically selected. Losses of buds, conelets, and mature cones were described by total number and apparent cause on each individually-marked branch; this description was made for each stage of cone development. The trees were climbed and data recorded four to seven times during the two-year cone-development periods for each of the cone crops that matured in 1953 through 1956.

In addition, a banding experiment was conducted to measure the effects of squirrels on seed production. To prevent squirrels from climbing the cone-bearing trees on the study plot at Dunn, all trees were protected in 1953 by 20-inch-wide aluminum bands. Stands used as check plots were not banded on the nearby Butler study area. In late 1953 four banded and four unbanded trees were climbed and the effectiveness of bands evaluated. Differences in seedfall at Dunn and Butler were measured by 20 seed traps on each of these two areas.

Results

Cone Mortality

Following bud formation, the number of developing pine cones decreased continuously until seed dissemination 2 years later. An average of only 6 percent of the ovulate buds matured and shed seed (table 2). Four cone crops, one rated fair (1954) and three rated poor (1953, 1955, and 1956), quantified these losses.

The percentage of cone survival was highest following the formation of the largest number of ovulate buds. The 1954 crop (rated fair) had 9 percent survival, but the 1955 crop (poorest of the 4 years) had no survival.

Seventy percent of the potential cones aborted (table 2), 64 percent during the first season and 6 percent during the second season. Squirrels reduced the potential cone crop an additional 14 percent and all other factors caused an additional 10 percent loss.

First Year of Development

An average of only 27 percent of the potential cone crop survived the first year of development. At the beginning of the first season, 5 percent of the buds failed to open. Following this, 64 percent of the cones aborted during the first season. Causes of these heavy losses from bud failure and abortion were not identified. Squirrel cuttings accounted for 2 percent of the first-year losses. Insects and other miscellaneous factors accounted for the remaining losses.

Second Year of Development

Only 23 percent of the pine conelets that survived the first year persisted until seedfall. During the second year an additional 6 and 12 percent of the potential cones aborted or were cut by squirrels, respectively. Insects and other miscellaneous factors accounted for the remaining losses. Consequently, only 6 percent of the buds matured and released seed at the end of the second year of development.

Table 2.--*Cause and amount of cone mortality during the 2-year development period*

Year of seed maturity	Ovulate buds	Bud failure	Abortions	Squirrel cutting	Insect loss	Miscel-laneous loss	Cones surviving and shedding seed
	Number	*-Percent-*					
1953	292	-	65	24	6	2	4
1954	648	4	79	5	1	2	9
1955	67	24	72	0	0	4	0
1956	102	19	26	47	8	0	1
All years	1,109	5	70	14	3	2	6

Effect of Douglas-fir Seed Supply

Douglas-fir seeds, when available, also constitute an important segment of the pine squirrel's diet. In 1954, squirrels left many more cones on the trees than in 1953 or 1956, most likely because a fair number of ponderosa pine cones were available and Douglas-fir produced a bumper seed crop that supplemented the food supply. In 1956, all but one pine cone was harvested before the seed could be dispersed. This was probably due to the absence of Douglas-fir cones.

Squirrel Cutting

The tree-banding experiment provided additional information about squirrel effects on seed production. Four trees with aluminum bands at Dunn produced 84 cones that shed seed. Three shoots were cut before the bands were installed. The unbanded trees at Butler still retained 58 cones at the time of seedfall, but careful examination revealed that 16 cones and 39 shoots were cut by squirrels.

Seed production from trees that had been banded in the Dunn area was more than three times greater in 1953 (9,300 seeds per acre) than it was in 1951 (2,800 seeds per acre), before these trees had been banded. Seed production from trees that had not been banded in the Butler and Bluesky areas, however, remained about the same: in the Butler area, it was 1,600 in 1951 and 1,700 in 1953; in the Bluesky area, it was 10,300 in 1951 and 10,400 in 1953.

Cone Crop Forecasting

At times it is desirable to forecast cone crops for purposes of timing seedbed preparation or scheduling seed tree removal. This can be done by examining branches in the upper half of the crown 2 years before a ponderosa pine seed crop will be disseminated. Data from this study indicate that when the number of ovulate buds average one or less per branch, few conelets will survive the period between bud formation and first-year cone development. Any that do survive are highly vulnerable to squirrels that are faced with a short food supply during the second year of cone development. The poor seed crops of 1953 and 1956 resulted from three or less ovulate buds per branch. The fair cone crop in 1954 was initiated by an average of six to seven ovulate buds per branch. It is likely that 10 or more ovulate buds are required per branch to produce a good ponderosa pine seed crop.

If management planning can be delayed until 1 year prior to seed release, then the observer, by counting the first-year conelets, can make a more accurate estimate of the potential seed crop. This study showed that when less than one conelet remained per branch after one year, a poor seed crop resulted. Fair seed crops resulted when more than one conelet remained at the end of the first year of development.

The number of Douglas-fir cones maturing at the same time as the ponderosa pine [illegible] probably influences the number of pine cones taken by squirrels. A good Douglas-fir crop provides a readily available source of food for squirrels. Apparently, the squirrels respond by feeding less heavily on the pine and a fair cone crop of pine may [illegible]. When an alternate source of food is not available, the squirrels usually feed heavily on pine and reduce its production.

A B

Figure 2.--Methods of girdling used: (A) In the wide girdling method, a 1- to 2-inch strip of bark and cambium was removed except for a 2- to 4-inch bridge left intact. (B) In the narrow girdling method the bark and cambium were cut through and around the entire bole circumference. Note the installation of a [illegible]-inch-wide aluminum band to prevent squirrels from climbing the tree.

CONE STIMULATION

Girdling and release has increased cone production in other pine species (Holmes and Matthews 1951; McCulley 1953; Wenger 1953a, 1953b; Godman 1962). These methods were also used in an attempt to stimulate cone production of ponderosa pine in western Montana.

Methods

Wide girdling (fig. 2a) of 15 trees (five each of immature, mature, and overmature trees) and narrow girdling (fig. 2b) of five immature trees was completed at Lick in May 1954. Wide girdles were made by removing a 1- to 2-inch strip of bark and cambium except for a 2- to 4-inch bridge left intact. Narrow girdles were made by a cut through the bark and cambium around the entire bole circumference. Each girdled tree was paired with a nearby untreated but morphologically similar tree.

Release of individual trees as a means to stimulate cone production was tested by removing competition within a radius of 12, 20, and 25 feet around immature, mature, and overmature trees (five of each). These release conditions were established for the immature trees in May 1954 at Lick and for the mature and overmature trees in May and June 1955 at Buck. Response to release was evaluated by pairing each treated tree with a nearby untreated tree. All of these trees were banded with 16-inch-wide metal strips to prevent squirrels from climbing the trees.

The average ages and sizes for girdled and released trees were:

Age		*D.b.h.*	*Height*
(Class)	*(Years)*	*(Inches)*	*(Feet)*
Immature	50	9	42
Mature	140	18	78
Overmature	220	25	98

Results

Girdling

Both wide and narrow girdling of 50-year-old ponderosa pines increased cone production of the first crop formed after treatment (table 3). Even though the analysis of variance showed a statistically significant (1 percent level) increase overall, about 20 percent of the trees showed no effects of treatment. Trees with either of the girdling treatments produced an average of over 20 cones per tree in 1956 while their untreated counterparts averaged only one cone per tree. In the years following the first crop, there were no significant cone-production differences between treated and untreated trees.

Wide girdling of 140- and 220-year-old pines prompted no statistically significant increase in cone production, but cone production from about half of the treated trees did increase considerably in 1957 which was the first cone crop that could have been affected by the girdling (table 3). Narrow girdling was not tried on these older trees.

Girdling usually did not change the subsequent appearance of the trees. In 1956, 2 years following treatment, two trees had slight yellowing of the foliage, but these improved later. No comparisons were made to see if girdling affected increment.

Table 3.--*Average cone production by age class on girdled and check trees before and after treatment*

Year	50-year age class		140- and 220-year age classes combined	
	Girdled	Check	Girdled	Check
	Cones per tree [1]			
1954	12	17	124	110
1956	[2] 22	[2] 1	100	70
1957	2	1	[2] 118	[2] 60
1958	37	28	150	148
1959	2	2	2	1

[1] Based on five 50-year-old trees, five 140-year-old trees, and five 220-year-old trees. The 140- and 220-year age classes were combined because they did not differ significantly.

[2] First possible cone crop that could have been affected by the girdling treatments.

Table 4.--*Average cone production by age class [illegible] before and after treatment*

Year	50-year age class: Release	50-year age class: Check	140- and 220-year age classes combined: Release	140- and 220-year age classes combined: Check
	- - - - - - - - - - - - - - Cones per tree	*- - - - - - - - - - - - -*		
1954	1	3	-	[illegible]
1956	1/ 1	1/ 1	30	[illegible]
1957	1	1	1/ [illegible]	[illegible]
1958	10	3	62	[illegible]
1959	1	1	1	[illegible]

[1] First possible cone crop that could have been affected by the release treatment.

Release

Release from nearby competing trees did not increase cone production significantly during the two or three cone crops following treatment (table 4). Large between-tree variation prevented any meaningful results.

Tree Age

The 140- to 220-year old trees produced about eight times more cones than the 50-year-old trees. The 5 years of record showed that the older trees yielded an average of 60 cones per tree, while the younger trees averaged only seven cones per tree. One mature tree produced 342 cones in 1958, a good seed year. Complete cone production failures were rare on the individual trees of the two older age classes. About three-fourths of these trees produced at least a few cones every year. Failures were much more common, occurring over 50 percent of the time, in the younger individuals.

SEED DISSEMINATION

Of 22 reported ponderosa pine cone crops in western Montana from 1908 to 1953, only one was rated good, but five others were rated fair (Boe 1954). During these same years, three Douglas-fir cone crops were rated good and nine were rated fair (Boe 1954). Boe (1954) concluded that pine was a poor seeder and Douglas-fir a prolific seeder in western Montana. This study provided additional data for evaluation of seed crops.

Methods

Seed crop variability and time of seedfall in partially-cut ponderosa pine and Douglas-fir stands were studied at five locations from seed trap collections made two to six times annually. These were sampled as follows:

Areas	*Years of collection*	*Size of seed trap*	*No. of seed traps*
Bluesky	1948-1955	1/4 milacre	20
Dunn & Butler	1952-1955	1/4 milacre	20
Marshall & Buck	1954-1958	1 sq. ft.	30

The relationship of seed production to varying stand volumes was also included in the observations at Bluesky. Half of the seed traps in Marshall and Buck Creek were in uncut stands.

Results

Yearly Variation (Periodicity)

Good ponderosa pine cone crops were produced in 1948 and 1958 and a fair crop developed in 1954 (table 5). Douglas-fir produced good crops in 1954 and 1958 and a fair crop in 1949. Poor or near-failure crops characterized all intervening years. Although good or fair crops were dispersed by both species in 1954 and 1958, ovulate bud formation was not correlated between the two species because pine and fir require a 2- and 1-year development period before seedfall, respectively.

The percent of filled pine and fir seeds increased with cone production (table 5): however, the pine maintained higher soundness than the fir. The good, fair, poor, and near-failure pine crops averaged 75, 69, 53, and 14 percent soundness, respectively; the fir averaged only 43, 25, 13, and 10 percent filled seeds.

Seasonal Variation (Timing)

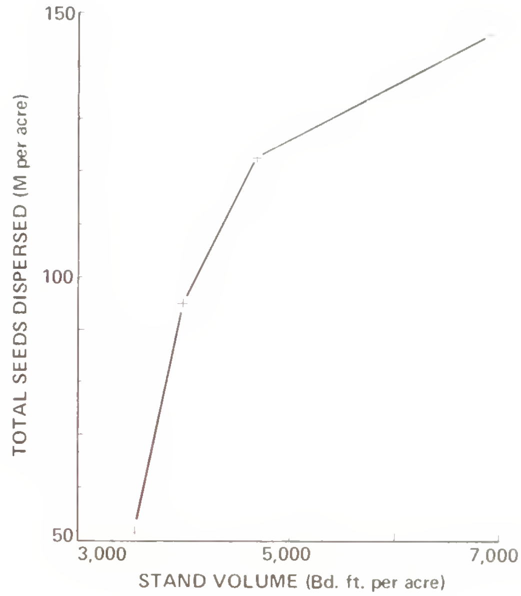
Sound (filled) pine and fir seeds generally fell earlier than the hollow seeds. Dispersal of sound pine seed was 90 percent complete about a month before the total seedfall reached the same point. Squillace and Adams (1950) previously reported that 78 percent of the pine seed that fell in September 1948 was sound, but only 50 percent was filled in later collections. Usually ponderosa pine and Douglas-fir seedfall began about the first of September and peaked in mid-September. Most of the seed was shed by the end of October. However, some hollow seeds continued to fall throughout the winter.

Table 5.--*Average number and percent of sound ponderosa pine and Douglas-fir seeds dispersed in five cutover stands of western Montana from 1948 to 1958*

Year	Ponderosa pine			Douglas-fir		
	Number	Percent	Ranking	Number	Percent	Ranking
	Thousands/ acre			*Thousands/ acre*		
1948	76	73	Good	4	11	Poor
1949	8	38	Poor	80	25	Fair
1950	([1])	8	Poor	4	12	Poor
1951	10	63	Poor	0	0	Poor
1952	([1])	20	Poor	([1])	29	Poor
1953	7	57	Poor	10	15	Poor
1954	42	69	Fair	229	41	Good
1955	0	0	Poor	1	4	Poor
1956	0	0	Poor	0	0	Poor
1957	0	0	Poor	0	0	Poor
1958	135	76	Good	232	46	Good

[1] Less than 500 sound seeds per acre.

Figure 3.--Relationship of reserve stand volume to the total number of seeds dispersed per acre. The trees ranged from 12 to 27 inches d.b.h. and averaged 19 inches d.b.h.



Seedfall was influenced by the climatic conditions prevailing during the time cones matured and seeds were shed. For example, in 1951, 90 percent of the sound pine seed was dispersed by October 1. This was due to the near normal rainfall and temperature that prevailed during August 1951. However, in 1954 only 70 percent of the sound seed was shed by October 1 because summer rainfall was heavy and temperatures remained well below average. Conversely, seedfall began earlier in 1949 because of dry, warm conditions.

Stand Volume

Seed production of ponderosa pine at Bluesky was directly related to residual volume in 1948, a good seed year (fig. 3). This relationship was not consistent in years of lower seed production and varied between areas from year to year. These differences may have been caused by unequal cone losses before seed dispersal or the sample may simply have been too small to detect any trend.

SEED SURVIVAL

Large numbers of ponderosa pine seeds are usually destroyed on the ground prior to spring germination. Seeds lost to rodents and other factors during the period from dispersal to germination were determined at Bluesky (1948-1951, and 1953) and at Dunn and Butler (1951, 1953, and 1954).

Methods

From 10 to 39 quarter-milacre duff samples were taken next to seed traps in May of each year to study the number of unprotected seeds remaining over winter. The differences between numbers of seed caught in the traps and the numbers found on these duff plots represented the take by rodents and other seed destroying agents.

Sunflower seeds coated with thallium sulphate were used to poison rodents and protect the seed at the Dunn and Butler plots in early September 1951. Also, a 1000-foot buffer zone was treated on each side of the plots.

Results

Most of the pine and fir seed that reached the ground were destroyed prior to germination. Squillace and Adams (1950) reported early in the study period that only 8 percent (5,800 seeds per acre) of the sound pine seed dispersed from the bumper 1948 seed crop at Bluesky remained undamaged at the time germination began in 1949. They also found that 40 percent (1,200 seeds per acre) of the Douglas-fir seed that fell from the poor crop in 1948 was available for germination the next spring. White-footed mice and chipmunks were blamed for most of this loss based on population counts and stomach analyses made on this area (Adams 1950). As this study continued, it was clear that most of the seeds that reached the ground were destroyed by mice, chipmunks, or other seed destroyers. The percent of seeds destroyed was always higher following dispersal of poor or medium crops.

During the 7-year period from 1949 to 1955, only 12 and 7 percent of the cumulative number of pine and fir seeds, respectively, survived until spring. This represented a total of only 14,000 pine and 20,200 Douglas-fir per acre.

Seed eaters on the Dunn and Butler plots were not effectively controlled by a single application of thallium sulphate-coated bait in early September of 1951. Initial control was obtained, but invading mice took most of the seed by the following spring. Although a few tree seeds probably were taken before poisoning, most were likely taken after the fall rains leached the chemical off the bait.

SEEDLING ESTABLISHMENT

Natural regeneration is almost always benefited by mineral soil seedbeds where competing vegetation has been reduced by scarification, burning, or with chemicals. Removal of competition increases the amount of water available for young seedlings. This is particularly true for ponderosa pine that grows in the drier sites in western Montana.

Table 6.--*Types and locations of seedbeds tested for establishing natural regeneration*

Location	Year of treatment	Seedbed treatment				
		None (control)	Bulldozer scarifying	Athens discing	Broadcast burning	Hand piling and burning slash
Bluesky	1948	X	X	--	X	X
Warland	1948	X	X	--	--	--
Jackson	1948	X	--	--	X	--
Dunn and Butler	1951	X	X	X	--	--

Methods

The effectiveness of different types of seedbeds for establishing natural regeneration was tested in various combinations at several locations (table 6). Seedbeds were prepared by:

1. *Bulldozer scarification.*--Exposed some mineral soil, piled slash, and disposed of some unmerchantable Douglas-fir.

2. *Athens discing.*--Exposed some mineral soil, but far less than by bulldozer scarification.

3. *Broadcast burning.*--Removed accumulations of logs and slash from the base of seed trees before treatment.

4. *Hand piling and burning.*--Exposed mineral soil only where the slash piles were burned.

A total of 730 systematically located milacre quadrats were established on the five seedbed conditions shown in table 6.

Results

Ponderosa pine was clearly a seral species on these study areas as demonstrated in the following tabulation of advance regeneration on untreated plots:

	Seedlings per acre (*Number*)	Stocking (*Percent*)
Ponderosa pine	51	4
Douglas-fir	1,415	48

The 1948 seed crop was responsible for nearly all of the pine regeneration during the 5-year study period at Bluesky, Warland, and Jackson. First-year results published by Roe and Squillace (1950) showed that the number of pine seedlings was about eight times greater on mineral soil (heavily scarified by bulldozer or on skid roads) than on duff when other conditions were similar. These data were derived from 700 of the 730 milacre plots plus an additional 241 temporary plots located on cutover areas at Bristow with larger numbers of seed trees. The number of pine seedlings per acre on mineral soil increased from 830 to 6,000 as the basal area of the residual stands went from 17 to 87 square feet per acre. Also, the distribution of pine became more uniform as the stand basal area increased. First-year stocking was satisfactory on mineral soil only in stands with over 40 square feet of basal area per acre. If rodents were controlled, stocking likely would have been adequate in stands with less basal area. Stands under 40 square feet of basal area ranged from 13 to 39 inches mean diameter and averaged 16 inches d.b.h. Stands over 40 square feet ranged from 16 to 33 inches mean diameter and averaged 23 inches d.b.h.

Initial survival of seedlings was far greater on heavily scarified seedbeds than on any other surfaces and this approximate percent of difference existed throughout the study period (fig. 4). By late June of 1949 more than five times as many pine seedlings were growing on heavily scarified seedbeds (primarily skid roads) as on duff at Bluesky, Jackson, and Warland (fig. 4); this is in contrast to nearly three times more than on burned seedbeds and almost six times more than on lightly scarified surfaces. It is not known whether these differences resulted from greater germination or less seedling mortality, or both, on the heavily scarified seedbeds. Mortality from late June through mid-October 1949 was low on all seedbeds because of above average rainfall from July through September. By early May of 1950 about half of the survivors died on seedbeds prepared by light scarification or burning and about one-fourth died on seedbeds prepared by heavy scarification or on duff. Frost heaving caused most of the pine seedling losses on burned and scarified surfaces in the early spring of 1950.

Five years after treatment, pine regeneration was still most abundant on the heavily scarified seedbeds (fig. 4). These surfaces maintained nearly four times more pine seedlings and three times greater stocking than on the other seedbeds. The numbers of seedlings counted in July 1953, stated as percents of the 1949 seedling count are as follows: 39 percent on burned seedbeds; 51 percent on untreated seedbeds; 55 percent on heavily scarified (skid road) seedbeds; and 60 percent on lightly scarified seedbeds. Most of the seedlings counted in July 1953 had germinated in May and June 1949.

At Bluesky, Jackson, and Warland, most of the Douglas-fir seedlings were established on all seedbeds prior to the beginning of the study. However, the only large increase occurred on heavily scarified seedbeds in 1953 following the heavy 1952 seed crop. All other seedbed treatments failed to enhance the initial survival of Douglas-fir.

Seedling establishment of ponderosa pine at Dunn and Butler from 1952 to 1961 was generally low, probably because of the lack of a receptive seedbed when seed was available. In addition, these plots were apparently established on the driest sites studied. Although from 200 to 7,000 pine seedlings per acre were established by 1961 on the seedbeds of both areas, poor seedling distribution resulted in an average of only 25 percent stocking 10 years after treatment. More pine seedlings became established on bulldozer scarified plots than on areas lightly scarified with an Athens disc or on duff. Additional pine seedlings became established at Dunn in 1954 and 1955 when the seed trees were banded with aluminum strips to prevent squirrels from climbing the trees and when the entire area was poisoned to decrease depredation by rodents.

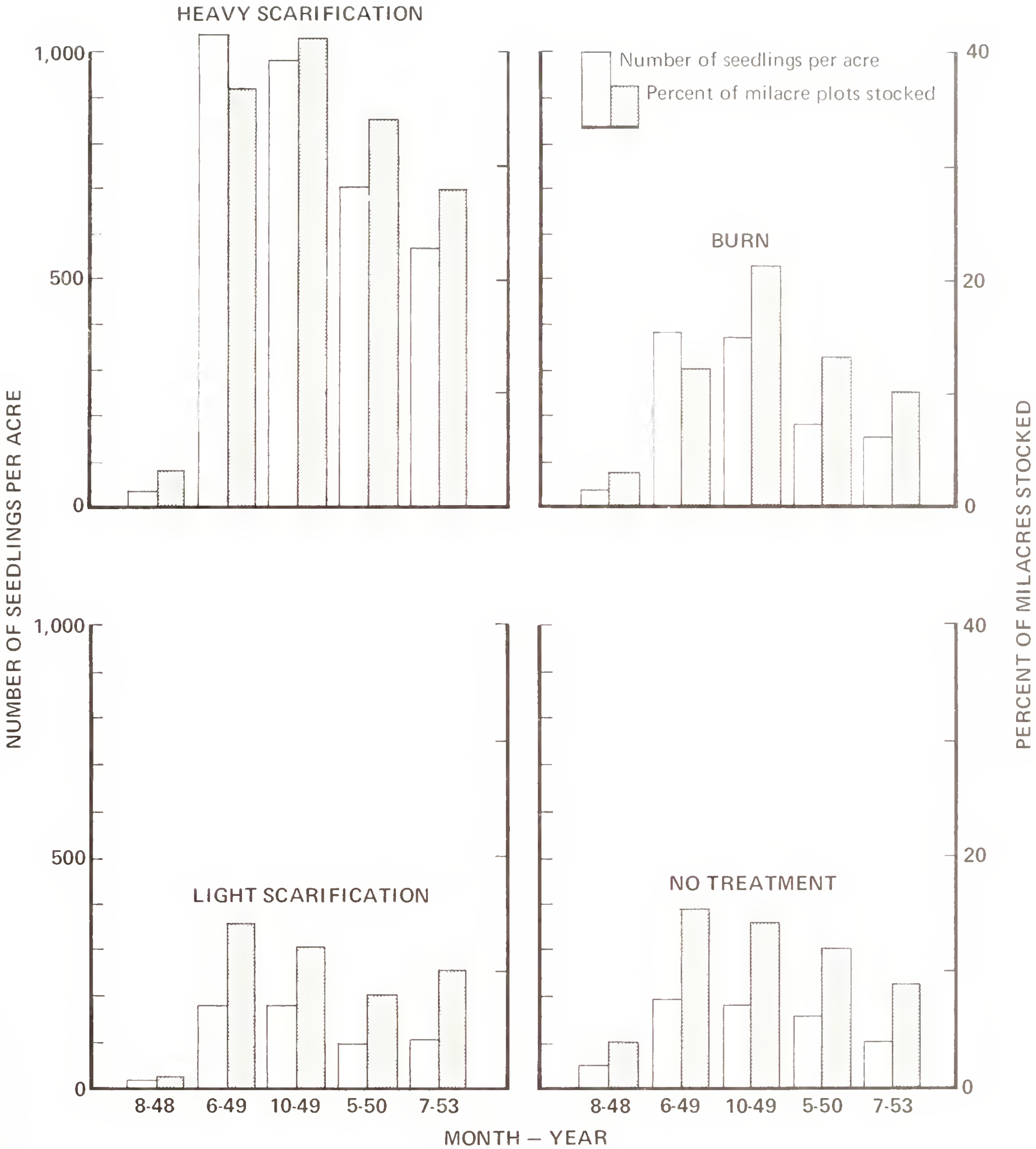


Figure 4.--Influence of seedbed on the regeneration of ponderosa pine by month and year. Open bars represent number of seedlings per acre; dotted bars are the percentage of milacre plots stocked.

Deer browsing was more common on pine seedlings growing at Bluesky than on those at Warland and Jackson. Douglas-fir seedlings were occasionally browsed. In the studies at Dunn and Butler deer damage on pine seedlings was 14 and 1 percent, respectively. Most of this damage occurred in the winter of 1953 and 1954.

DISCUSSION

Natural regeneration of ponderosa pine is spasmodic throughout its range except in the Black Hills (USDA Forest Service 1965). Successful establishment usually is dependent on: (1) adequate viable seed; (2) receptive seedbed; and (3) favorable climatic conditions during the first year. Of these three, the forest manager is able to manipulate the seed source and seedbed most easily. At present, little can be done to predict or influence climatic conditions, but through judicious control of seed source and seedbed the micro-environment around young seedlings can be enhanced during most years.

These studies quantify the effect of some physical and biological factors that limit seedling establishment in western Montana. Chief among these limiting factors are: (1) heavy losses of the potential seed crop during the 2-year cone development period; (2) heavy seed loss following dispersal; and (3) high seedling mortality. The odds are close to one or two in a thousand that a potential pine seed in the ovulate bud stage will become a surviving seedling. The additive effect of the above losses point to why it is difficult to successfully regenerate stands of ponderosa pine under normal conditions in most years (table 7).

The probabilities of establishing ponderosa pine seedlings are greatest when good seedbed preparation is coordinated with maximum seed production. Consequently, forest managers need to know as early as possible when a good crop of seeds can be expected. Factors that affect the initiation of ovulate buds as well as their subsequent development are not well understood. However, above average temperatures during the period of flower bud initiation (24 to 28 months before cone maturity) have been found to be closely correlated with good flower bud initiation and subsequent cone crops (Daubenmire 1960, Maguire 1956). Although it is unlikely that foresters will ever be able to predict cone crops with great accuracy, examination of the ovulate buds or first-year conelets can provide an estimate of the developing cone crop as much as 2 years before seed dispersal.

These studies have identified factors that drastically reduce the potential cone crop. Most of the first year cone losses resulted from abortions, but squirrels caused a majority of the second year losses. At present we do not understand the reason for the consistently high abortion rates and consequently can do nothing to reduce them.

Squirrels not only reduce current cone crops but future crops as well (Squillace 1953, Adams 1955). Squirrels usually sever the cone-bearing shoots just below the mature cones. This also eliminates any 1-year-old conelets or ovulate buds developing on the shoot beyond the cut. Also, such cutting may reduce the flowering potential for a few seasons. Squirrels also frequently cut shoots from the ends of branches in the winter to feed on the cambium layer, thus reducing still further the potential for cone production (Adams 1955). As a corrective measure, it may be necessary at times to place metal bands on seed trees in partially cut stands or in seed orchards to prevent squirrels from climbing (Tackle 1957, 1959).

Table 7.--*Theoretical 45-month development of cones, seeds, and seedlings from ovulate bud formation to the second year of seedling growth under normal conditions, compared with development using recommended management conditions*

Stage of development	Potential seedlings	
	Number	*Percent*
NORMAL CONDITIONS		
Ovulate buds (1,000)	[1] 80,000	100.00
First-year survival of conelets (270)	21,600	27.00
Second-year survival of cones (60)	4,800	6.00
Filled seeds after seedfall (75% of above)	3,600	4.50
Overwintering survival of seed (12% of above)	432	0.54
Surviving seedlings at beginning of second growing season (50% of above)	[2] 216	0.27
RECOMMENDED MANAGEMENT CONDITIONS		
Ovulate buds (1,000)	80,000	100.00
First-year survival of conelets (290)	23,200	29.00
Second-year survival of cones (200)	16,000	20.00
Filled seeds after seedfall (75% of above)	12,000	15.00
Overwintering survival of seed (50% of above)	6,000	7.50
Surviving seedlings at beginning of second growing season (50% of above)	3,000	3.75

[1] Based on 80 seeds per cone in mature, scattered stands in central Idaho [James D. Curtis and Marvin W. Foiles. Regeneration of ponderosa pine in the Northern Rocky Mountains. USDA Forest Serv., Intermountain Forest and Range Experiment Station, Ogden, Utah. (In preparation).]

[2] Based on 50 percent survival recorded for ponderosa pine from June 1949 to May 1950 in western Montana. This figure is probably high because of the favorable growing conditions that year. A closer estimate would be about 20 percent survival which occurred in 1959 in central Idaho (Foiles and Curtis 1965b) and from 1934 to 1941 in the Sierra Nevada of California (Fowells and Stark 1965). This would decrease the theoretical survival to 86 seedlings or 0.11 percent of the potential.

Other small mammals and birds also destroy ponderosa pine seed before it is disseminated (Curtis 1948). In addition, many insects such as pine seed moths (*Laspeyresia* spp.) or the ponderosa pine cone beetle (*Conophthorus ponderosae* Hopk.) infest the cones and seeds of this species (Keen 1958). During years of low production, insects may nearly destroy the entire crop of seeds.

Because good cone crops are infrequent, it may be desirable under some circumstances to stimulate cone production. The inherent genetic differences governing cone production presently preclude accurate predictions of which individual trees will respond to cone stimulation treatments. However, these studies indicate that girdling can stimulate production of ovulate buds for one season in about 80 percent of the 50-year-old pine trees. Older trees may respond to girdling also but stimulation will likely occur in only about one-half of the trees and the effect may be delayed a year longer than in the younger trees. These differences between young and old trees are probably due to the decreasing physiological activity associated with older age. Girdled trees recover rapidly from these wounds; stimulating effects are of short duration. Release did not increase cone production of the selected trees during the first two or three years; however, these trees may require several years to adjust to their new growing space before cone production is influenced.

Only the abundant seed years produce enough seed for germination and a level of survival that will assure adequate natural regeneration. Mice and chipmunks as well as other ground-dwelling mammals rely upon dispersed ponderosa pine seed for a significant part of their fall and winter diet. Attempts at control with one application of poison bait were unsuccessful here as well as in many other areas (Foiles and Curtis 1965b). Successful rodent eradication in Oregon required three applications of poisoned bait (Stein 1964).

Seeds that have survived the series of depredations up to the time of germination are potential seedlings, but as seedlings they will still face formidable survival barriers. In most years, competing vegetation reduces soil moisture to a level which is inadequate for survival of young seedlings.

Treatments that reduce competing vegetation and conserve soil moisture will promote seedling establishment in most years. Prescribed burning when fuels are dry, or heavy scarification in well distributed spots throughout a cutover area, offer two good choices for seedbed preparation. However, when an occasional heavy seed crop is followed by above average rainfall during the next growing season, as happened in 1949, some pine seedlings survive and restock many areas even though mineral soil may not be exposed (Pearson 1950, Foiles and Curtis 1965a).

Many old-growth ponderosa pine stands in western Montana grow on sites that are climax for Douglas-fir. As a result, most sites are usually well stocked with advance Douglas-fir seedlings. If the forest manager desires this regeneration, nothing more than some thinning and weeding is necessary to maintain these areas in a well-stocked condition. However, if he wants to establish ponderosa pine, the fir competition must be removed or drastically reduced.

In addition to the usual physical and biological factors limiting seedling establishment in western Montana, high deer populations in some localities frequently kill or severely browse the trees. Such browsing may occur until the trees are tall enough so the foliage is out of reach of these animals (Adams 1949, 1951a, 1951b).

SUMMARY

Several major factors influencing natural regeneration in ponderosa pine forests of western Montana were identified:

1. During the 2-year developmental period, cone production was decreased to 6 percent of the original potential. Cone abortions and squirrel cutting accounted for most of these losses.

2. Stimulation of cone production was largely unsuccessful although young trees did show a short-term favorable response to girdling.

3. Seedfall for both species began about September 1 and was nearly complete by the end of October. Weather conditions strongly influenced the time at which seeds were disseminated.

4. Seed overwintering in the duff was susceptible to large losses, primarily from rodents. Of the dispersed seed, only about 12 percent of the pine and 7 percent of the fir survived to germinate in the following spring.

5. Pine seedling establishment was greatest on heavily scarified seedbeds during the period studied but fir survived well on most seedbeds.

RECOMMENDATIONS

To successfully regenerate cutover ponderosa pine and Douglas-fir stands, the land manager must consider several alternatives. When thrifty advance regeneration of Douglas-fir is already established, it can usually be cultured to form a vigorous new stand, largely without pine. However, when restocking of ponderosa pine is desired, the most reliable method is planting on adequately prepared sites. Where natural regeneration of pine is desired, the following safeguards must be considered:

1. Protect seed crops from squirrels.

2. Reduce rodent population.

3. Time site preparation to coincide with predicted cone crops.

When any one of these recommendations are implemented, the land manager can expect a corresponding increase in the number of established seedlings and in the percent of milacres stocked. He can reasonably expect to control: (1) most squirrel depredations by banding the seed trees; (2) 50 percent of the seed losses on the ground by controlling seed-eating rodents; and (3) 50 percent of the first-year seedling losses by thorough site preparation. If this is done, then he may increase the number of surviving seedlings about 14 times as shown in the hypothetical example (table 9, "Recommended Management Conditions").

Successful application of all these recommendations could result in overstocking that would require thinning, especially in years with above average summer rainfall. However, land managers may want to take this gamble rather than risk inadequate stocking.

LITERATURE CITED

Adams, Lowell.
1949. The effects of deer on conifer reproduction in northwestern Montana. J. Forestry 47(11): 909-913, illus.

__________. 1950. Consumption of ponderosa pine seed by small mammals. U.S. Forest Serv., Northern Rocky Mountain Forest and Range Exp. Sta. Res. Note 80, 4 p.

__________. 1951a. White-tailed deer browsing on natural conifer seedlings. U.S. Forest Serv., Northern Rocky Mountain Forest and Range Exp. Sta. Res. Note 105, 3 p.

__________. 1951b. White-tailed deer browsing on ponderosa pine plantations. U.S. Forest Serv., Northern Rocky Mountain Forest and Range Exp. Sta. Res. Note 89, 5 p.

__________. 1955. Pine squirrels reduce future crops of ponderosa pine cones. J. Forestry 53(1): 35.

Boe, Kenneth N.
1954. Periodicity of cone crops for five Montana conifers. Mont. Acad. Sci. Proc. 14: 5-9.

Curtis, James D.
1948. Animals that eat ponderosa pine seed. J. Wildlife Manage. 12(3): 327-328.

Daubenmire, R.
1960. A seven-year study of cone production as related to xylem layers and temperature in *Pinus ponderosa*. The Amer. Midland Natur. 64(1): 187-193, illus.

__________, and Jean B. Daubenmire.
1968. Forest vegetation of eastern Washington and northern Idaho. Wash. Agr. Exp. Sta. Tech. Bull. 60, 104 p., illus.

Foiles, Marvin W., and James D. Curtis.
1965a. Natural establishment of ponderosa pine in central Idaho. U.S. Forest Serv. Res. Note INT-35, 4 p., illus.

__________, and James D. Curtis.
1965b. Natural regeneration of ponderosa pine on scarified group cuttings in central Idaho. J. Forestry 63(7): 530-535, illus.

Fowells, H. A., and N. B. Stark.
1965. Natural regeneration in relation to environment in the mixed conifer forest type of California. U.S. Forest Serv. Res. Pap. PSW-24, 14 p., illus.

Godman, R. M.
1962. Red pine cone production stimulated by heavy thinning. USDA Forest Serv., Lake States Forest Exp. Sta. Tech. Note 628.

Holmes, G. D., and J. D. Matthews.
1951. Girdling or banding as a means of increasing cone production in pine plantations. Forestry Comm. Forest Rec. 12. London, 8 p.

Keen, F. P.
1958. Cone and seed insects of western forest trees. U.S. Dep. Agr. Tech. Bull. 1169, 168 p.

McCulley, Robert D.
1953. Natural regeneration of loblolly pine in the southeastern coastal plain. Southeastern Forest and Range Exp. Sta., Sta. Pap. 26, 13 p.

Maguire, William P.
1956. Are ponderosa pine cone crops predictable? J. Forestry 54(11): 778-779.

Meyer, W. H.
1938. Yield of even-aged stands of ponderosa pine. U.S. Dep. Agr. Tech. Bull. 630, 59 p., illus. (Rev. April 1961.)

Pearson, G. A.
1950. Management of ponderosa pine in the southwest. U.S. Dep. Agr., Agr. Monogr. 6, 218 p., illus.

Roe, Arthur L., and A. E. Squillace.
1950. Can we induce prompt regeneration in selectively-cut ponderosa pine stands? Northern Rocky Mountain Forest and Range Exp. Sta. Res. Note 81, 7 p.

Roeser, Jacob, Jr.
1941. Some aspects of flower and cone production in ponderosa pine. J. Forestry 39(6): 534-536.

Squillace, A. E.
1953. Effect of squirrels on the supply of ponderosa pine seed. U.S. Forest Serv., Northern Rocky Mountain Forest and Range Exp. Sta. Res. Note 131, 4 p.

__________, and Lowell Adams.
1950. Dispersal and survival of seed in a partially-cut ponderosa pine stand. U.S. Forest Serv., Northern Rocky Mountain Forest and Range Exp. Sta. Res. Note 79, 4 p.

Stein, William I.
1964. More natural regeneration by controlling seed-eating rodents. U.S. Forest Serv. Res. Note PNW-12, 10 p.

Tackle, David.
1957. Protection of ponderosa pine cones from cutting by the red squirrel. J. Forestry 55(6): 446-447, illus.

__________.
1959. A furtner test of tree bands for cone protection. J. Forestry 57(5): 373.

U.S. Dep. Agriculture, Forest Service.
1965. Silvics of forest trees of the United States. U.S. Dep. Agr., Agr. Handb. 271, 762 p., illus.

Wenger, K. F.
1953a. The effect of fertilization and injury on the cone and seed production of loblolly pine seed trees. J. Forestry 51(8): 570-573.

__________.
1953b. Preharvest release of loblolly pine seed trees will increase seed supply at harvest. Southeastern Forest and Range Exp. Sta. Res. Note 45, 2 p.

AFLC, HAFB, Ogden

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

USDA Forest Service
Research Paper INT-87
1970

IMPROVEMENT AND MAINTENANCE OF CAMPGROUND VEGETATION IN CENTRAL IDAHO

Roscoe B. Herrington and Wendell G. Beardsley

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Ogden, Utah 84401

THE AUTHORS

ROSCOE B. HERRINGTON is Recreation Resource Analyst at the Intermountain Forest and Range Experiment Station. Prior to his present appointment, his experience included assignments in timber resource inventory, timber marketing research, and production economics research in Idaho, Colorado, Montana, and Utah.

WENDELL G. BEARDSLEY is an Economist at the Intermountain Forest and Range Experiment Station. His previous experience includes National Forest Administration in Oregon, and recreation economics and ecology research in Minnesota, Colorado, Idaho, and Utah.

USDA Forest Service
Research Paper INT-87
December 1970

IMPROVEMENT AND MAINTENANCE OF CAMPGROUND VEGETATION IN CENTRAL IDAHO

Roscoe B. Herrington and Wendell G. Beardsley

Intermountain Forest and Range Experiment Station
In cooperation with Sawtooth National Forest

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

CONTENTS

ABSTRACT

Vegetation in heavily-used campgrounds is often seriously depleted. When popular sites are rehabilitated, a combination of better campground design and better cultural practices can probably reverse this deterioration. At Point Campground in central Idaho, 2 years of treatment of a rehabilitated site produced substantial improvement of ground cover vegetation on units receiving water, fertilizer, and seed. Units receiving water and fertilizer, or water and seed, improved only slightly; seed alone produced no improvement. Although weekly watering required overnight closing of the campground, visitor acceptance was very good.

INTRODUCTION

The adverse ecological effects of people on recreation sites have been well documented (Meinecke 1928; Lutz 1945; Dotzenko, Papamichas, and Romine 1967; Magil and Nord 1963; and Ripley 1962). Improved design of sites and intensified cultural treatment can probably do much to minimize their impacts. A recent study (Beardsley and Wagar, in preparation) in Utah indicates relatively little loss of vegetation in a new campground after 4 years of fairly heavy use. This campground was designed to minimize visitor impact on vegetation. However, improved design and reconstruction of facilities alone might not be sufficient to allow natural revegetation on existing campgrounds. Therefore, it is important to develop techniques for protecting camping sites from further deterioration and to improve them whenever possible because most older and presently deteriorated campgrounds are at choice locations in scenic areas.

Successful upkeep of millions of home lawns, city parks, and golf courses using grass seed, water, and fertilizer indicate that vegetation can be maintained despite heavy use. Yet there is almost no published information that indicates grass or other vegetation can be successfully reestablished in old, badly deteriorated campgrounds. In Georgia, for example, Cordell and Talhelm (1969) reported that attempts to establish grass by seeding an old campground failed even after giving the planted areas the "best possible treatment for growth and survival." Although the seed germinated and a fairly dense stand of grass seedlings developed during early spring, virtually no grass remained on the test plots at the end of one full season of use by campers.

Establishing grass in public campgrounds is complicated by visitor use during the growing season. It is possible to close a campground while the new grass becomes established, and every few years thereafter to insure its continued survival. But total available campground capacity is limited. Closing one campground may simply shift the use load to adjacent campgrounds and worsen the ecological impacts. The heavy demand for recreation areas generally makes such closures prohibitive.

This paper reports the satisfactory results achieved at Point Campground on the Sawtooth National Forest in Idaho using improved design in association with seeding, water, and fertilizer. Although design alternatives were not studied, the apparent superiority of the layout of this reconstructed campground afforded favorable conditions for testing various vegetation treatments.

CAMPGROUND ENVIRONMENT

Located on scenic Redfish Lake in the Sawtooth National Forest, Idaho, Point Campground had been used for over 30 years so that by 1965, vegetation on the site was badly deteriorated.

This campground's popularity was established early because of nearby salmon and trout fishing opportunities, but early use was light. In 1936, the camp was expanded and improved under the Civilian Conservation Corps program. More or less typical for campgrounds of that day, it contained water hydrants, a pit-toilet, six elaborate stone fireplaces, and a varying number of movable wooden picnic tables.

Lodgepole pine (*Pinus contorta*) was and still is the predominant tree cover for the area; Douglas-fir (*Pseudotsuga menziesii*) and aspen (*Populus tremuloides*) are found occasionally. The lodgepole pine overstory trees are approximately 100 years old and have rather thin, small crowns. Dwarfmistletoe apparently infected the stand during its early years and now affects virtually every tree.

Figure 1.--*Point Campground, Sawtooth National Forest, 1963. Trampling had eliminated nearly all vegetation except that protected by trees.*

The campground is located on a gently rolling outwash terrace remnant at the toe of a steep lateral moraine. Slopes vary from 5 to 15 percent. Soil materials are dominantly of mixed granitic composition. Depth to bedrock is at least 15 feet everywhere in the campground (Arnold 1966).

Two distinct soil types are found: (a) a well-drained sandy loam, and (b) a moderately well-drained fine sandy loam. The sandy loam soil is on the upper portion of the terrace, generally 12 feet or more above the lake surface. Typically it has 15 percent coarse rock surface fragments. The water table for sandy loam soil is usually more than 10 feet below the surface.

The fine sandy loam soil occurs on the lower portion of the terrace. Here depth to the water table is generally 3 to 5 feet during the fall season. Undoubtedly the water table is higher during early spring. The coarse rock content of the soil on this lower portion of the terrace is much lower and its water holding capacity is greater than that of the soil on the upper portion of the terrace.

Both soils exhibit low erosion and compactibility potentials. Laboratory tests showed a low fertility level for herbaceous vegetation production and indicated a need for fertilizer, especially nitrogen.

Annual precipitation averages about 15 inches, more than half of which falls as snow. Temperatures are generally cool because the campground is at an elevation of 6,500 feet. Mean annual temperature is 35° F.; an average of 10 frost-free days can be expected each summer.

Judging from the surrounding area this combination of climate and soil never produced a particularly lush herbaceous ground cover or dense shrubbery. The most frequent understory species found today are pinegrass (*Calamagrostis rubescens*), elk sedge (*Carix geyeri*), strawberry (*Fragaria* sp.), low huckleberry (*Vaccinium* sp.), spiraea (*Spiraea lucida*), big sagebrush (*Artemisia tridentata*), buffaloberry (*Shepherdia argentea*), bitterbrush (*Purshia tridentata*), and gooseberry (*Ribes* sp.). Occasional clumps of alder (*Alnus tenuifolia*) and willow (*Salix* sp.) grow near the edge of the lake. Heavy use over much of the area had eliminated virtually all understory vegetation. Isolated patches could be found near rocks or trees where the vegetation had been protected from humans and vehicles (fig. 1).

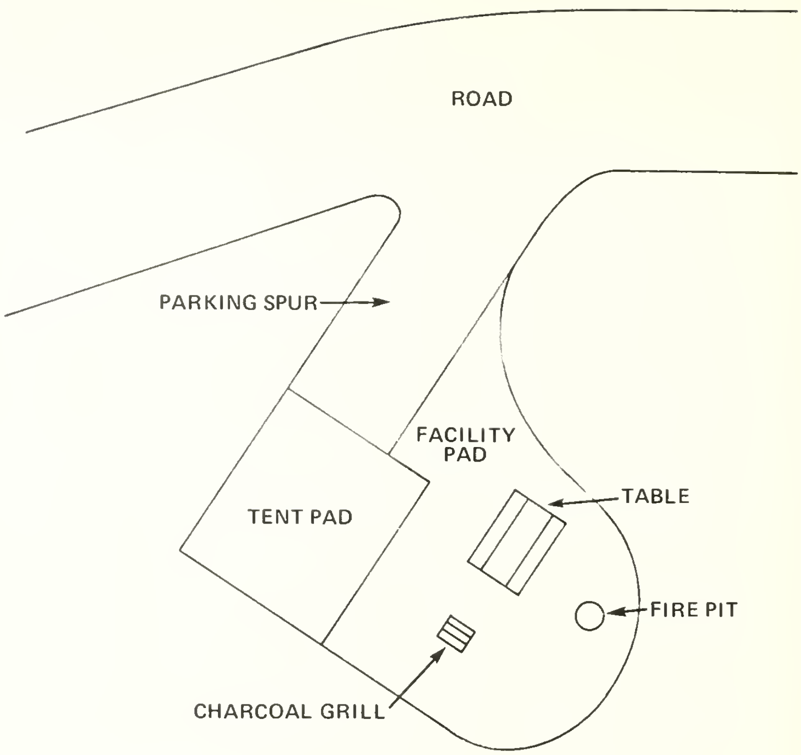
REHABILITATION PROGRAM

Because of its generally rundown appearance and outmoded facilities, Point Campground was rehabilitated during 1966 and 1967. The rehabilitation plan was based on the explicit assumption that ground-cover vegetation could not be maintained on certain heavy-use portions of the campground. Accordingly, roads, parking spurs, trails, and a "facility pad" (for a table, fireplace, and charcoal grill) were surfaced with a gravel-asphalt mixture. In addition, a "tent pad" was located adjacent to the "facility pad"; this consisted of a 16- by 16-foot redwood frame filled with coarse sand (fig. 2).

The size and shape of the "facility pad" and parking spurs were contingent upon such factors as location of trees and ground slope. As a result, the total surfaced area within individual units (including the tent pad) ranged from 646 square feet to 1,572 square feet--an average of 1,188 square feet per unit.

An underground pipe system was installed to deliver water to a single sprinkler head at the approximate center of each unit. Water pressure and flow were adequate to sprinkle all eight camping units simultaneously.

Figure 2.--*Layout of typical unit at Point Campground, Sawtooth National Forest.*



The entire campground was closed during construction for the 1966 and 1967 seasons. This permitted replacement of tables, fireplaces, and charcoal grills, as well as installation of a water hydrant system and central flush toilets. The campground closure was continued until July 1, 1968, to give the seeded grass more time to become established.

HOW TREATMENTS WERE APPLIED

Four cultural treatments were applied to 16 units during the 1968 and 1969 growing seasons: (1) grass seed only (control); (2) water and seed; (3) fertilizer and seed; and (4) water, fertilizer, and seed. Variations between the apparent plant growth potential of the soil on the upper and the lower portions of the terrace dictated a block design for the study. Fortunately, eight units could be located on each of the lower and upper sites of the terrace. Each treatment was randomly assigned to two units on the upper site and two units on the lower site. The treatment area around each unit consisted of an 85-foot square area that included the "facility pad" and "tent pad."

During June of 1968 grass seed, trees, and shrubs were planted. Indigenous tree and shrub seedlings were moved with a soil ball to the campsite from an adjacent area. They were planted in locations selected to block discontinued paths and roads. An unknown quantity of Kentucky bluegrass (*Poa pratensis*) seed was broadcast over all parts of the campground where the soil had been disturbed during construction--road ditches, pipeline trenches, and any fill around parking spurs or table pads. Discontinued roads were tilled and seeded. Seed was raked by hand into the soil.

The campground is located on a gently rolling outwash terrace remnant at the toe of a steep lateral moraine. Slopes vary from 5 to 15 percent. Soil materials are dominantly of mixed granitic composition. Depth to bedrock is at least 15 feet everywhere in the campground (Arnold 1966).

Two distinct soil types are found: (a) a well-drained sandy loam, and (b) a moderately well-drained fine sandy loam. The sandy loam soil is on the upper portion of the terrace, generally 12 feet or more above the lake surface. Typically it has 15 percent coarse rock surface fragments. The water table for sandy loam soil is usually more than 10 feet below the surface.

The fine sandy loam soil occurs on the lower portion of the terrace. Here depth to the water table is generally 3 to 5 feet during the fall season. Undoubtedly the water table is higher during early spring. The coarse rock content of the soil on this lower portion of the terrace is much lower and its water holding capacity is greater than that of the soil on the upper portion of the terrace.

Both soils exhibit low erosion and compactibility potentials. Laboratory tests showed a low fertility level for herbaceous vegetation production and indicated a need for fertilizer, especially nitrogen.

Annual precipitation averages about 15 inches, more than half of which falls as snow. Temperatures are generally cool because the campground is at an elevation of 6,500 feet. Mean annual temperature is 35° F.; an average of 10 frost-free days can be expected each summer.

Judging from the surrounding area this combination of climate and soil never produced a particularly lush herbaceous ground cover or dense shrubbery. The most frequent understory species found today are pinegrass (*Calamagrostis rubescens*), elk sedge (*Carix geyeri*), strawberry (*Fragaria* sp.), low huckleberry (*Vaccinium* sp.), spiraea (*Spiraea lucida*), big sagebrush (*Artemisia tridentata*), buffaloberry (*Shepherdia argentea*), bitterbrush (*Purshia tridentata*), and gooseberry (*Ribes* sp.). Occasional clumps of alder (*Alnus tenuifolia*) and willow (*Salix* sp.) grow near the edge of the lake. Heavy use over much of the area had eliminated virtually all understory vegetation. Isolated patches could be found near rocks or trees where the vegetation had been protected from humans and vehicles (fig. 1).

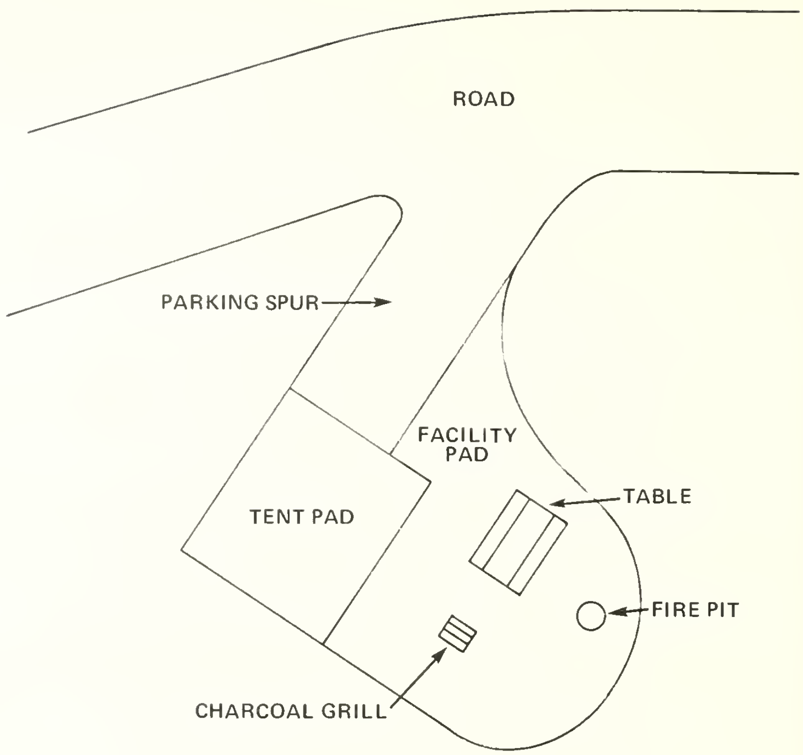
REHABILITATION PROGRAM

Because of its generally rundown appearance and outmoded facilities, Point Campground was rehabilitated during 1966 and 1967. The rehabilitation plan was based on the explicit assumption that ground-cover vegetation could not be maintained on certain heavy-use portions of the campground. Accordingly, roads, parking spurs, trails, and a "facility pad" (for a table, fireplace, and charcoal grill) were surfaced with a gravel-asphalt mixture. In addition, a "tent pad" was located adjacent to the "facility pad"; this consisted of a 16- by 16-foot redwood frame filled with coarse sand (fig. 2).

The size and shape of the "facility pad" and parking spurs were contingent upon such factors as location of trees and ground slope. As a result, the total surfaced area within individual units (including the tent pad) ranged from 646 square feet to 1,572 square feet--an average of 1,188 square feet per unit.

An underground pipe system was installed to deliver water to a single sprinkler head at the approximate center of each unit. Water pressure and flow were adequate to sprinkle all eight camping units simultaneously.

Figure 2.--*Layout of typical unit at Point Campground, Sawtooth National Forest.*



The entire campground was closed during construction for the 1966 and 1967 seasons. This permitted replacement of tables, fireplaces, and charcoal grills, as well as installation of a water hydrant system and central flush toilets. The campground closure was continued until July 1, 1968, to give the seeded grass more time to become established.

HOW TREATMENTS WERE APPLIED

Four cultural treatments were applied to 16 units during the 1968 and 1969 growing seasons: (1) grass seed only (control); (2) water and seed; (3) fertilizer and seed; and (4) water, fertilizer, and seed. Variations between the apparent plant growth potential of the soil on the upper and the lower portions of the terrace dictated a block design for the study. Fortunately, eight units could be located on each of the lower and upper sites of the terrace. Each treatment was randomly assigned to two units on the upper site and two units on the lower site. The treatment area around each unit consisted of an 85-foot square area that included the "facility pad" and "tent pad."

During June of 1968 grass seed, trees, and shrubs were planted. Indigenous tree and shrub seedlings were moved with a soil ball to the campsite from an adjacent area. They were planted in locations selected to block discontinued paths and roads. An unknown quantity of Kentucky bluegrass (*Poa pratensis*) seed was broadcast over all parts of the campground where the soil had been disturbed during construction--road ditches, pipeline trenches, and any fill around parking spurs or table pads. Discontinued roads were tilled and seeded. Seed was raked by hand into the soil.

In May 1969 a mixture of equal parts (by weight) of hard fescue (*Festuca ovina* var. *duriuscula*), Kentucky bluegrass, Dutch clover (*Trifolium repens*), and sodar wheatgrass (*Agropyron saundersii*) was applied at a rate of 40 pounds per acre. Seed was broadcast with particular attention being given to bare soil areas. Where needles formed a mat over 1 inch deep, they were raked aside and the seed spread over the underlying mineral soil. Mulch was not applied to any of the seeded areas.

The eight units that were fertilized each received a total of 45 pounds of nitrogen, 7 pounds of phosphate (P_2O_5), and 3.5 pounds of potassium during the two growing seasons. (On a per-acre basis, these quantities were equivalent to 315 pounds of nitrogen, 49 pounds of P_2O_5 and 24.5 pounds of potassium.) Roughly one-third of this total amount was applied in two applications (one in June and one in September) in 1968 while the young grass seedlings were becoming established. The remainder was applied in two applications (one in May and one in June) in 1969.

Each of the eight irrigated units received at least 1 inch of water weekly during each season over a circular area 110 feet in diameter.[1] This quantity of water tripled the moisture normally available from summer rainfall. The watered units were so located that neither overland water flow nor drifting spray could reach units not scheduled for irrigation. However, the water could not be evenly applied to all parts of the plot because of interference from standing trees.

Application of the weekly water treatment was complicated by the presence of visitors using the campground. To avoid drenching tents and other camping gear, all visitors were required to leave the campground with their equipment by 2 o'clock each Tuesday afternoon. Signs as well as brochures were used to inform campers of the need for the 1-day closure of the campground and the purpose of the irrigation program. The entire campground was reopened at 8 o'clock on Wednesday morning at which time all units were available on a "first-come-first-served" basis. Surprisingly few complaints were received over the weekly closure, perhaps because other nearby campgrounds were available or because of the efforts made to explain the program to visitors. In any event, the weekly closure of this campground did not produce any discernible public hostility.

HOW EFFECTS WERE DETERMINED

Vegetative and other ground cover conditions were sampled at 1-foot intervals along each of 10 permanent, equally spaced, 85-foot line transects within each unit. Each sample point was judged as falling within one of the following nine ground cover condition categories: (1) trees (low branches, exposed roots, etc.); (2) shrubs; (3) grass; (4) herbaceous vegetation; (5) litter (dead plant residue); (6) bare soil; (7) rock; (8) man-installed facilities; and (9) miscellaneous (nonnatural material such as glass, bottle caps, etc.).[2] The quantity of vegetation at each unit was initially measured in mid-September of 1967 following completion of any construction activity that might have disturbed vegetation. It was remeasured twice--in mid-September of 1968 and in mid-September of 1969. Figure 3 shows an example of change that occurred on a unit that received water, fertilizer, and seed.

---

[1]Because of pressure variations, the amount of water could not be completely controlled. Individual units received between 1.1 and 2.6 inches of water weekly.

[2]The first four conditions were noted only for those portions of the vegetation which were 1 foot or less in height.

BEFORE
(1967)

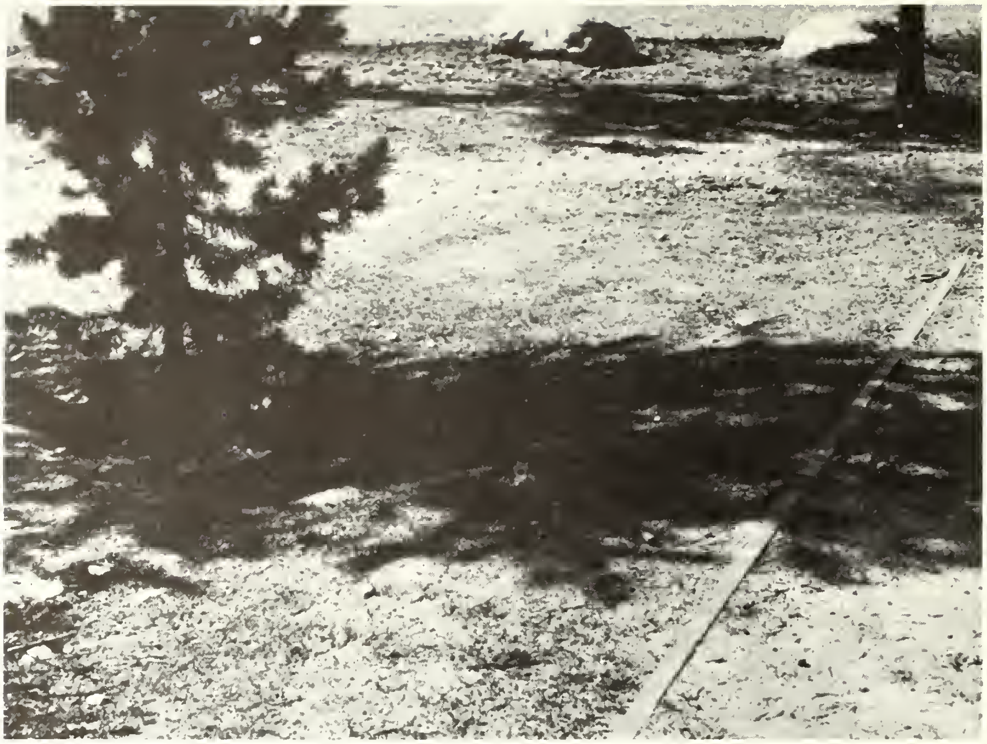
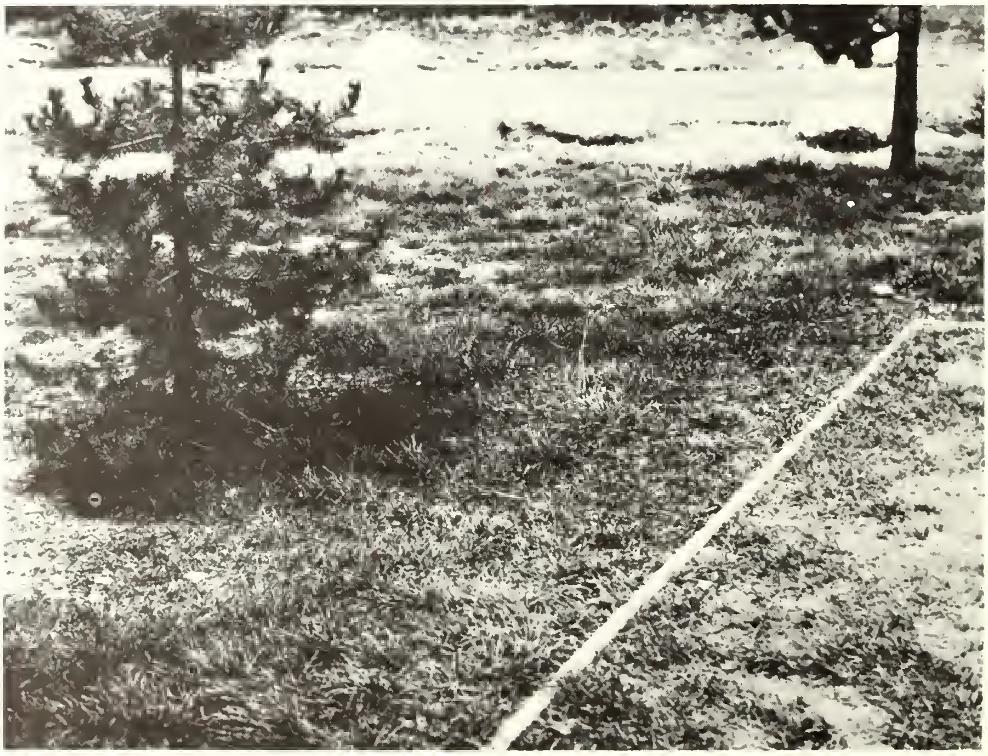


Figure 3.--*Before-and-after treatment photographs show substantial increase in ground-cover vegetation on units that were watered and fertilized as well as seeded.*

AFTER
(1969)



In May 1969 a mixture of equal parts (by weight) of hard fescue (*Festuca ovina* var. *duriuscula*), Kentucky bluegrass, Dutch clover (*Trifolium repens*), and sodar wheatgrass (*Agropyron saundersii*) was applied at a rate of 40 pounds per acre. Seed was broadcast with particular attention being given to bare soil areas. Where needles formed a mat over 1 inch deep, they were raked aside and the seed spread over the underlying mineral soil. Mulch was not applied to any of the seeded areas.

The eight units that were fertilized each received a total of 45 pounds of nitrogen, 7 pounds of phosphate (P_2O_5), and 3.5 pounds of potassium during the two growing seasons. (On a per-acre basis, these quantities were equivalent to 315 pounds of nitrogen, 49 pounds of P_2O_5 and 24.5 pounds of potassium.) Roughly one-third of this total amount was applied in two applications (one in June and one in September) in 1968 while the young grass seedlings were becoming established. The remainder was applied in two applications (one in May and one in June) in 1969.

Each of the eight irrigated units received at least 1 inch of water weekly during each season over a circular area 110 feet in diameter.[1] This quantity of water tripled the moisture normally available from summer rainfall. The watered units were so located that neither overland water flow nor drifting spray could reach units not scheduled for irrigation. However, the water could not be evenly applied to all parts of the plot because of interference from standing trees.

Application of the weekly water treatment was complicated by the presence of visitors using the campground. To avoid drenching tents and other camping gear, all visitors were required to leave the campground with their equipment by 2 o'clock each Tuesday afternoon. Signs as well as brochures were used to inform campers of the need for the 1-day closure of the campground and the purpose of the irrigation program. The entire campground was reopened at 8 o'clock on Wednesday morning at which time all units were available on a "first-come-first-served" basis. Surprisingly few complaints were received over the weekly closure, perhaps because other nearby campgrounds were available or because of the efforts made to explain the program to visitors. In any event, the weekly closure of this campground did not produce any discernible public hostility.

HOW EFFECTS WERE DETERMINED

Vegetative and other ground cover conditions were sampled at 1-foot intervals along each of 10 permanent, equally spaced, 85-foot line transects within each unit. Each sample point was judged as falling within one of the following nine ground cover condition categories: (1) trees (low branches, exposed roots, etc.); (2) shrubs; (3) grass; (4) herbaceous vegetation; (5) litter (dead plant residue); (6) bare soil; (7) rock; (8) man-installed facilities; and (9) miscellaneous (nonnatural material such as glass, bottle caps, etc.).[2] The quantity of vegetation at each unit was initially measured in mid-September of 1967 following completion of any construction activity that might have disturbed vegetation. It was remeasured twice--in mid-September of 1968 and in mid-September of 1969. Figure 3 shows an example of change that occurred on a unit that received water, fertilizer, and seed.

---

[1]Because of pressure variations, the amount of water could not be completely controlled. Individual units received between 1.1 and 2.6 inches of water weekly.

[2]The first four conditions were noted only for those portions of the vegetation which were 1 foot or less in height.

BEFORE
(1967)

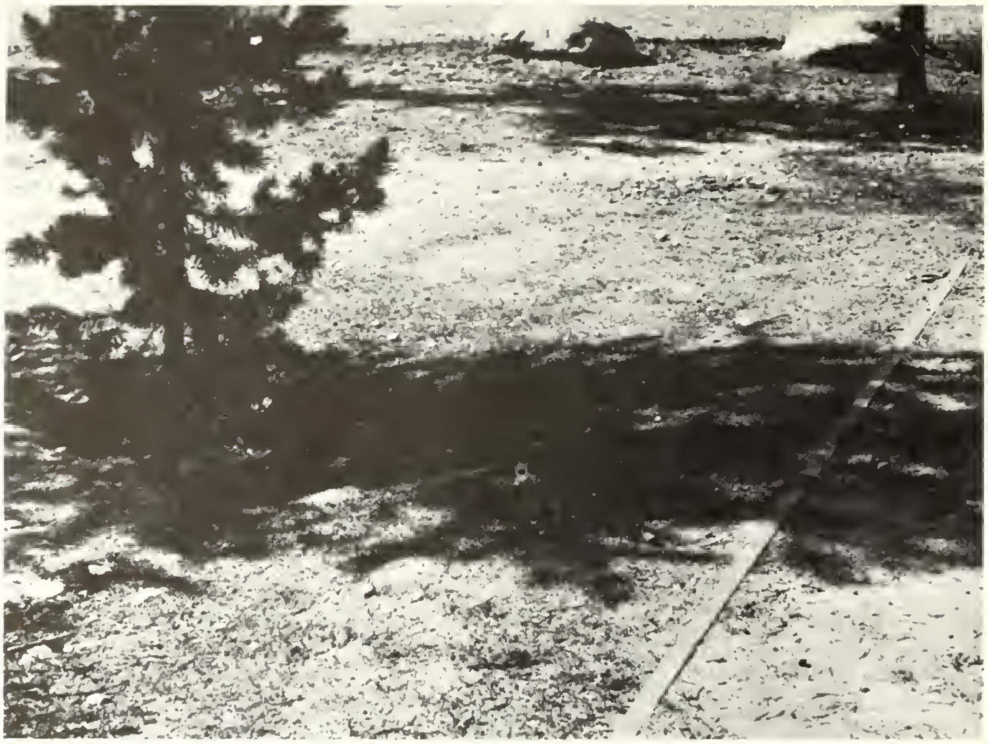
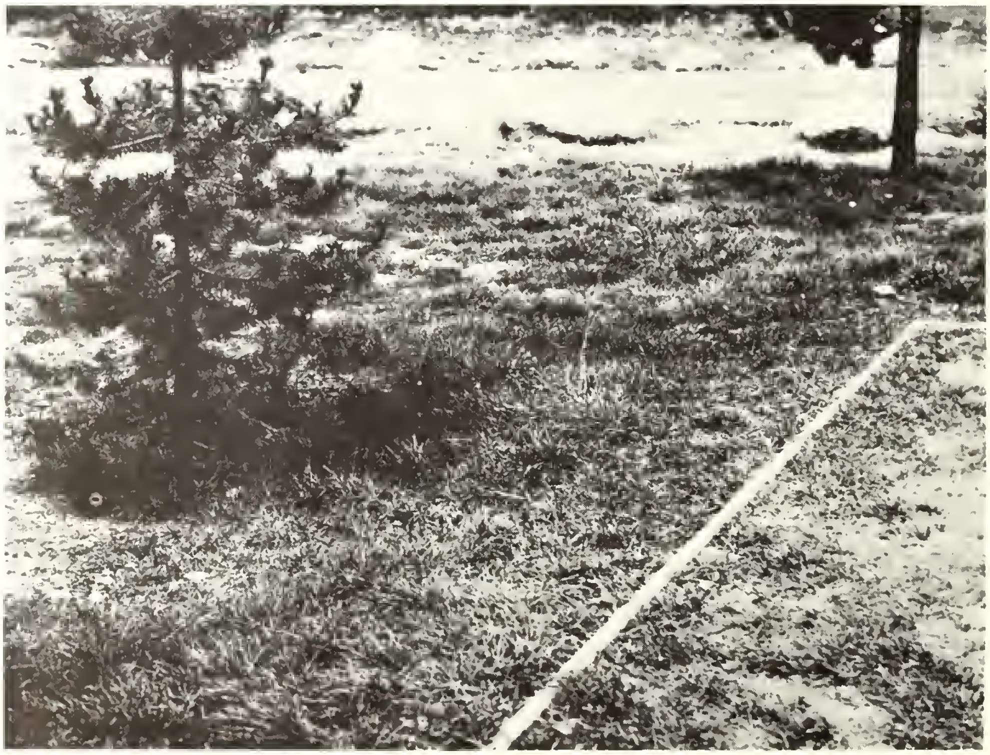


Figure 3.--*Before-and-after treatment photographs show substantial increase in ground-cover vegetation on units that were watered and fertilized as well as seeded.*

AFTER
(1969)



The sample of 850 points within each unit allowed rather precise estimation of the proportion of the surface area of that unit falling within each category. For example, the true proportion of a unit in one ground-cover category would lie between 2 and 8 percent (at the 95-percent level of confidence) if the sample estimate was 5 percent.

RESULTS

By the end of the second season of growth, units treated with water, fertilizer, and seed had noticeably more grass and other herbaceous vegetation than units that had been treated only with seed (control units). Differences between the other treatments were recognizable but less obvious. In general, statistical evaluation of the measurement data confirmed these observations.

Analysis of variance of the data showed that the covariant, visitor use, was nonsignificant. Therefore, the means for various treatments did not require adjustment for differences in visitor use between units. The model accounted for 95 percent of the total variation in measurements of vegetation growth (R^2). The majority--85 percent of the total--was attributed solely to the main effects of treatment. In other words, treatment accounted for the major portion of all squared differences from overall mean growth.

Tests of significant differences between the treatment means by Scheffé Test (Bancroft 1968) indicated no differences between the sites. That is, treatment responses were not influenced by site. Treatment responses were found to be markedly different from one another at the 95-percent level of significance.

(1) Most important, the water-fertilizer-seed combination produced significantly more vegetation than any of the other treatments.

(2) Water and seed produced significantly more than seed alone.

(3) Fertilizer and seed together were not significantly different from seed alone (control).

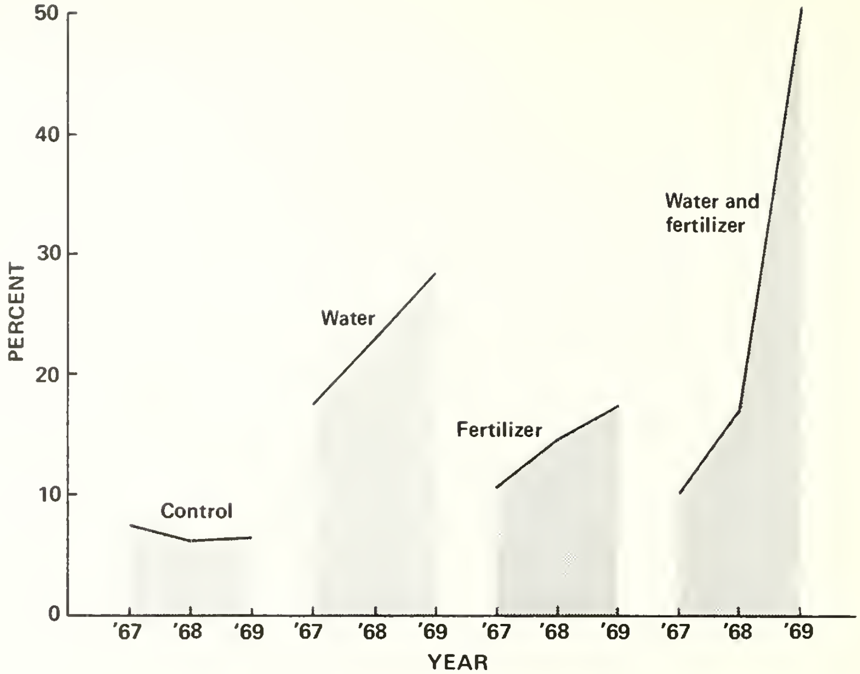
The average change in proportion of ground cover vegetation for each of the four treatments is listed below and presented in figure 4.

Treatment	*Growth*[3]
Water, fertilizer, seed	40
Water, seed	11
Seed, fertilizer	6
Seed	-1

The control units, which show a slight decline in ground cover vegetation since the campground was reopened for use in 1968, will probably stabilize at some rather low level of vegetation.

[3]Change in percent of vegetative cover of total available area. For example, the seed (control) treatment decreased from 8 percent in September 1967 to 7 percent in September 1969.

Figure 4.--*Percent of available growing space covered by grass, shrubs, and herbs. Available growing space includes all portions of the unit except pad, parking spur, trails, rocks, trees, and tree stumps. (All units received grass seed.)*



CONCLUSIONS

It is undoubtedly premature to attempt to project the time required to achieve a satisfactory level of ground cover with the various treatments. Data for two seasons of growth are not conclusive. Nevertheless, the dramatic results achieved with water, fertilizer, and seed strongly suggest that a satisfactory level of ground cover can be expected at the end of the third full growing season. Rates of change observed so far indicate that, without water, it could take 20 years or longer to revegetate a badly worn campground, as shown in the following tabulation:

Treatment	*Years required to produce 70-percent cover*
Seed only	Never
Fertilizer and seed	At least 20
Water and seed	At least 10
Water, fertilizer, and seed	At least 3

These time estimates assume that: (1) 70-percent ground cover is adequate and realistic; and (2) the vegetation will continue to improve at the same rate as was observed during the 2-year study period.

REFERENCES

Arnold, J. F.
1966. A soil survey report for the Point Campground on Redfish Lake. USDA Forest Serv., Intermountain Region, Office Rep.

Bancroft, T. A.
1968. Topics in intermediate methods. Vol. 1, p. 109. Ames: Iowa State Univ. Press.

Beardsley, W. G., and J. A. Wagar.
Vegetation management on a forested recreation site. USDA Forest Serv., Intermountain Forest and Range Exp. Sta. (In preparation.)

Cordell, H. K., and D. R. Talhelm.
1969. Planting grass appears impractical for improving deteriorated recreation sites. USDA Forest Serv. Res. Pap. SE-105.

Dotzenko, A. D., N. T. Papamichas, and D. S. Romine.
1967. Effect of recreational use on soil and moisture conditions in Rocky Mountain National Park. J. Soil and Water Conserv. 22(5): 196-197.

Lutz, H. J.
1945. Soil conditions on picnic grounds in public forest parks. J. Forestry 43: 121-127.

Magill, A. W., and E. C. Nord
1963. An evaluation of campground conditions and needs for research. USDA Forest Serv. Res. Note PSW-4.

Meinecke, E. P.
1928. A report on the effect of excessive tourist travel on the California Redwood Parks. Calif. State Printing Office.

Ripley, T. H.
1962. Recreation impact on southern Appalachian campgrounds and picnic sites. USDA Forest Serv., Southeastern Forest Exp. Sta. Pap. 153.

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

USDA Forest Service
Research Paper INT-88
1971

SAMPLING WITH PROBABILITY PROPORTIONAL TO SIZE FROM A SORTED LIST

Albert R. Stage

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Ogden, Utah 84401

USDA Forest Service
Research Paper INT-88
February 1971

SAMPLING WITH PROBABILITY PROPORTIONAL TO SIZE FROM A SORTED LIST

Albert R. Stage

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

THE AUTHOR

ALBERT R. STAGE is Leader of Intermountain Station's Timber Measurement and Management Planning research work unit located at the Forestry Sciences Laboratory, Moscow, Idaho. His studies have included research on forest growth, yield, and site quality, as well as on sampling methods and inventory design.

CONTENTS

ABSTRACT

Describes a method for pps sampling developed by H. O. Hartley (1966). To facilitate drawing samples using this method, a computer subroutine is provided that identifies the units in the sample, calculates their sampling probability, and summarizes the distribution of this probability over the entire population for use in subsequent estimates of the population total and its variance. An estimate of the error variance is derived in the case that the ratio of measured value to size is a polynomial function of size. This error estimate is a multivariate analog of Hartley's linear model for the superpopulation. To permit sampling without replacement, excessively large units in the population are assigned to a stratum to be measured with absolute certainty.

THE SAMPLING METHOD

Sampling with unequal probabilities of selecting a sample unit frequently can result in increased efficiency in estimating population totals. The technique requires that each unit in the population be characterized by a "size" measure that is correlated with the variable of real interest to be measured on that unit. If a list of the size variable can be obtained cheaply for all units in the population, then sampling with probability proportional to size (pps) according to the method developed by Hartley (1966) can be more efficient than pps sampling by other methods. How much more efficient depends on the character of the functional relation between size and the variable of real interest.

The distinguishing feature of Hartley's method is that the units of the population are sampled at uniform intervals of accumulated size from a random start in the list of units sorted into order by size. Hence, the sample that is drawn is more likely to contain both small and large units than would a pps sample drawn from a randomly ordered list. Hartley has provided an expression for the true variance of estimates based on this method of selecting the sample. However, the sample estimate of this variance that he suggests is based on the assumption that the ratio of the variable of interest to the size variable is a linear function of the size variable. In a subsequent part of this paper, the assumption concerning the linearity of this relation is relaxed to include polynomial functions of the size variable.

PPSORT--A COMPUTER SUBROUTINE FOR SELECTING THE SAMPLE

PPSORT is a FORTRAN IV computer subroutine that implements Hartley's procedure for drawing samples from a population list sorted by size. The program is complete with its own composite random number generator (Marsaglia and Bray 1968; Grosenbaugh 1969) and sorting algorithm. The execution speed of the version of PPSORT listed in appendix 1 was markedly improved over earlier versions by adopting a sorting method developed by D. L. Shell, as it was programed by Robert M. Russell of the Pacific Southwest Forest and Range Experiment Station.

The pps selection method used by PPSORT is without replacement. Accordingly, the number of sample units must be less than the measure of size accumulated over the entire population divided by the size of the largest element in the population. The logic of PPSORT is such that if this condition is not satisfied for the number of sample units requested, then the population is divided into two strata. The largest unit in the population is assigned to one stratum in which every unit will be designated for measurement with absolute certainty. The other stratum is comprised of the remaining units of the population. The number of sample units to be drawn is reduced by one, and the inequality is tested again. If the number of sample units is still too large, the process is repeated until the inequality is satisfied. Fortunately, the expression for estimating the population total can ignore the separation into sampled and completely measured strata. If a stratum for the largest units is required to satisfy the above inequality, all the units assigned to this stratum can be given a sampling probability of exactly unity. Thus, the estimated population total can be seen to be the sum of the estimated total for all the sampled stratum plus the total of the stratum of excessively large units.

To provide the proper elements for the variance estimate based on the units in the sampled stratum, PPSORT returns values of the total size of the sampled stratum and the number of units selected from it for measurement along with their identification and probability of inclusion. Certain other values depending on the distribution of the inclusion probabilities over the entire population are also saved by PPSORT for later use in calculating the variance estimate.

CALLING PPSORT

To use PPSORT, a computer program would be prepared that enters the data describing the entire population, calls PPSORT, and then displays the identification and sampling probabilities for each member of the sample drawn by PPSORT, and the values required for the subsequent variance estimate. A simple version of such a program with test data that can be used to verify the functioning of the PPSORT program is provided in appendix II. Three random odd integers must be assigned to the variables KR, LR, and MR to start the pseudorandom number generator used in PPSORT (Marsaglia and Bray 1968).

The subroutine is executed by the statement

```
CALL PPSORT (NP,ID,CHAR,NSAM,IDSAM,PP,TX,TS,TP,NRS,N,LR,MR,KR)
```

in which the first four and the last three arguments of the calling sequence are established prior to the execution of the CALL statement.

NP contains the number of units in the population. (If NP exceeds 498, the DIMENSION statement in the PPSORT program should be changed accordingly.)

ID is a vector of NP elements identifying the units of the population.

CHAR is a vector of NP elements containing the sizes of the units of the population corresponding to the same sequence as the ID vector.

NSAM contains the number of units to be measured (sample units plus those that may be designated for measurement with absolute certainty).

The intervening seven arguments contain information about the sampling as it was accomplished by PPSORT.

IDSAM is a vector of NSAM elements containing the values copied from the ID vector for only those units selected for measurement.

PP is a vector of NSAM elements containing the value of the probability with which each unit was selected for measurement. Their sequence is the same as the sequence of ID's in IDSAM. (PP(I) = P_i)

TX contains the sum of the size variable for the stratum to be sampled.

TS,TP contain components of the sample variance estimate defined on page 4.

NRS contains the number of units drawn from the stratum to be sampled (NRS = n).

N contains the total number of elements in the sampled stratum.

KR, LR, MR contain odd random integers used by the random number generator.

CALCULATING ESTIMATES

Population Total

The population total is estimated from a pps sample by

$$\hat{Y} = \sum_{i=1}^{n+l} \frac{Y_i}{P_i} = \sum_{i=1}^{n} \frac{Y_i}{P_i} + \sum_{i=n+1}^{l} Y_i$$

in which

n is the number of units measured in the sample.

l is the number of units assigned to the stratum of too-large units to be measured with absolute certainty.

Y_i is the variable of interest for the ith measured unit.

P_i $= n\, x_i / \sum_{j=1}^{N} x_j$, the probability with which the ith unit was selected for measurement where x_i equals the measure of size of the ith unit in the sampled stratum. P_i equals unity for units in the too-large stratum.

The last summation would not contribute to the variance of $\hat{Y}$.

Note that P_i depends on n. Accordingly, inadvertent change in n after the P_i is calculated should be avoided. If u sample units are not measured for reasons independent of their sizes, then $\hat{Y}$ could be estimated by

$$\hat{Y} = \frac{n}{n-u} \sum_{i=1}^{n} \frac{Y_i}{P_i} + \sum_{i=n+1}^{l} Y_i$$

in which $Y_i = 0$ for the omitted sample units.

Variance of Population Total

The variance of the population total is estimated from a sample drawn with PPSORT by the expression[1/]

$$\hat{\text{Var}}\ \hat{Y} = n^2\ (b^2 - \hat{\text{Var}}\ b)\ TS + n\ TP\ \hat{\sigma}^2$$

in which

$$b = \frac{\sum_{i=1}^{n} Y_i - (\sum_{i=1}^{n} Y_i/P_i) \sum_{j=1}^{n} P_j/n}{\sum_{i=1}^{n} P_i^2 - (\sum_{j=1}^{n} P_j)^2/n}$$

$$\hat{\sigma}^2 = \frac{\sum_{i=1}^{n} (Y_i/P_i)^2 - (\sum_{j=1}^{n} Y_j/P_j)^2/n - b\ [\sum_{i=1}^{n} Y_i - (\sum_{i=1}^{n} Y_i/P_i) \sum_{j=1}^{n} P_j/n]}{n-2}$$

$$\hat{\text{Var}}\ b = \hat{\sigma}^2 / \left[\sum_{i=1}^{n} P_i^2 - (\sum_{i=1}^{n} P_i)^2/n \right]$$

s_k = probability with which the sample cluster of n units was selected for measurement

N = total number of units in the population to be sampled

$$TS = \sum_{k=1}^{N} s_k \left(\sum_{i=1}^{n} P_i/n - \sum_{j=1}^{N} s_j \sum_{i=1}^{n} P_i/n \right)^2$$

$$TP = 1 - \sum_{k=1}^{N} s_k^2$$

The last two values are calculated by PPSORT.

This expression is appropriate when the trend of Y_i/P_i is linear with respect to P_i. If the sample indicates that the trend is curvilinear, the variance will be overestimated unless the formula is modified as described in the following section.

---

[1]The factor $(N\text{-}1)/N$ in Hartley's expression is replaced here by the exact value $(1 - \Sigma s_k^2)$ because it is readily available when PPSORT is used.

Derivation of Variance Estimate for Polynomial Model

The variance estimate given above assumes that the trend of Y_i/P_i is a linear function of P_i. If the relation is known to be curvilinear in advance, a suitable transformation of the size variable should restore the linearity. However, if the curvilinear trend is not observed until after the sample has been measured, the variance estimate based on the linear model would be too large. In such a case, the following analysis shows how a multivariate analog of the linear model could be used to estimate the variance of the population total.

Let the following symbols represent vectors or matrices of the indicated dimensions. The subscript k designates the kth sample cluster defined by the sorted order and the sampling interval. The range of k is from 1 to N.

r_k	$= (Y_i/P_i)$	of dimension	nx1
m	$= (1)$	" "	nx1
R	$= (m'r_k)$	" "	Nx1
x_k	$= (P_i, P_i^2, \ldots, P_i^q)$	" "	nxq
X	$= \frac{1}{n}(m'x_k)$	" "	Nxq
W	$= (s_k \delta_{ik})$	" "	NxN
M	$= (1)$	" "	NxN

In the above vectors and matrices, the scalars are defined as follows:

Y_i is the measured value of the variable of interest for the ith unit in the population.

P_i is the probability with which Y_i is measured.

s_k is the probability that the kth sample cluster of Y_i is measured.

$$\delta_{ij} = \begin{cases} 1 \text{ if } & i = j \\ 0 \text{ if } & i \neq j \end{cases}$$

N is the total number of units in the population.

n is the number of units in the sample.

q is the degree of the polynomial function of P_i.

Note that M is a matrix and m is a vector having unity in all elements. The effect of multiplying a vector by M or m is to replace each element in the vector with the column total. In particular,

$$MWM = M \text{ because } \sum_{k=1}^{N} s_k = 1$$

With this notation, define three additional matrices:

$Z = X - MWX$	of dimension	Nxq
$B = (Z'WZ)^{-1} Z'WR$	" "	qx1
$E = R - ZB$	" "	Nx1

in which Z' is the transpose of Z.

Now $Z'WZ$ is the analog of

$$n^2 \sum_{k=1}^{N} s_k (\bar{x}_k - \bar{x})^2 / (\sum_{i=1}^{N} x_i)^2$$

and $(R-MWR)'W(R-MWR)$ is the analog of

$$\sum_{k=1}^{N} s_k (\bar{r}_k - \bar{r})^2 \quad (\sum_{i=1}^{N} x_i)^2$$

in Hartley's notation.

Furthermore, because $MWM = M$, it can be shown that $MWZ = 0$, the null matrix of dimension nxq. It is also true that $Z'WE = 0$, the null vector of dimension qx1.

The objective is to derive an estimate for the variance of the estimate of the population total $\hat{Y} = m'r_k$. The variance of $\hat{Y}$ is given by

$$\begin{aligned} \text{Var } \hat{Y} &= n^2 (R-MWR)' W (R-MWR) \\ &= n^2 (ZB + E - MWZB - MWE)' W (ZB+E - MWZB - MWE) \\ &= n^2 (ZB + E - MWE)' W (ZB+E - MWE) \\ &= n^2 (B'Z'WZB + (E - MWE)' W (E - MWE) + 2 B'Z'W (E-MWE)) \end{aligned}$$

The last product is zero because

$$B'Z'WE = B'0 = 0$$

and

$$B'Z'WMWE = B'(MWZ)' WE = B'0'WE = 0$$

In the variance expression, the first matrix product, $Z'WZ$ is the multivariate analog of the factor TS computed in PPSORT.

To estimate the $B'Z'WZB$ component of Var $\hat{Y}$ requires first an estimate of B based only on the sample. Let b represent the vector of q estimates of the elements of B, and let z be the matrix of deviations of the q powers of P_i for each of the n units in the sample:

$$z \doteq (P_j - \sum_{i=1}^{n} P_i/n,\ P_j^2 - \sum_{i=1}^{n} P_i^2/n,\ \ldots,\ P_j^q - \sum_{i=1}^{n} P_i^q/n)$$

for $j = 1, \ldots, n$.

Finally, let r be the n element column vector of ratios:

$$r = (Y_i/P_i)$$

Then define the estimate of B to be

$$b = (z'z)^{-1} z'r$$

Next, define Σ as the expected value of

$$(b-B)'Z'WZ(b-B)$$

Because Z'WZ is a matrix of constants,

$$\Sigma = \varepsilon\ (b'Z'WZb) - B'Z'WZB$$

in which ε (•) means "the expected value of" (•).

Under the assumption that r is drawn from a superpopulation having a mean of zB and variance equal to $\varepsilon\ (e'e) = \sigma^2$,

$$\begin{aligned}(b-B) &= (z'z)^{-1}\ z'\ (zB+e) - B\\ &= B + (z'z)^{-1}\ z'e - B\\ &= (z'z)^{-1}\ z'e\end{aligned}$$

Then,

$$\varepsilon\ (b-B)'\ Z'WZ\ (b-B) = \varepsilon\ (e'z(z'z)^{-1}\ Z'WZ(z'z)^{-1}\ z'e)$$

To simplify notation, designate the symmetric matrix between e' and e by C, then

$$\varepsilon(e'Ce) = \sum_{i=1}^{n} \varepsilon\ (e_i^2)\ C_{ii} + 2 \sum_{i=1}^{n} \sum_{j=1}^{i-1} \varepsilon\ (e_i e_j C_{ij})$$

The expected value of e_i^2 is σ^2 and the expected value of $e_i e_j$ is zero if the errors are independent for a sufficiently high degree polynomial.

Therefore,

$$\Sigma = \sigma^2 \sum_{i=1}^{n} C_{ii} = \sigma^2\ \mathrm{tr}(C)$$

Because one can commute matrices under the trace operator,

$$\begin{aligned}\mathrm{tr}(C) &= \mathrm{tr}\ (z(z'z)^{-1}\ Z'WZ\ (z'z)^{-1}\ z')\\ &= \mathrm{tr}\ (Z'WZ\ (z'z)^{-1}\ z'z\ (z'z)^{-1}\\ &= \mathrm{tr}\ (Z'WZ\ (z'z)^{-1})\end{aligned}$$

Hence, Σ can be estimated by the residual mean square error times the sum of the diagonal elements of $Z'WZ(z'z)^{-1}$.

The final component of Var $\hat{Y}$ to be estimated is (E - MWE)' W (E - MWE) which equals E'WE - E'WMWE, or returning to the summation notation:

$$\sum_{i=1}^{N} s_i E_i^2 + 2 \sum_{i=1}^{N} \sum_{j=1}^{i-1} s_i E_i E_j s_j - \sum_{i=1}^{N} s_i^2 E_i^2 - 2 \sum_{i=1}^{N} \sum_{j=1}^{i-1} s_i E_i E_j s_j$$

Taking expectations, and noting that each element E_i is the average of n residuals,

$$\varepsilon \quad (\text{E-MWE})' \, \text{W}(\text{E-MWE}) = \frac{\sigma^2}{n} \sum_{i=1}^{N} s_i - \frac{\sigma^2}{n} \sum_{i=1}^{N} s_i^2 \quad = \frac{\sigma^2}{n} \left(1 - \sum_{i=1}^{N} s_i^2\right)$$

Putting all the components together,

$$\hat{\text{Var}}\ \hat{Y} = n^2\ \text{b'Z'WZB} - \hat{\sigma}^2\ \text{tr}\ [\text{Z'WZ}(\text{z'z})^{-1}] + \frac{\hat{\sigma}^2}{n} \left(1 - \sum_{i=1}^{N} s_i^2\right)$$

in which

$$\hat{\sigma}^2 \quad = (\text{r'r} - \text{bz'r}) / \ (n - q - 1)$$

and

$$\text{tr(C)} \quad = \sum_{i=1}^{N} C_{ii}$$

When q = 1, the above matrix equation reduces to the variance estimate in the previous section for the linear model. Obviously the order q of the polynomial is not known when PPSORT is executed, so the qxq matrix Z'WZ must be calculated subsequently by a procedure analogous to the computation of *TS* in PPSORT. Such a program could be prepared by omitting from PPSORT the selection of random sample units and by making *SX* a q-element vector of powers of the difference *CP*(J+1) - *CP*(J).

EXAMPLES

The first example shows the output from sampling the same population described by Hartley (1966).

```
      ID               EST. SIZE        NO. OF UNITS TO BE
                                            MEASURED =     3

      10              130.00000
       8              109.00000
       6              105.00000
       4               93.00000
       2               82.00000
       9              115.00000
       7              109.00000
       5               95.00000
       3               93.00000
       1               80.00000
                                                  SAMPLES DRAWN

                                        ( NO. IN STRATUM =     10)
                                        ( NO. OF SAMPLES =      3)
                                        ( TX    =    0.1011000E 04)
                                        ( TS    =    0.3359580E-03)
                                        ( TP    =    0.8516406E 00)

                                                ID  PROBABILITY

                                                 3  0.2759644E 00
                                                 6  0.3115721E 00
                                                 9  0.3412457E 00
```

From the population of 10 units, three are to be drawn for measurement. The third, sixth, and ninth units comprise the sample. Table 1 shows the calculation of the estimates of the population total and its variance based on the measurements (Y') of these three sample units. The estimate of the population total is the sum of Y_i/P_i = 578. The sample standard error of this value is $\sqrt{642.61}$[2] or $\pm$ 25.3.

[2] This value differs from Hartley's calculated variance of 653.2 only because the exact value of $(1 - \Sigma\, s_k^2)$ has replaced his $(N-1)/N$ approximation.

Table 1.--Calculation of sample mean and variance estimates (N=10, n=3)

Unit	P_i	Y_i	Y_i/P_i
3	0.27596	56.	202.924
6	.31157	62.	198.990
9	.34125	60.	175.825
Sums	.9287834	178.	577.74128
Means	.309593	59.3333	192.581
Sum of Squares	0.2896829	10580.00	111690.465

$\hat{Y} = \Sigma\ Y_i/P_i = 577.7$

$\Sigma\ (P_i)^2 - (\Sigma\ P_i)^2/n = 0.2896829 - (0.9287834)^2\ /\ 3 = .0021367334$

$\Sigma\ Y_i - \Sigma\ (Y_i/P_i)\ \Sigma\ P_i/n = 178. - (577.74128)(0.9287834)/\ 3 = -0.8655035$

$\Sigma\ (Y_i/P_i)^2 - (\Sigma\ Y_i/P_i)^2/n = 111690.465 - (577.74128)^2/\ 3 = 428.80126$

$b = -.8655035\ /\ .00213673 = -405.059$

$\hat{\sigma}^2 = [428.80126 - (-405.059)^2\ (.00213673)]\ /\ (3-2) = 78.22111$

$b^2 - \hat{\text{Var}}\ b = 164072.7935 - 78.2211\ /\ .0021367334 = 127464.9976$

$TS = .000385958$

$TP = 0.85164$

$\hat{\text{Var}}\ \hat{Y} = 9\ (127464.9976)\ (.000385958) + 3\ (0.85164)\ (78.22111)$

$= 442.765 + 199.849 = 642.614$

The next example illustrates the way in which PPSORT stratified the excessively large elements (added to the same population used previously) into a stratum to be measured with absolute certainty.

```
ID              EST. SIZE        NO. OF UNITS TO BE
                                    MEASURED =     4

 1               80.00000
 2               82.00000
 3               93.00000
 4               93.00000
 5               95.00000
 6              105.00000
 7              109.00000
 8              109.00000
 9              115.00000
10              130.00000
11              999.00000
                                         SAMPLES DRAWN

                                  ( NO. IN STRATUM =    10)
                                  ( NO. OF SAMPLES =     3)
                                  ( TX   =    0.1011000E 04)
                                  ( TS   =    0.3359580E-03)
                                  ( TP   =    0.8516406E 00)

                                       ID  PROBABILITY

                                       11  0.1000000E 01
                                        4  0.2759644E 00
                                        6  0.3115721E 00
                                        9  0.3412457E 00
```

Notice that there are three samples, although four units are to be measured. Consequently, the error components are exactly the same as in the previous example, although the estimate of the population total is increased by the measured value of the eleventh sample unit.

The last example illustrates a situation in which two units must be assigned to the stratum for measurement with probability equal to one. The remaining three sample units happen to include all of the remaining "large" units in the population. Nevertheless, the smaller units could have been a part of the sample had the random number been small enough.

```
ID          EST. SIZE      NO. OF UNITS TO BE
                              MEASURED =    5
 3            3.00000
 4            3.00000
 5            5.00000
 6            5.00000
 7          109.00000
 8          109.00000
 9          115.00000
10          130.00000
11          999.00000
 1            1.00000
 2            1.50000
                                  SAMPLES DRAWN

                           ( NO. IN STRATUM =       9)
                           ( NO. OF SAMPLES =       3)
                           ( TX    =   0.3515000E 03)
                           ( TS    =   0.1206964E-01)
                           ( TP    =   0.2865710E 00)

                                 ID  PROBABILITY

                                 11  0.1000000E 01
                                 10  0.1000000E 01
                                  7  0.9302982E 00
                                  8  0.9302988E 00
                                  9  0.9815083E 00
```

LITERATURE CITED

Grosenbaugh, L. R.
1969. More on FORTRAN random number generators. Commun. ACM 12(11): 639.

Hartley, H. O.
1966. Systematic sampling with unequal probability and without replacement. J. Amer. Statist. Assoc. 61: 739-748.

Marsaglia, George, and T. A. Bray.
1968. One-line random number generators and their use in combinations. Commun. ACM 11(11): 757-759.

APPENDIX I

PPSORT Program

```
      SUBROUTINE PPSORT(NNN,ID,CHAR,NNSAM,IDSAM,PP,TX,TS,TP,NSAM,D,LR,
     1 MR,KR)
      DIMENSION VEC(500),CP(500),IND(500),CCP(500)
C     THE ABOVE FOUR VECTORS MUST BE DIMENSIONED GREATER THAN NNN + 2
      DIMENSION  ID(NNN),CHAR(NNN),IDSAM(NNSAM),PP(NNSAM),NR(128)
      EQUIVALENCE ( VEC,CCP)
C     MLR,MMR,MKR, AND NR ARE USED IN THE RANDOM NUMBER GENERATOR.
C     TO START THE RANDOM NUMBER GENERATOR, THREE ODD RANDOM INTEGERS
C        SHOULD BE ASSIGNED TO LR, KR, AND MR, RESPECTIVELY.
C        SEE THE REFERENCE CITED BELOW.
      DATA MLR, MMR, MKR / 65539, 33554433, 362436069/
      DATA NR /
     1  221, 361, 109, 281, 445, 273, 475, 437, 277, 353, 153, 237, 465,
     2   61, 287, 413, 441, 369,  99,  51, 463, 179,  55, 483,  95, 363,
     3  487, 253, 197, 409, 303, 231, 435, 209, 357, 143, 205, 255,  91,
     4    3, 131, 489, 399, 371, 453,  97, 271, 307,  31, 123, 243,  29,
     5  343, 217, 391,  35, 337, 229, 493, 263, 317,  75, 449,  45, 279,
     6  245, 323,  57, 191,  17, 133,  73, 339, 187, 165, 137, 121, 365,
     7   33, 289, 473, 405, 301,  77, 481, 351, 159, 349, 295,  47, 359,
     8  393,  19, 265, 235,   7, 167, 451, 479, 103, 257, 459,  93, 331,
     9  149, 203, 325, 215, 259,  33, 115, 233, 145, 117, 139,   9, 431,
     X  319, 141, 443, 129,  13,  71, 383,  85, 305,  63, 379  /
      N = NNN
      NSAM = NNSAM
C     THIS PROGRAM WILL DRAW 'NSAM' SAMPLES FROM THE'ID' POPULATION OF
C     'N' UNITS WITH PROBABILITY PROPORTIONAL TO THE ASSOCIATED VALUE
C     OF 'CHAR' WITHOUT REPLACEMENT.
C     THE SAMPLE IS  DRAWN SYSTEMATICALLY FROM THE LIST ORDERED BY
C     INCREASING VALUES OF 'CHAR', USING THE THEORY DESCRIBED IN:
C        HARTLEY, H.O.; JOUR. AMER. STAT. ASSOC. 61(315):739-748.
C
C     THE UNITS SELECTED WILL BE IDENTIFIED IN THE VECTOR 'IDSAM'.
C
C     'NSAM' MAY BE DECREASED SO THAT THE STEP IS GREATER THAN THE
C     MAXIMUM VALUE OF 'CHAR'.  IN THAT EVENT,
C     THE LARGEST ELEMENT OF THE POPULATION WILL BE ASSIGNED A SAMPLING
C     PROBABILITY OF UNITY AND DELETED FROM THE POPULATION.
C
C     'D' IS THE STEP SIZE USED IN THE SYSTEMATIC SELECTION.
C
C     FOR PURPOSES OF ERROR CALCULATION, THE SUM OF SQUARED DEVIATIONS
C     OF THE MEAN OF CHAR FOR EACH OF THE 'N' POSSIBLE SAMPLES
C     FROM THE WEIGHTED MEAN OF THE SAMPLE MEANS, EACH WEIGHTED BY THE
C     PROBABILITY WITH WHICH THAT SAMPLE CLUSTER MAY BE SELECTED, IS
C     COMPUTED IN 'TS'.  ONE MINUS THE SUM OF SQUARES OF THE PROBABILITY
C     IS CALCULATED IN 'TP'.
C     THE REMAINING PARTS OF THE EXPRESSION FOR SAMPLING ERROR MUST BE
C     CALCULATED AFTER THE SAMPLE IS MEASURED.  (SEE HARTLEY'S EQ.(29)).
C
      IF ( N .LT. NSAM) NSAM = N
      IF ( NSAM .LE. 0 ) RETURN
      VEC(1) = 0.0
      IND(N+1) = 1
      CHAR(N+1) = 0.0
C     FIRST SORT INTO INCREASING ORDER OF CHAR WITHOUT RE-ARRANGING
      DO 2 J = 1,N
    2 IND(J) = J
      NM1 = N - 1
```

```
      IF (NM1) 4,4,5
    4 VEC(2) = CHAR(1)
      IMAX = 1
      GO TO 25
    5 M = 1
   12 M = M + M
      IF ( M .LT. N ) GO TO 12
      M = MAX0(1,M/2 - 1 )
   13 I = 1
      IM = I + M
   14 J = I
      JM = IM
      IHOLD = IND(IM)
   15 JR = IND(J)
      IF( CHAR(JR) .LT.CHAR(IHOLD) ) GO TC 16
      IND(JM) = IND(J)
      JM = J
      J = J - M
      IF ( J .GT. 0 ) GO TO 15
   16 IND(JM) = IHOLD
      I = I + 1
      IM = I + M
      IF ( IM .LE. N ) GO TO 14
      M = M/2
      IF ( M .GT. 0 ) GO TO 13
      DO 20 J = 1,N
   20 VEC(J+1) = VEC(J) + ABS(CHAR(IND(J)))
C        NOTE 'VEC' IS INDEXED PLUS ONE)
C     NOW COMPUTE TRIAL STEP.
      I = 1
   23 IMAX = IND(N)
   25 D = VEC(N+1)/ FLOAT (NSAM)
      IF ( D.GT.CHAR(IMAX)) GC TO 30
      IDSAM(I) = ID(IMAX)
      PP(I) = 1.0
      I = I + 1
      NSAM = NSAM-1
      N=N-1
      IF ( NSAM .GT. 0 ) GO TC 23
      D = VEC(1)
      TS = 0.
      TP = 1.0
      RETURN
   30 CONTINUE
C         UNIFORM RANDOM NUMBER GENERATCR FOR IBM 36C
C             FOR OTHER COMPUTERS,SEE THE FOLLOWING
C                 REF: MARSAGLIA AND BRAY, CCMM. ACM 11(11),757-759
C                        GROSENBAUGH, L. R.,COMM. ACM 12(11),639
C
      LR = LR*MLR
      MR = MR*MMR
      JR = 1 + IABS(LR)/16777216
      SEL=(0.5 + FLOAT(NR(JR) + LR + MR)*0.23283064E-9)*D
      KR = KR*MKR
      NR(JR) = KR
C
C     FIND SAMPLE UNITS.
      FNS = FLOAT(NSAM)
```

```
      CP(1) = 0.0
      DO 40 J = 1,N
      CP(J+1) = FNS*VEC(J+1)/VEC(N+1)
      CCP(J) = CP(J+1)- FLOAT(IFIX(CP(J+1)))
      IF ( SEL.GT.VEC(J+1)) GO TO 40
C     FOUND A SAMPLE UNIT.
      JJ = IND(J)
      IDSAM(I) = ID(JJ)
      PP(I) = CP(J+1) - CP(J)
      I = I + 1
      SEL = SEL + D
C     NOW CALCULATE THE ERROR COMPONENTS DEPENDING ON DISTRIBUTION OF
C              'CHAR' THROUGHOUT THE POPULATION.
   40 CONTINUE
      TX = VEC(N+1)
      TSS = 0.0
      TS = 0.0
      SEL = FNS/FLOAT(N)
      SX = CP(2)
      SP = 0.0
      TP = 1.0
      I = 1
      CCP(N) = 1.0
C     CALCULATE SUM OF P(I) FOR FIRST SAMPLE CLUSTER
      DO 120 J = 2,N
      IF ( I .GT. IFIX(CP(J+1)) ) GO TO 120
      SX = SX + CP(J+1) - CP(J)
      I = I + 1
      IF ( I .GE.NSA1 ) GO TO  130
  120 CONTINUE
  130 CONTINUE
      DO 180 J = 1,N
      TRY = 6.E+35
      DO 160 I = 1,N
      IF ( CCP(I) .GE. TRY )  GO TO 160
      TRY = CCP(I)
      IMIN = I
C     IMIN INDEXES UNIT TO DROP FROM PAST SAMPLE CLUSTER
  160 CONTINUE
      P = CCP(IMIN) - SP
      SP = CCP(IMIN)
      CCP(IMIN) = 8.E+35
      XBAR = SX/FNS - SEL
      TSS = TSS + P*XBAR*XBAR
      TS = TS + P*XBAR
      TP = TP - P*P
  180 SX = SX + CP(IMIN) + CP(IMIN+2) - 2.0*CP(IMIN+1)
      TS = TSS - TS*TS
      RETURN
      END
```

APPENDIX II

Calling Program Example

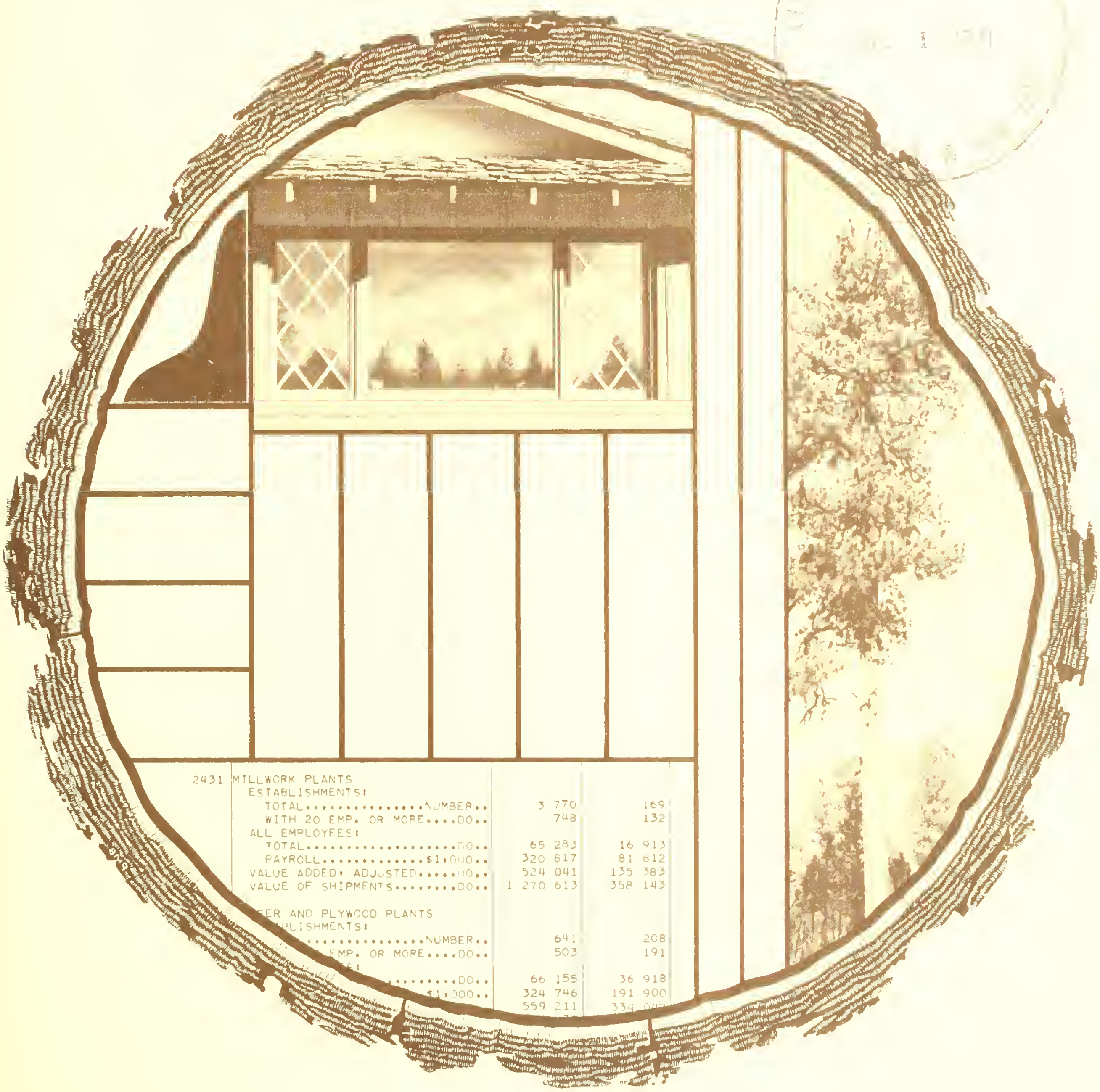
```
      DIMENSION    PP(20),IDSAM(20),ID(200),CHAR(200)
      KR = -328609067
      LR = 1409859205
      MR = 402656419
      WRITE (6,906)
  906 FORMAT(1H1)
   10 READ(5,908,END=200)NP,NSAM
  908 FORMAT(3I5)
   12 READ (5,909) (ID(I),CHAR(I),I=1,NP)
  909 FORMAT(I5,F10.5)
      WRITE (6,904) NSAM, ( ID(I),CHAR(I),I=1,NP)
  904 FORMAT(///14X,'POPULATION'//1H 8X,'ID',11X,'EST. SIZE'6X,'NO. OF U
     1NITS TO BE'/40X,'MEASURED =',I5/(I11,F20.5))
   20 CALL PPSORT(NP,ID,CHAR,NSAM,IDSAM,PP,TX,TS,TP,NRS,N,LR,MR,KR)
      IF ( NSAM .GT. NP) NSAM = NP
      WRITE (6,907) N,NRS,TX,TS,TP,(IDSAM(I),PP(I),I=1,NSAM)
  907 FORMAT(46X'SAMPLES DRAWN'//40X'( NO. IN STRATUM =',I5,')'/40X,
     1'( NO. OF SAMPLES =',I5,')'/40X,'( TX   =',E16.7,')'/40X,'( TS   =',
     2 E16.7,')'/40X,'( TP   =',E16.7,')',//45X,'ID',2X,'PROBABILITY'//
     3 (42X,I5,E15.7))
      READ (5,908,END=200) NP,NSAM,NEW
      IF ( NEW .LE. 0 ) GO TO 12
      WRITE (6,910) NSAM
  910 FORMAT('0 ADDITIONAL  ',I8,'  UNITS TO BE MEASURED FROM SAME POPUL
     IATION.'//)
      GO TO 20
  200 RETURN
      END
```

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

WOOD FOR MILLWORK

ROBERT E. BENSON



USDA Forest Service Research Paper INT-89, 1971
INTERMOUNTAIN FOREST AND RANGE
EXPERIMENT STATION
Ogden, Utah 84401

AUTHOR

Robert E. Benson is Project Leader, Forest Products Marketing Research, at the Forestry Sciences Laboratory in Missoula, Montana. His career includes experience in forest and land use surveys, economic studies of timber production, and analysis of markets and marketing systems for wood products manufactured in the Rocky Mountain States.

USDA Forest Service
Research Paper INT-89
March 1971

WOOD FOR MILLWORK

ROBERT E. BENSON

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U. S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

CONTENTS

ABSTRACT

A growing demand for millwork products is anticipated in light of the projected levels of residential construction. The millwork industry appears to have the manufacturing and marketing capacity to meet this need, but there is some uncertainty about the availability of lumber suitable for millwork manufacture. The use of a wide range of species and grades of lumber might help increase the supply of lumber suitable for millwork products. However, more information is needed on the technical and economic requirements for wood used in millwork, and also about the amount and availability of timber that is potentially suited to produce lumber for millwork products.

INTRODUCTION

The wood industry faces a tremendous challenge in this decade - that of providing, in part, materials for 2.6 million new and rehabilitated residential housing units per year, to meet the acute housing needs of the nation. The bright prospect of this much building activity, assuring strong markets for building materials and skills, is dimmed by the threat of a shortage of wood products in the immediate future.

After several years of reasonably stable prices and markets, the wood industry was buffeted in 1966 and 1967 by a severe slump in homebuilding followed by the expectation of a boom in building and other wood use. The combination of real and threatened shortages of wood sent prices skyrocketing to alarming levels in 1969, and resulted in congressional hearings, legislation affecting log exports and timber harvest, and administrative directives curtailing federal purchase of wood materials. Although the demand and prices for wood products have since dropped, the public as well as key people in government, the housing industry and the wood industry are taking one of the hardest looks ever at the future, and at the spectre of more wild price gyrations induced by a heavy demand for wood and a short supply. The prognostication of some is that a supply-demand gap will persist throughout the next decade and that substitutes for wood must be developed to meet construction needs.[1]

The purpose of this paper is to appraise the supply and anticipated demand for wood used in millwork. If supply could be measured in board feet of timber, the analysis would be simple in concept, if not in compilation. However, trees standing in the forest are only potential supply. Converting trees into windows, doors, moldings and other millwork items depends upon decisions and capabilities of forest managers, primary processors, and secondary manufacturers. Likewise, the demand for millwork depends on such factors as level of building activity, homeowners' preferences, and the ability of millwork to compete in the market.

---

[1]*Robert P. Mayo, former Director, Bureau of the Budget, in a speech to the National Forest Products Association Meeting, Boca Raton, Fla., Nov., 11, 1969, cited the need for satisfactory substitutes to supplement softwood supplies. The report of the Cabinet Committee on Economic Policy, Task Force on Softwood Lumber and Plywood, released by President Nixon on June 19, 1970, directed the Secretary of Housing and Urban Development in cooperation with the Secretaries of Agriculture and Commerce to continue programs to develop and utilize substitute materials.*

MILLWORK IN THE MARKET

The demand for wood in millwork products depends primarily on the amount of construction activity in the country. New residential construction creates the largest segment of the millwork market, but new nonresidential construction and upkeep and improvements also consume a sizable amount of wood in millwork.

Volume used in millwork and trim, 1969

Activity	Lumber (million board ft.)	Plywood (million sq. ft., 3/8-inch)
New residential	1,943.9	983.0
New nonresidential	58.2	87.5
Residential upkeep and improvement	433.2	192.0
Nonresidential upkeep and improvement	230.0	98.0
All construction	2,665.3	1,360.5

The total amount of millwork products[2] used has tripled during the past two decades. The rate of growth in demand for millwork products and the pattern of yearly fluctuations have been about the same as the growth rate and fluctuation pattern for new residential construction activity (fig. 1).

Of course, millwork includes many different products and growth in demand has not been equal among all. For example, the output of flush doors increased rapidly from 1954 to 1963, while window sash output and the output of panel doors declined in that period. However, some of these trends have since been reversed, according to the most recent (1967) census of manufacture (fig. 2).

A major factor behind market trends has been the impact of nonwood materials, particularly metal windows and screens, and screen doors, on millwork markets (fig. 3). Aluminum windows became increasingly popular beginning in the 1950's; currently the window market is about equally divided between wood and aluminum. Wood kitchen cabinets now hold a major share of the market, but metal screen and storm doors remain strong competitors for wooden screen and storm doors.

Homebuyers have a considerable influence on millwork markets. Although builders almost always make the selection and purchase of millwork (2)[3], they frequently offer buyers a choice of materials and styles, and basically use materials homebuyers in the area will accept.

Recent studies have attempted to explain market preferences for millwork and related finishing products. These studies indicate that choices and preferences often reflect a rather complex interaction among several key factors.

---

[2] *Based on the value of shipments.*

[3] *Numbers in parentheses refer to References at the end of this paper.*

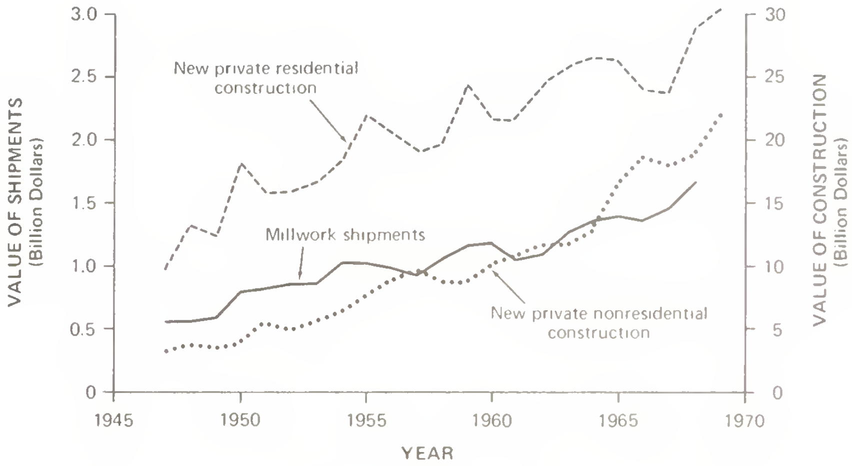
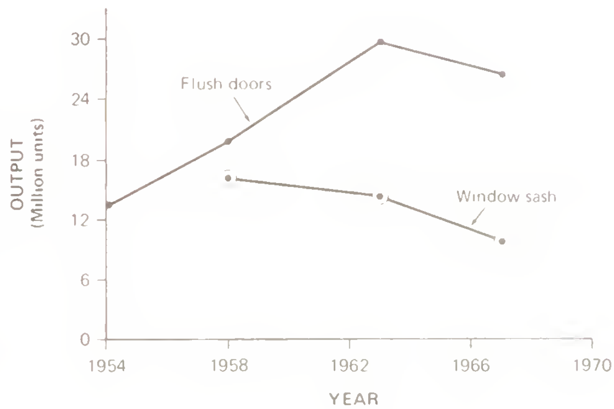


Figure 1 — Value of millwork shipments and construction.

For example, image, appearance, and esthetic appeal are considered highly important. One study showed homeowners considered genuine hardwood wall paneling "luxurious" and "rich," but viewed hardboard paneling with wood grain printed on as imitation (5). On the other hand, there has been a recent trend toward more elaborate panel type doors, particularly for front entrances. However, many of these doors are made from metal, molded wood fiber, or other material rather than lumber.

Utilitarian and cost considerations often modify the esthetic and prestige factors when a builder decides whether wood or some other material should be used in construction. Wood windows are considered to have a prestigious image and to lend an authentic appearance, especially to traditional style homes. However, aluminum windows predominate in some areas because homeowners want to avoid the repainting or other maintenance and performance problems (3). Builders report that aluminum windows are installed in some houses because their purchase price is lower than that of wood windows and the total installed cost is often 30 to 40 percent less because they require no painting.

Other critical factors in the market outlook for millwork are future trends in style of living and the development of new construction



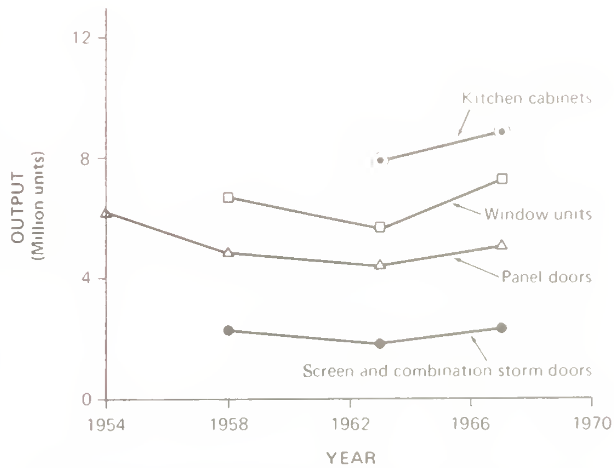


Figure 2 — Output of selected millwork products (Source: Census of Manufacture).

techniques. The current trend in living style has been toward urbanization and apartment living. If this trend continues, the demand for millwork could be reduced because apartment buildings use less millwork than single-family houses. Future construction techniques may be influenced by experiments now being conducted with new building materials. There are numerous experimental houses in which wood products have been replaced by metal, concrete, brick, paper, and other nonwood materials. Several of the "assembly line" houses tested under federal programs to stimulate construction of low-cost housing use little or no wood.

The uncertainties of these factors — preferences, construction types, and style of housing — make it impossible to predict exactly how much lumber will be needed for millwork in the long run. In the immediate future, however, it appears that the demand for wood will grow. The national housing goals that have been adopted reflect a strong potential market; recent trends indicate most millwork products will maintain their share of this market. Consumers generally have a favorable attitude toward millwork products, provided these products can give satisfactory performance and are reasonably competitive in cost with nonwood products.

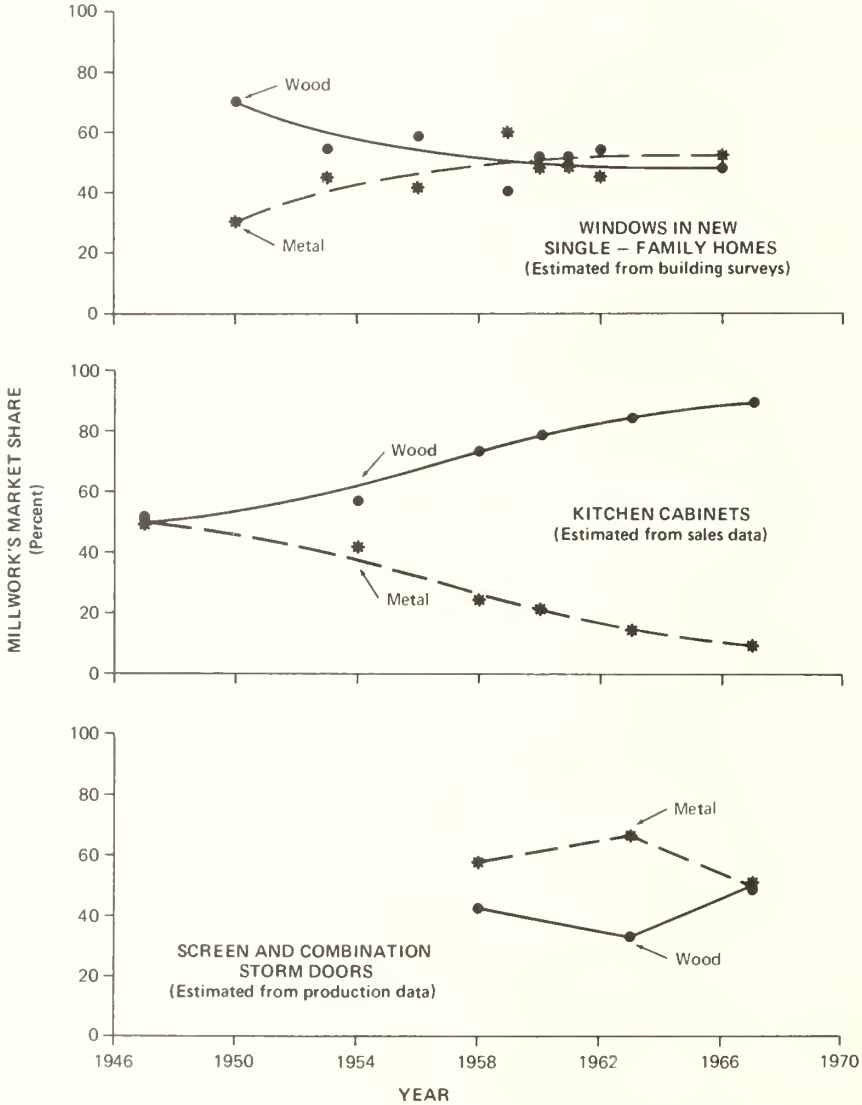


Figure 3 — Millwork's share of market, selected products.

WOOD USE IN MILLWORK

Nearly 2½ billion board feet or equivalent of wood was used for millwork products in 1965 — most of which was softwood lumber (fig. 4). However, the amount of hardwood lumber and such forms of wood as plywood and hardboard accounted for over 25 percent of the wood used for millwork in 1965, compared to 10 percent in 1940. Ponderosa pine and Douglas-fir are the principal softwood lumber species used. The early millwork industry developed around eastern white pine, and later used substantial amounts of southern pine, but western species, particularly ponderosa pine and Douglas-fir, now dominate (6).

A high proportion of the ponderosa pine and Douglas-fir lumber used in millwork is upper-grade lumber. This proportion has increased, according to the following percentile tabulation:

	Ponderosa pine		Douglas-fir	
	1960	1965	1960	1965
High (select and better)	30	47	56	72
Medium (shop, 1 and 2 common)	55	45	31	22
Low (3 common or lower)	15	8	13	6

(Source: Wood used in manufacturing industries, 1965. USDA Forest Serv. Stat. Bull. 440.)

Figure 4 — Wood used in millwork manufacture, selected years. (Source: Wood used in manufacturing industries, USDA Forest Service Statistical Bulletins 353 and 440.)

Recent lumber price trends have been of real concern to the millwork industry. From a fairly stable level in the early and mid-1960's, the price of shop- and select-grade pine and fir nearly doubled during 1968 and 1969. Even when the effect of general inflation in the economy is taken into account, the real price of softwood lumber was 70 percent higher in 1969 than in 1965. Although prices of shop-grade lumber have dropped, they are higher than in 1967, and the prices of select grades have remained high (fig. 5). Estimating material costs and establishing prices for products is difficult when lumber prices change this rapidly. Furthermore, such price gyrations are symptomatic of shortages and uncertainty about lumber supplies which in turn hampers orderly planning of lumber purchases and millwork production.

One potential solution to wood supply and price problems is to shift to alternate materials. As noted earlier, there has been a substantial increase in plywood and hardboard use for some millwork products. One study estimates that half the wood moldings used are finger jointed, and overlain moldings have also had some success in the market (9). However, in items such as windows, doors, door jambs, and louvered panels there has been little substitution for regular lumber (not finger jointed or overlain). Structural requirements, appearance, reluctance of the buyers to accept substitutes, and high costs are the principal reasons why alternate materials have not been more widely used for these products.

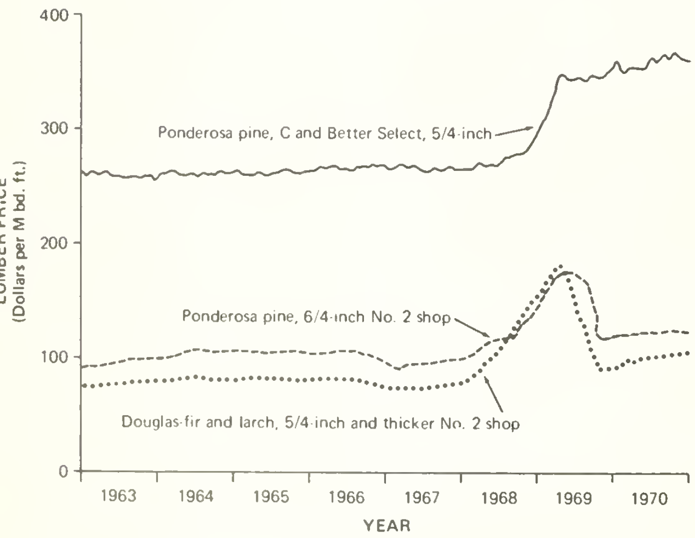


Figure 5 — Wholesale lumber price (WWPA weekly price summary).

Another potential solution would be to use a wider range of species and grades in millwork. Most western softwoods are allowed in millwork products under current industrial and commercial standards, but only a few species are used to any great extent. Ponderosa pine and Douglas-fir account for 63 percent of all lumber used in millwork; in some products, ponderosa pine is used almost exclusively. Specific data on the texture of lumber used in millwork are not available, but in practice fine-textured old-growth material is usually used (8).

A recent survey of millwork manufacturers dealt with the use or testing of 24 different species as alternates to ponderosa pine.[4] Almost half of these were considered technically suitable by the majority of those who tried them. However, many users indicated that ponderosa pine is still their preferred species. Some technical shortcomings were reported for different species, but it appeared from this survey that two other problems may be of greater consequence. First, there are some uncertainties about the basic physical properties and the availability of alternate species, and the changes in manufacturing procedures that would be required if they could be adapted. Second, there appears to be some resistance to alternate species on the part of the manufacturers' customers; this was reported even for some species that were highly suitable technically.

Therefore, it appears that the potential for using alternate species and grades cannot be evaluated until more information is developed on their characteristics and also on the criteria they must meet to be technically and economically feasible for millwork use. Standard grades provide a basis for lumber purchases and provide a general idea of the quality of wood currently used, but comprehensive data on how well lesser known species would work, the specific technical criteria they must meet, and the economics of their use have not been compiled.

---

[4] *National Woodwork Manufacturers Association survey of members, 1970. Unpublished.*

THE SUPPLY OF LUMBER AND TIMBER FOR MILLWORK

Most millwork manufacturers purchase their lumber in the lumber market: therefore, their supply of materials is dependent on the conditions and activities in the sawmill industry.[5]

In recent years, a notable change in the output of pine lumber products has occurred. Total pine lumber production increased from about 3.2 billion feet in 1960 to 3.7 billion feet in 1965, but it has remained about constant since then. The output of select grades of pine has also remained about constant since 1965, but the output of shop-grade pine has grown substantially.

Percent of total pine lumber

Year	Shop	Select
1959	20.8	14.7
1964	20.4	12.1
1965	23.4	14.2
1966	25.2	11.9
1967	27.3	11.9
1968	26.7	12.1
1969	27.2	11.9
1970	29.7	11.8

(Source: Estimated from Western Wood Products Association weekly price summary of past sales, Inland region.)

The decline in use of common boards coupled with the recent high prices demanded for shop-grade lumber provided an incentive for sawmills to produce more shop lumber. There may be some potential for this increase to continue. Only about half the sawmills in the West are producing shop lumber (1, 4), in part because not all mills are set up to do the more costly sawing, finishing, drying, and inventorying this grade of lumber requires. Periodic high prices for easier-to-produce dimension lumber and boards give less incentive to produce shop-grade lumber. Also, there is reportedly a shortage of qualified shop lumber graders. If these factors can be resolved, shop lumber output might increase, but just how much is not certain.

The question of lumber supplies for millwork ultimately depends upon the amount of suitable timber available. Forest inventory data are not refined enough to estimate the volume of wood suitable for millwork that is standing in the forest. Future supplies are also uncertain because wood quality may depend on management measures not yet undertaken and utilization methods not yet developed. The clear fine textured wood currently preferred in millwork manufacture comes primarily from large diameter old-growth trees (8). At present rates of cut, the harvest of these larger trees will diminish by about 50 percent in the next 30 years (fig. 6).

The actual amount of wood used in millwork need not and probably will not decline by 50 percent, if (a) wood in nonlumber form continues to increase in millwork use, and (b) other species can be adapted. For example, in the inland area of the West[6] only a small proportion of species other than ponderosa pine are now being manufactured into select and shop grades:

Percent of sales, 1969

Species	Select	Shop
Ponderosa pine	11.9	27.2
Western white pine	7.8	3.3
White fir	.6	7.2
Douglas-fir — larch	6.9	4.6
Engelmann spruce	2.7	0
Western redcedar	5.7	.3

(Source: WWPA weekly price summary of past sales, Inland region.)

[5] *Some millwork manufacturers have integrated subsidiary sawmill operators.*

[6] *The States and portions of States lying east of the Cascade Range to the Great Plains.*

The extent to which these other species could be used for millwork products depends on the two factors discussed earlier — their adaptability in millwork products and the feasibility of sawmills sawing them into shop grades or for millwork use. Only when these criteria are available will it be possible to evaluate the quality and availability of current stands in terms of millwork use.

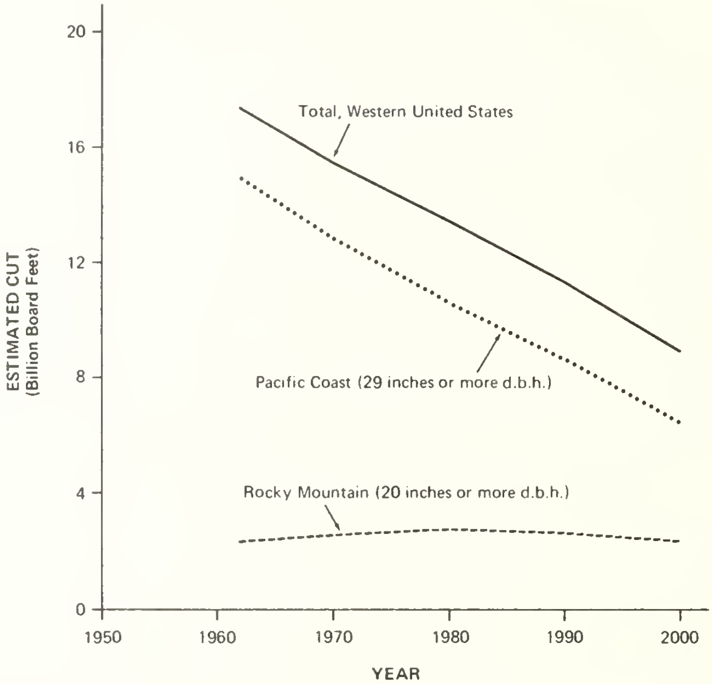


Figure 6 — Projected cut of large diameter trees in the West.

CONCLUSIONS

In a recent editorial, Hal D. Mayhew, editor of Crows Forest Products Digest, commented:

> *The wood window industry has not regained all the ground it had lost to aluminum, but with the present supply situation for raw materials it is obvious that it could not meet the demand if the market was entirely regained.*
> *. . . the price and availability of the raw material are taking on a completely different complexion.*
> *. . . millwork manufactures . . . must now wonder whether this industry can supply . . . two million housing starts per year . . . (7).*

The projected demand and the anticipated supply of softwood lumber for use in millwork seem to substantiate these comments, even though there are too many unknowns to make a very precise quantitative expression of the situation.

The residential and other construction that is projected for the nation assures a strong demand for millwork products. Although competing materials made a strong bid for millwork markets during the 1950's, more recent trends indicate millwork is retaining or increasing its share of the market. Productivity has improved and it appears the millwork industry is in a good position to compete in markets and to supply housing needs if raw materials are available at a price compatible with competing market situations and competing uses for wood.

The availability of raw material is more difficult to assess. Even though timber supplies are finite, there is an inventory of wood available. Consequently, millwork with its relatively high-value end products should be able to compete in the wood market. However, the economic and technological suitability of the available timber for manufacturing millwork is a major unknown that needs further research.

Projecting the total volume of timber supplies and assuming that millwork will maintain its current share of wood supplies may serve as a useful first approximation. But to make a more definitive study of the supply situation, and to develop a raw material base to supplement the type of wood currently demanded by the millwork industry, it would be desirable to:

1. Define with greater precision the technical and economic criteria that lumber must meet to be used in millwork. The technical criteria include the physical and other properties required in the finished product and in the manufacturing process. The economic criteria include such things as relative cost, quantities needed, availability, and delivery schedules required.
2. Use these criteria to evaluate the technical suitability of alternate wood species, and to estimate the quality (grades and textures) of lumber that would be most common in future second-growth ponderosa pine and Douglas-fir, the species usually used for millwork products.
3. Evaluate the potential for increasing the output of shop lumber from sawmills; if it is substantial, identify the changes in structure or practices needed to develop this potential.
4. Use technical, economic, and operational criteria derived from the above to refine the timber resource data so as to have a better picture of the current and future raw material supply of wood suitable for millwork lumber.

REFERENCES

1. Anonymous.
   1965. Study tells what is happening to softwood lumber clears. Forest Ind. December: 36-42.

2. Anonymous.
   1966. The homebuilding market, its characteristics and buying practices. Sweets Construction Catalog Services, F. W. Dodge Co. New York: McGraw-Hill.

3. Benson, Robert E.
   1968. Factors that affect the single family home market for wood windows. USDA Forest Serv. Res. Pap. INT-55, 13 p., illus.

4. Brown, Lloyd.
   1968. Let's talk shop. Crows Forest Products Digest. September: 16-17.

5. Evans, Richard.
   1966. Homeowner selection and preference of building materials in residential construction. 109 p. Mimeo report on file at USDA Forest Serv., Intermountain Forest and Range Exp. Sta., Odgen, Utah.

6. Lloyd, William B.
   1966. Millwork, principles and practices. 426 p. Chicago, Ill.: Cahners Pub. Co. and National Woodwork Mfg. Assoc., Inc.

7. Mayhew, H. D.
   1968. The changing world of millwork. Crows Forest Products Digest. September: Editorial page.

8. National Woodwork Manufacturers Association.
   1969. Statement concerning the Short Supply of Lumber for Millwork Products to Senate Committee on Banking and Currency Subcommittee on Housing and Urban Affairs. 2 p. Wash. D.C. (March 20).

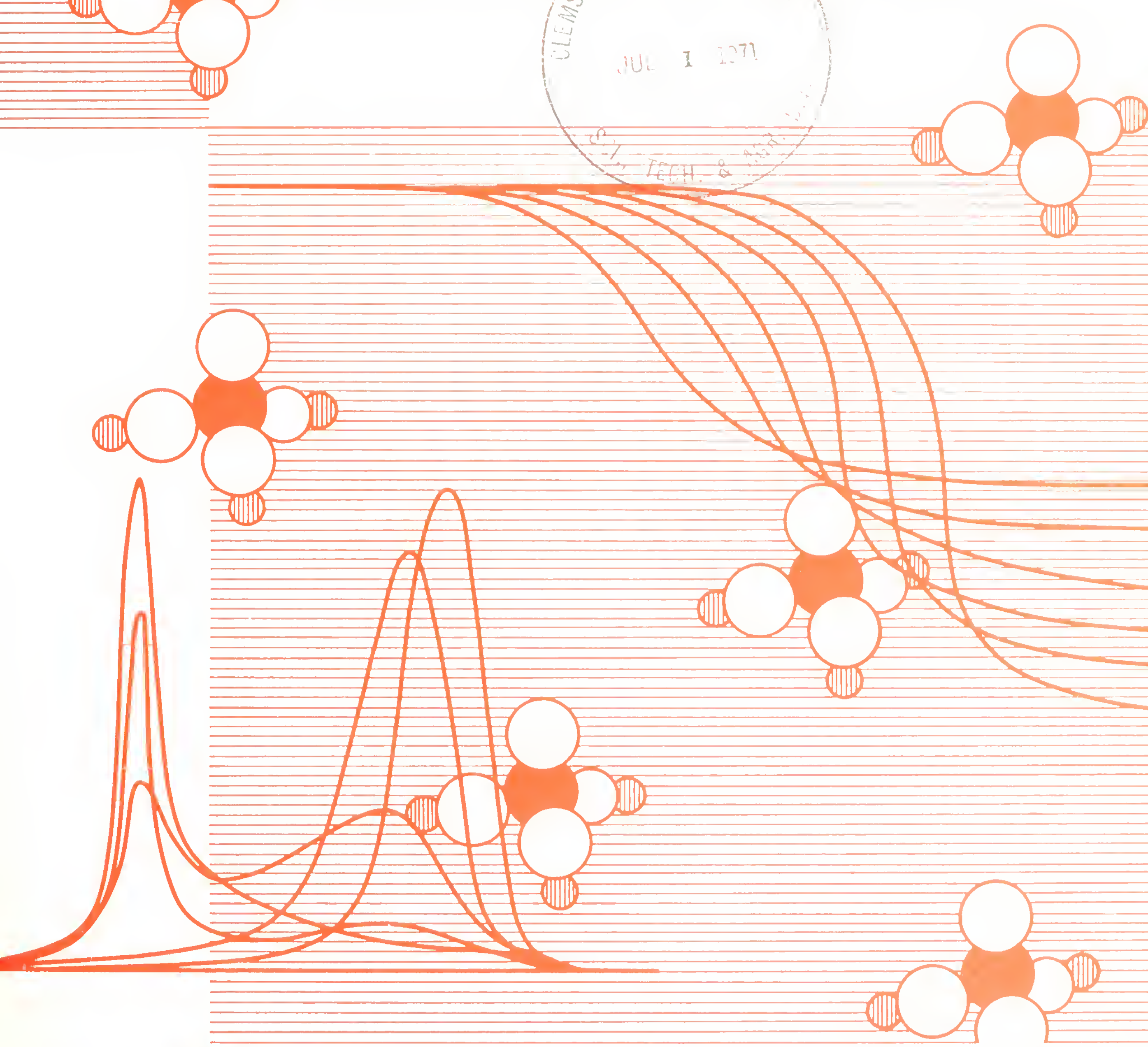
9. Seymour Kroll and Associates.
   1968. A study of the marketability of overlaid lumber products. 90 p. USDA Forest Serv., Rocky Mountain Forest and Range Exp. Sta., Fort Collins, Colo.

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

Effects of Ammonium Phosphate And Sulfate On The Pyrolysis And Combustion Of Cellulose

CHARLES W. GEORGE AND RONALD A. SUSOTT



U S D A FOREST SERVICE
RESEARCH PAPER INT-90
1971

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
OGDEN, UTAH 84401

THE AUTHORS

CHARLES W. GEORGE was graduated from the University of Montana in 1964 in Forest Engineering. He received his master's degree at the University of Montana in 1969. In 1965, he joined the Northern Forest Fire Laboratory staff in Missoula, Montana, where he is now responsible for research dealing with forest fire retardant chemicals.

RONALD A. SUSOTT received his bachelor's degree in 1966 and his Ph.D. in 1970, both from the University of Montana in Chemistry. Since 1970, he has worked as a Research Associate at the wood chemistry laboratory, University of Montana, Missoula, Montana. He is studying the thermal analysis of model compounds.

USDA Forest Service
Research Paper INT-90
April 1971

EFFECTS OF AMMONIUM PHOSPHATE AND SULFATE ON THE PYROLYSIS AND COMBUSTION OF CELLULOSE

Charles W. George and Ronald A. Susott

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U. S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

ABSTRACT

Differential thermal, thermogravimetric, and derivative thermogravimetric analyses were used to study the effects of two important fire retardant chemicals--ammonium phosphate and ammonium sulfate--on the pyrolysis and combustion of cellulose. To aid in the interpretation of treated cellulose thermograms, the thermal behavior of the fire retardant chemicals was investigated.

An increase in the concentration of either flame retardant lowered the threshold temperature and activation energy required to initiate cellulose pyrolysis and combustion, generally decreased maximum weight loss rates, and caused an increase in the production of residue or char. Although these general similarities were found, there were distinct differences in the temperatures at which the rates changed when treated with the same quantity (on a molar fraction basis) of retardant chemical. The difference in which these chemicals alter pyrolysis and combustion is due to a difference in the availability of the inorganic fraction involved in the reaction or to a difference in the reaction mechanism, or both.

The study demonstrated that direct comparison of retardant chemicals on the basis of their thermal effects on pyrolysis and combustion at one treatment level could lead to erroneous interpretation and improper classification.

CONTENTS

(con. next page)

INTRODUCTION

For the past 10 years, ammonium phosphate $(NH_4)_2HPO_4$ and ammonium sulfate $(NH_4)_2SO_4$ have been used as primary ingredients in forest fire retardant formulations. These chemicals, when applied to forest fuels, are known to alter or inhibit thermal degradation and combustion reactions. Because of the reduced flammability of chemically treated fuels, the use of such fire retarding chemicals has become an important tool in wildfire suppression. Knowledge of the reactions or mechanisms taking place and their relation to flammability will assist in a systematic selection of fire retardant chemicals and may lead to more effective methods of application.

Recent studies performed at the Northern Forest Fire Laboratory have indicated significant differences in the effects ammonium phosphate and ammonium sulfate have on flammability as measured indirectly by such parameters as rate of spread, fire intensity, radiant energy, flame height, and residue.[1] We do not know whether these differences in effects are due to the chemicals' physical differences, a difference in their thermal decomposition and availability, or to a difference in the actual mechanism by which they alter fuel degradation.

Truax, Harrison, and Baechler (1956) noted that both compounds were effective in retarding flaming combustion, but ammonium phosphate was superior in retarding glowing combustion. Browne and Tang (1963), on the basis of thermogravimetric analyses in a nitrogen atmosphere, found that the compounds have similar effects on the volatilization of wood and the threshold temperature for pyrolysis, although a difference in their volatilization rate was exhibited. Tang (1967) in a similar study found that ammonium phosphate had the same effects as ammonium sulphate on the pyrolysis of wood and cellulose but had little effect on the volatilization rate of lignin; the cellulose portion of wood was found to have the highest volatilization rate. The volatilization rate for wood seemed to be a combination of the effects on alpha-cellulose and lignin. Tang and Eickner (1968), using differential thermal analysis, compared the effects of 2-percent by weight ammonium sulfate and a 2-percent by weight ammonium phosphate treatment on pyrolysis and combustion of wood, cellulose, and lignin. Little difference was noted in thermograms and relative maximum heat intensities and it was concluded that these parallel results probably were produced by a similar mechanism.

Past research (Shafizadeh 1968; Kilzer and Broido 1965) has indicated that combustion adds secondary and competitive reactions to initial degradation reactions. It is likely that the occurrence of flaming combustion causes cellulose as well as the retardant chemicals to undergo different reactions and at different rates. Although relationships undoubtedly exist between the pyrolysis and combustion of cellulose and the role retardant chemicals play in altering related reactions, it may not be possible to predict combustion characteristics on the basis of pyrolysis characteristics. Thermal analysis in oxygen, or in an air atmosphere, may or may not accurately represent flaming and glowing combustion.

The purpose of the study was to provide extensive thermal analysis data that could be used to categorize the effects of these retardant chemicals on the pyrolysis and combustion of cellulose.[2]

---

[1]Charles W. George and Aylmer D. Blakely. Study of the effects of diammonium phosphate and ammonium sulfate on flammability. 1968. (Unpublished report on file at the Northern Forest Fire Laboratory, USDA Forest Serv., Missoula, Montana.)

[2]For the purpose of this paper, pyrolysis is defined as the degradation of a material in an inert atmosphere or vacuum. Combustion refers to the process taking place when the initial material, as well as its degradation products, are in contact with oxygen or air.

EXPERIMENTAL PROCEDURE

The two flame retardants selected for investigation in this study were ammonium phosphate $(NH_4)_2HPO_4$ and ammonium sulfate $(NH_4)_2SO_4$. In determining the effect these additives have on the pyrolysis and combustion of cellulose, differential thermal (DTA), thermogravimetric (TGA), and derivative thermogravimetric (DTG) analyses were used.

Samples

The cellulose samples used in this experiment were prepared from high purity Munktell's chromatographic cellulose powder (smaller than 170 mesh) containing less than 0.02-percent ash. After the cellulose was dried in a desiccator over silica gel, the moisture content was determined using thermogravimetric analysis. The desired percent by weight chemical was obtained by adding a stock solution of known concentration to a previously weighed sample of the cellulose. The weight of cellulose was corrected for 2.6-percent moisture content and weight percents expressed on a dry basis. Each sample was prepared by combination of the desired chemical and cellulose (the total equaled 1 gram) and addition of 10 milliliters of distilled water. After thorough mixing, the samples were dried to approximately 2-percent moisture content in an oven at 32° C. Twenty samples between 0- and 25-percent treatment of both ammonium phosphate and ammonium sulfate were prepared. Both chemicals were analytical reagent grade. An untreated sample was prepared by adding 10 milliliters of distilled water to 1 gram of cellulose and drying as for the treated samples.

Differential Thermal Analyses

Differential thermal analysis (DTA) data were taken using a DuPont 900 Thermal Analyzer.[3] The standard temperature cell (ambient to 500° C.) was used for all treated cellulose samples. The intermediate temperature cell (ambient to 850° C.), similar to the standard cell, was used only to obtain thermograms of the inorganic compounds.

The sample of 10 (±1) milligrams was placed in macrocapillary tubes, 4 millimeters in diameter. Glass beads were used as the inert reference material. Chromel-alumel thermocouples were used to determine the differential temperature of the sample and reference material. A heating rate of 25° C. per minute was used for all analyses.

Pyrolysis of all samples was studied using nitrogen to provide the inert atmosphere. After the cell had been purged by evacuation and addition of N_2, a flow rate of 1 liter N_2 per minute was established. An atmosphere of moisture-free air was used for studying combustion. In order to increase the contact between the sample and reactive gas, a fluidizer requiring a lower flow rate (100 cubic centimeters per minute) was used for tests in air.

Thermogravimetric and Derivative Thermogravimetric Analyses

Thermogravimetric analyses (TGA) were made using the DuPont 950 Thermogravimetric Analyzer while recording weight and temperature signals on the DuPont 900. Ten-milligram samples were placed in a tared aluminum pan with a chromel-alumel thermocouple about 1 millimeter above the center of the sample to record sample temperature. The sample weight was adjusted to the 100-percent chart line following initial water loss near 150° C. so that all sample weights would be on a percent-weight-remaining and moisture-free basis.

---

[3]The use of corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official approval by the U.S. Department of Agriculture of any product to the exclusion of others which may be suitable.

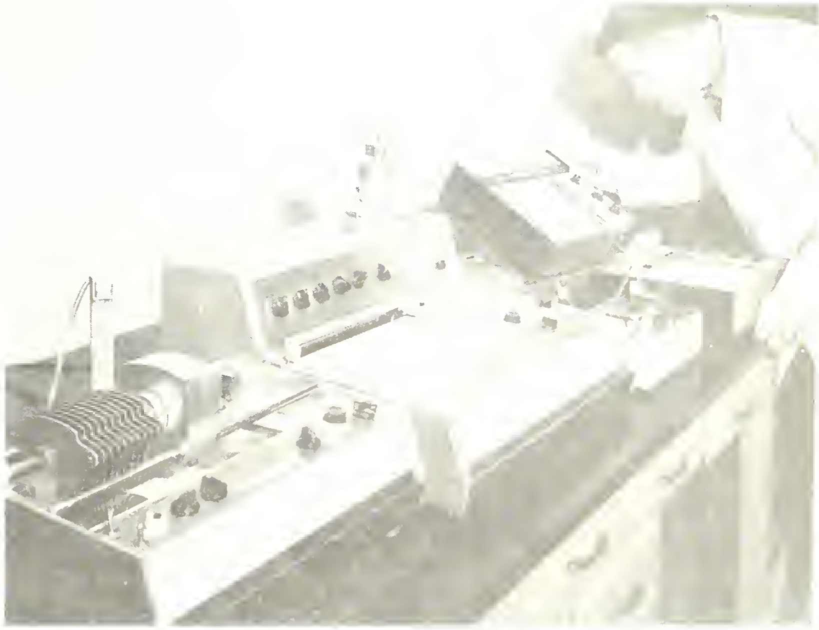


Figure 1.--Thermal analysis apparatus for obtaining DTA, TGA, and DTG thermograms.

Pyrolysis was studied in a nitrogen atmosphere at a flow rate of 100 cubic centimeters per minute. A similar flow rate of air was used in investigations of combustion. For samples pyrolyzed in nitrogen, the percent of weight remaining as a function of sample temperature was monitored. For combustion analysis, an alternate method of recording data was needed due to the highly exothermic character of the reaction. The oven temperature and sample temperature were monitored for several blank runs using a Moseley Autograf 7100B two-pen strip-chart recorder. After correlating the two readings, the percent of weight remaining as a function of sample environment temperature could be calculated. In this way, decomposition in nitrogen and air could be compared in terms of similar environmental temperatures instead of sample temperatures. Endotherms and exotherms in N_2 had a negligible effect making sample and sample environment temperature essentially equivalent.)

Derivative thermogravimetric analyses (DTG) were obtained simultaneously with TGA by differentiating the mass signal from the DuPont 950 using a Cahn 2030 Time Derivative Computer.[4] Calibration was accomplished using a constant weight loss rate, provided by a Knudsen diffusion cell containing a 50 μl sample of 95 percent ethanol. The Knudsen cell was placed in the furnace at 40° C. and TGA-DTG curves recorded. The Moseley two-pen recorder was used to record both the DTG curves and sample or sample environment temperature so a comparison of rate of weight loss and temperature could be made.

The apparatus used for obtaining DTA, TGA, and DTG data is shown in figure 1.

---

[4]This derivative computer provided a noisefree response that was not significantly different in time to the weight loss response.

RESULTS

Thermal Behavior of $(NH_4)_2HPO_4$ and $(NH_4)_2SO_4$

An understanding of the thermal behavior of flame retardants will assist in interpretation of the effects they have on the pyrolysis and combustion of cellulose. A and B, page 11, show DTA and TGA thermograms of $(NH_4)_2HPO_4$ and $(NH_4)_2SO_4$ in an atmosphere of air. No significant change in their thermal behavior in nitrogen was found. Changes in the heating rate (between 5° and 30° C. per minute) and gas flow rate (50 to 150 cubic centimeters per minute) caused minor shifts in the thermograms.

The small endotherm at 166° C. in the thermogram for $(NH_4)_2HPO_4$ is caused by decomposition and partial conversion to $NH_4H_2PO_4$. The second endotherm at 190° C. is produced by melting of the $NH_4H_2PO_4$. TGA curves indicate about 13 percent weight loss by 185° C. and is noted by a slight plateau. This weight loss corresponds closely to loss of the first mole of NH_3. A nearly linear weight loss of the remaining sample (equivalent to $NH_4H_2PO_4$) is observed up to 550° C. where the remaining sample is rapidly volatilized. Weight loss following loss of the first mole NH_3 indicates a complex decomposition consisting of more products than simply NH_3 and H_3PO_4 and probably accounts for the difference in melting point between $NH_4H_2PO_4$ and $(NH_4)_2HPO_4$. It is likely that polymerization of the phosphate occurs with formation of water:

$$2H_3PO_4 \xrightarrow{> 190^\circ \text{ C.}} H_2O + H_4P_2O_7$$

and

$$H_4P_2O_7 \longrightarrow 2H_2O + P_2O_5$$

Although the temperatures at which these reactions occur depend on sample size, configuration, etc., the general reaction equations are in agreement with equations given by Van Wazer (1958, p. 503) and Tang and Eickner (1968).

Thermal analysis of monoammonium phosphate helped substantiate these possibilities. DTA of $NH_4H_2PO_4$ shows melting and decomposition to begin at 190° C. (A, page 11). The TGA curve was identical to the TGA curve for $(NH_4)_2HPO_4$ after loss of its first mole of NH_3.

In $(NH_4)_2SO_4$, the only endotherm occurs at 360° C. and is due to melting and decomposition. The TGA curve shows initiation of weight loss near 225° C. with the rate being nearly constant until 350° C. where rapid decomposition begins. The weight loss at this point (20 percent) is less than necessary for loss of the two moles NH_3. This can be explained by the likely simultaneous decomposition of $(NH_4)_2SO_4$ and H_2SO_4, a possible initial product in addition to NH_3. The absence of the peak in the DTA curve near 225° C. indicates either the NH_3 is weakly associated or the heat exchange at this point is very small in comparison to the large endotherm at 360° C.

Differential Thermal Analyses

DTA thermograms for the pyrolysis of cellulose at several treatment levels of ammonium phosphate and sulfate on cellulose are shown on page 12; those leading to combustion are shown on page 13. The peak temperatures of primary endotherms and exotherms for pyrolysis and combustion are given in tables 1 and 2.

A major difference in thermograms for the pyrolysis of the two cellulose treatments is indicated. As $(NH_4)_2HPO_4$ is added to cellulose and pyrolyzed in nitrogen (page 12), the strong endotherm at 364° C. in untreated cellulose gradually shifts to lower temperatures. However, as the $(NH_4)_2SO_4$ concentration is increased to 0.50 percent, a new endotherm appears near 250° C.; this endotherm dominates the DTA curves at higher concentrations. The endotherm near 210° C. for $(NH_4)_2HPO_4$ treatments of cellulose greater than 4.00 percent is attributed to the inorganic fraction. Monoammonium phosphate $NH_4H_2PO_4$, which could be formed as the sample was dried, has an endotherm near 210° C. (A, page 11). An endotherm due to the presence of $(NH_4)_2SO_4$ is not readily discernible.

The DTA thermograms for combustion in air (page 13) of both $(NH_4)_2HPO_4$ and $(NH_4)_2SO_4$ treated cellulose are dominated by a strong exotherm from about 300° to 450° C. The endotherm near 250° C. for $(NH_4)_2SO_4$ treated samples is apparent at a concentration of 0.70 percent, and above, but is small compared to the latter exotherm. A prominent difference between the effects of the two chemicals on the combustion of cellulose is that $(NH_4)_2SO_4$ causes a larger exotherm (note the difference in the ΔT scale used, pages 12 and 13).

Thermogravimetric and Derivative Thermogravimetric Analyses

The cellulose samples, treated with $(NH_4)_2HPO_4$ and $(NH_4)_2SO_4$ in concentrations from 0 to 25 percent by weight were investigated for thermal behavior in air and nitrogen by TGA and DTG. After initial water loss and setting of sample weight to 100 percent, the TGA curves are horizontal until pyrolysis (pages 14, 15) and combustion (pages 16,17) begin. As the chemical percent is increased, there is a lowering of the pyrolysis and combustion threshold temperature. The threshold temperature was determined using the DTG curves and arbitrarily denoted as the temperature required to produce a weight loss rate of 0.09 milligram per minute (~1 percent of the maximum weight loss rate). Table 3 shows the effect of amount of $(NH_4)_2HPO_4$ and $(NH_4)_2SO_4$ on the threshold temperature for pyrolysis and combustion. The slight difference (8° C.) in the threshold temperatures for untreated cellulose in nitrogen and air is probably due to the difference in procedures for obtaining the environmental temperature in nitrogen and air. The lowering of threshold temperatures for treated fuels in air and nitrogen is also accompanied by a lowering of the temperature at which the maximum weight loss or reaction rate is observed. The temperature of the maximum weight loss was equally useful in comparing the effect of the different chemical concentrations.

Although the trends in TGA curves appear very similar for both chemicals, the DTG curves (pages 18, 19, 20, 21) which were run simultaneously with TGA, were much more sensitive to small differences in weight loss rates. These DTG curves, as well as the TGA curves, were very reproducible. In both air and nitrogen, the DTG curves show $(NH_4)_2SO_4$ treatment causes a rate of weight loss peak at about 250° C. In nitrogen, treatments as low as 0.500 percent cause this peak; in air, 1.00-percent treatments have the same effect. The curves for $(NH_4)_2HPO_4$ show a much more gradual shift of the peak to lower temperatures, with a peak at 250° C. developing only with high (greater than 10.0 percent) concentrations of chemical. Tables 4, 5, 6, and 7 give data for the rate of weight loss for peaks in the DTG curves and the temperature at which those peaks occur. Although numerical data are useful for comparison purposes, viewing the entire DTG thermograms (pages 18-21) provides a better picture of reaction differences.

The rate was normalized to correct for decreasing initial cellulose weights with increasing chemical treatment. The normalized rate was determined by:

$$\text{Normalized peak rate (mg. per minute)} = \frac{\text{Actual peak rate (mg. per minute)}}{\text{Fraction of cellulose in sample}}$$

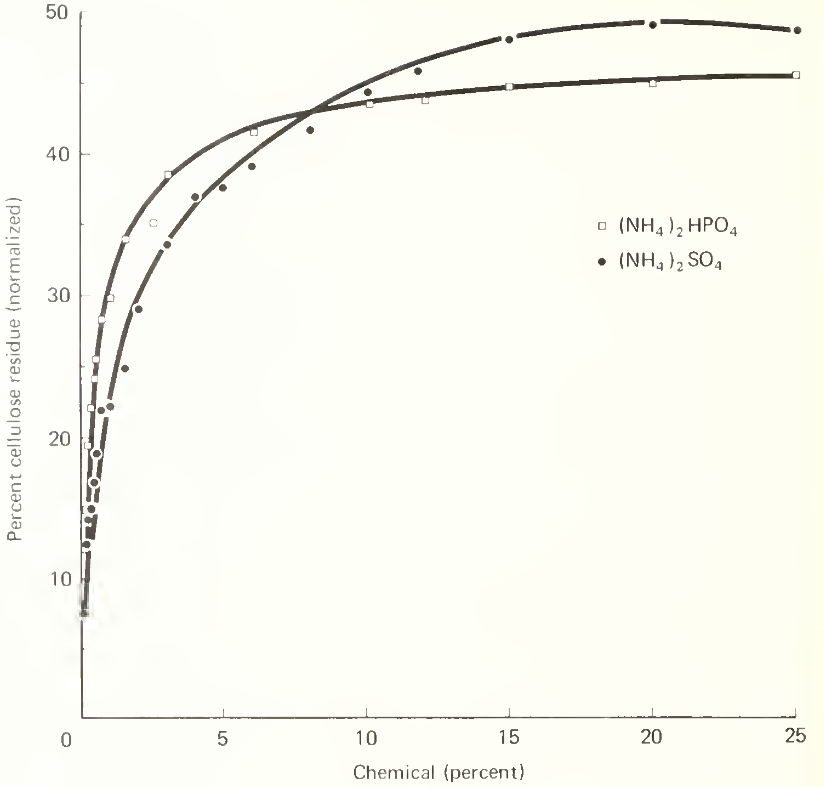


Figure 2.--Effect of $(NH_4)_2HPO_4$ and $(NH_4)_2SO_4$ on cellulose residue at 450° C. following pyrolysis.

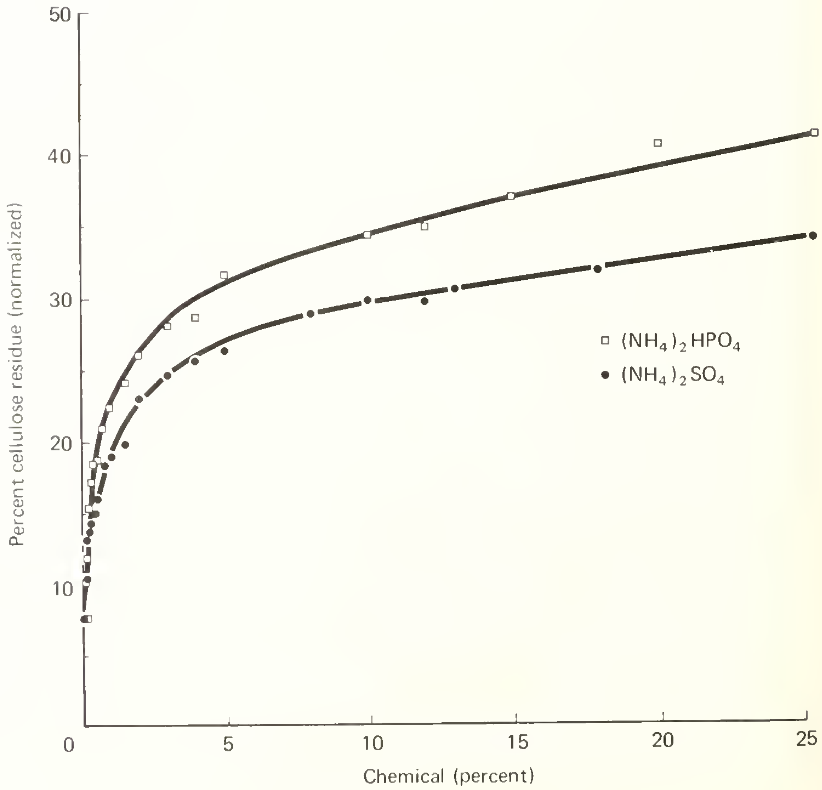


Figure 3.--Effect of $(NH_4)_2HPO_4$ and $(NH_4)_2SO_4$ on cellulose residue at 450° C. following combustion.

An increase in the percent by weight chemical usually was accompanied by a decrease in the peak rate of weight loss. However, cellulose treated with 0.050 percent $(NH_4)_2HPO_4$ caused an increase over untreated in the maximum peak rate of weight loss during pyrolysis (page 18). The only other peak rates which exceeded untreated occurred at the low temperature peak (250° C.) with higher levels of $(NH_4)_2SO_4$ treated cellulose during pyrolysis. The maximum rate of weight loss for the low temperature peak increased with percent by weight chemical until a 10-percent treatment was reached. The rate decreased at treatment levels above 10 percent (page 19). The DTG curves for each particular chemical are quite similar for nitrogen and air except that rates of weight loss are somewhat higher in air.

Tables 4 through 7 also give data taken from TGA curves showing the effect of $(NH_4)_2HPO_4$ and $(NH_4)_2SO_4$ on residue at 450° C. in both nitrogen and air. Cellulose residue can be estimated if the amount of inorganic chemical remaining at 450° C. is known. The TGA curves, shown on page 11, for the two chemicals indicate a 100-percent weight loss for $(NH_4)_2SO_4$ and 37-percent weight loss for $(NH_4)_2HPO_4$. Assuming the inorganic chemicals decompose the same whether cellulose is present or not, the normalized cellulose residue can be determined:

Normalized cellulose residue at 450° C. (percent) =

$$\frac{\text{Percent residue - (percent chemical residue} \times \text{fraction chemical treatment)}}{\text{Fraction cellulose in sample}}$$

The effect of $(NH_4)_2HPO_4$ and $(NH_4)_2SO_4$ on cellulose residue after pyrolysis and combustion is shown in figures 2 and 3. As the chemical is increased (percent by weight), both chemicals increase residue at 450° C. In air and at the lower concentrations in nitrogen, $(NH_4)_2HPO_4$ causes a greater increase in residue than $(NH_4)_2SO_4$. The rate of volatilization of residue at 450° C. is less for $(NH_4)_2HPO_4$ treatments and the temperature required for its complete volatilization is higher (compare pages 16 and 17).

COMPARISON OF METHODS AND RESULTS

Comparison of DTA, TGA, and DTG curves for cellulose pyrolysis and combustion and cellulose treated with various concentrations of $(NH_4)_2HPO_4$ and $(NH_4)_2SO_4$ shows reasonable agreement for each method. Small endothermic and exothermic reactions made determination of maximum rate temperatures impossible in TGA. The use of DTG provided information not otherwise obtainable and its sensitivity greatly added to ease of interpretation.

When cellulose is treated with $(NH_4)_2HPO_4$ and this retardant is increased between 0 and 25 percent, the following temperatures are lowered: the threshold temperatures for pyrolysis and combustion (table 3); the temperature of maximum rate of weight loss (tables 4 and 6); the temperature of the major pyrolysis endotherm (table 1); the temperature of the combustion exotherm (table 1). This increase in retardant exponentially increases the amount of cellulose residue (tables 4 and 6). Similar trends are observable in $(NH_4)_2SO_4$ treatments; furthermore, the effects of this retardant are usually more pronounced for lower treatment levels than for $(NH_4)_2HPO_4$ treatments. For example, a treatment of 0.0500 percent $(NH_4)_2SO_4$ lowers the threshold temperature for pyrolysis 33° C. while the same treatment of $(NH_4)_2HPO_4$ lowers it only 4° C. Though similar comparisons can be made for other treatments of less than 1.00 percent, treatments from 1.50 to 25 percent result in nearly the same threshold temperature for both $(NH_4)_2HPO_4$ and $(NH_4)_2SO_4$ (table 3).

The differences in chemicals and similarities in analysis methods are graphically depicted in figure 4.

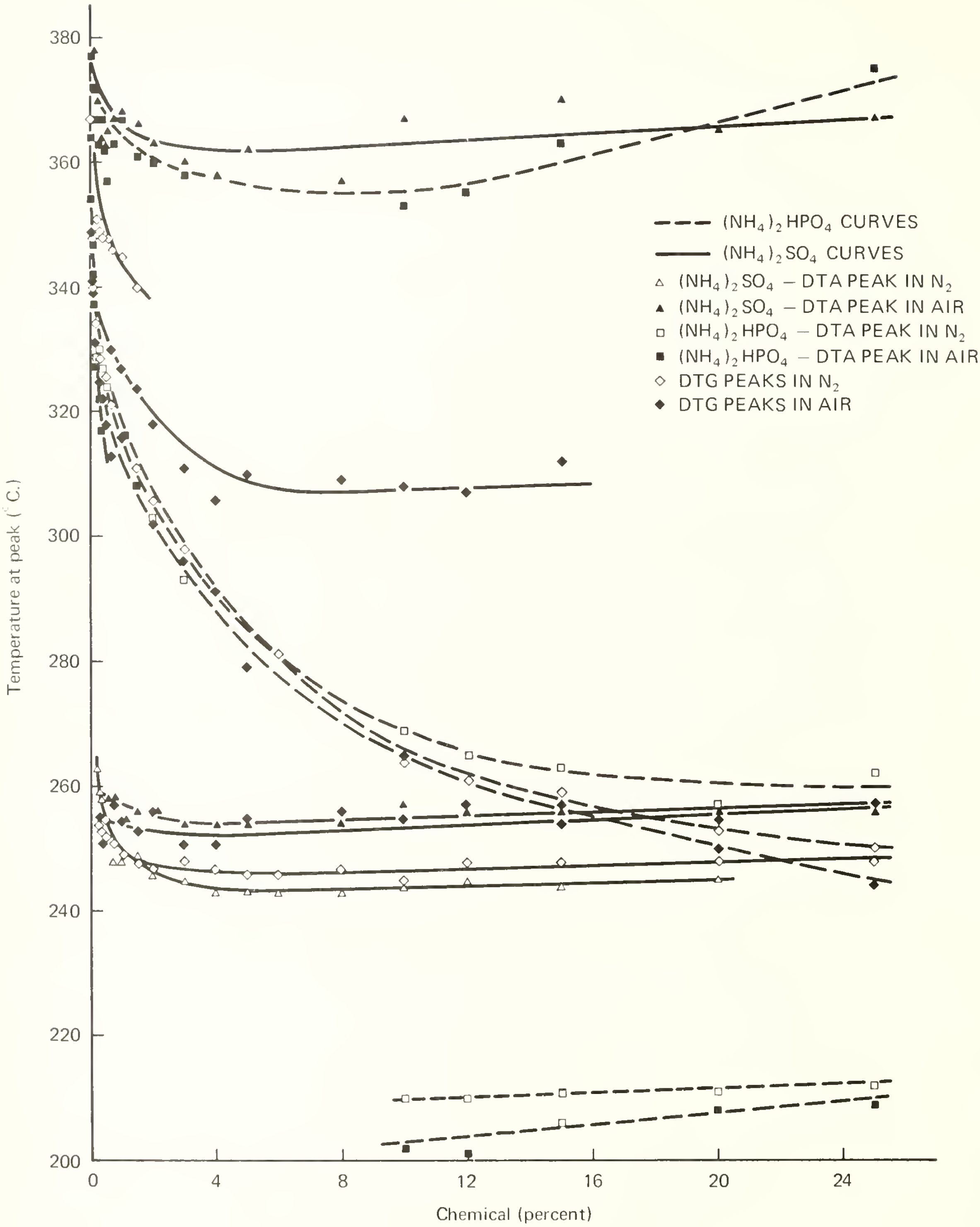


Figure 4.--Comparison of the peak temperatures for chemicals and thermal analysis method.

Discussion

Differential thermal (DTA), thermogravimetric (TGA), and derivative thermogravimetric (DTG) methods of analyses show significant differences in the effect ammonium sulfate and ammonium phosphate have on the degradation of cellulose in either nitrogen or air atmosphere. Some of the general effects and the differences can be summarized:

1. Both ammonium sulfate and ammonium phosphate lower the threshold temperature and activation energy required to initiate cellulose decomposition in nitrogen and air.

2. Increasing the amount of either retardant chemical decreases the maximum weight loss rate occurring during decomposition until the temperature of the peak nears 250° C. An increase in the amount of either retardant beyond the concentration required to obtain a maximum rate at 250° C. causes an increase in the peak rate without shifting its temperature. Any additional increase further reduces the maximum weight loss rate.

3. Increasing retardant chemical causes an increase in the residue or char production.

4. Ammonium phosphate is more effective in increasing char production in an air atmosphere than is ammonium sulfate.

5. While a 2-percent treatment of ammonium sulfate causes a shift to near 250° C. in the maximum decomposition rate, five times this quantity of ammonium phosphate (on a molar fraction basis) is required to produce the same effect, indicating a sizable difference in the action of the two chemicals on cellulose.

It is theorized that the differences ammonium sulfate and phosphate have on cellulose pyrolysis and combustion are either due to the availability of the inorganic fraction involved in the reaction or to a different mechanism by which these chemicals alter pyrolysis and combustion.

1. Such theorizing is based on the fact that ammonium sulfate decomposes at a lower temperature than ammonium phosphate and may not be available in similar concentrations or at the necessary time. For instance, ammonium sulfate is completely decomposed by 420° C., a temperature which may preclude glowing combustion reactions. This is borne out by the fact that ammonium sulfate treated cellulose produces less residue at 450° C. than does ammonium phosphate.

2. Major shifts in cellulose decomposition occurred prior to losses of significant amounts of the sulfate or phosphate portion of the compound. Because the molecular weight is the same for both compounds (132.05 and 132.14 for $(NH_4)_2HPO_4$ and $(NH_4)_2SO_4$, respectively), the treatments can be considered as being on a molar basis. Thus, provided the difference in NH_3 production rates is not responsible for the difference (equal total amounts of NH_3 are produced by both compounds) it is likely there is a difference in the mechanism by which these compounds alter both pyrolysis and combustion. It is unlikely that NH_3 is important in the process since $(NH_4)_2HPO_4$ and $NH_4H_2PO_4$ have the same effect on pyrolysis and combustion when the comparison is made on an equivalent PO_4 basis. This is also supported by the fact empirical fire tests have shown H_3PO_4 as well as $(NH_4)_2HPO_4$ and $NH_4H_2PO_4$ to be equally effective when compared on an equivalent PO_4 basis.

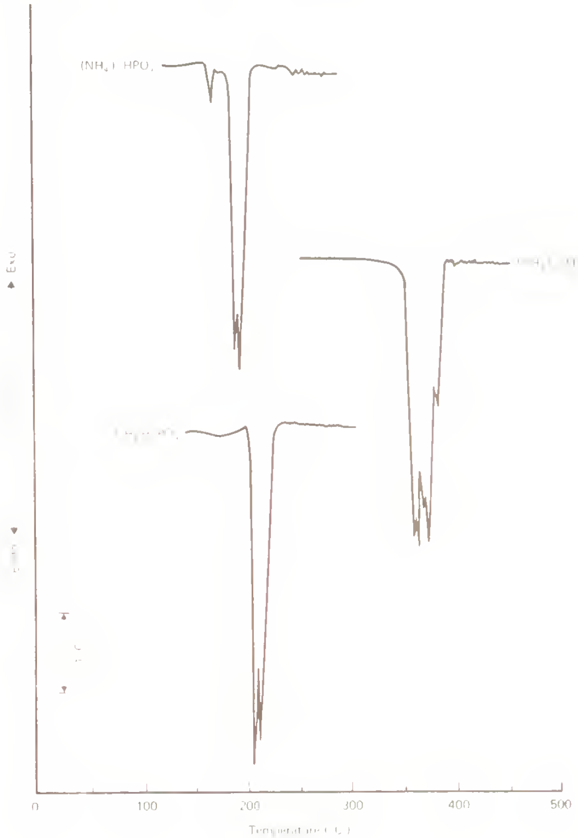
It is possible that the differences in the effects of $(NH_4)_2SO_4$ and $(NH_4)_2HPO_4$ can be attributed to both theorized causes previously mentioned. A different mechanism by which pyrolysis and combustion are altered may exist at lower temperatures for the compounds while the difference in high temperature availability of a portion of the compound may affect glowing combustion, and thus residue, differently.

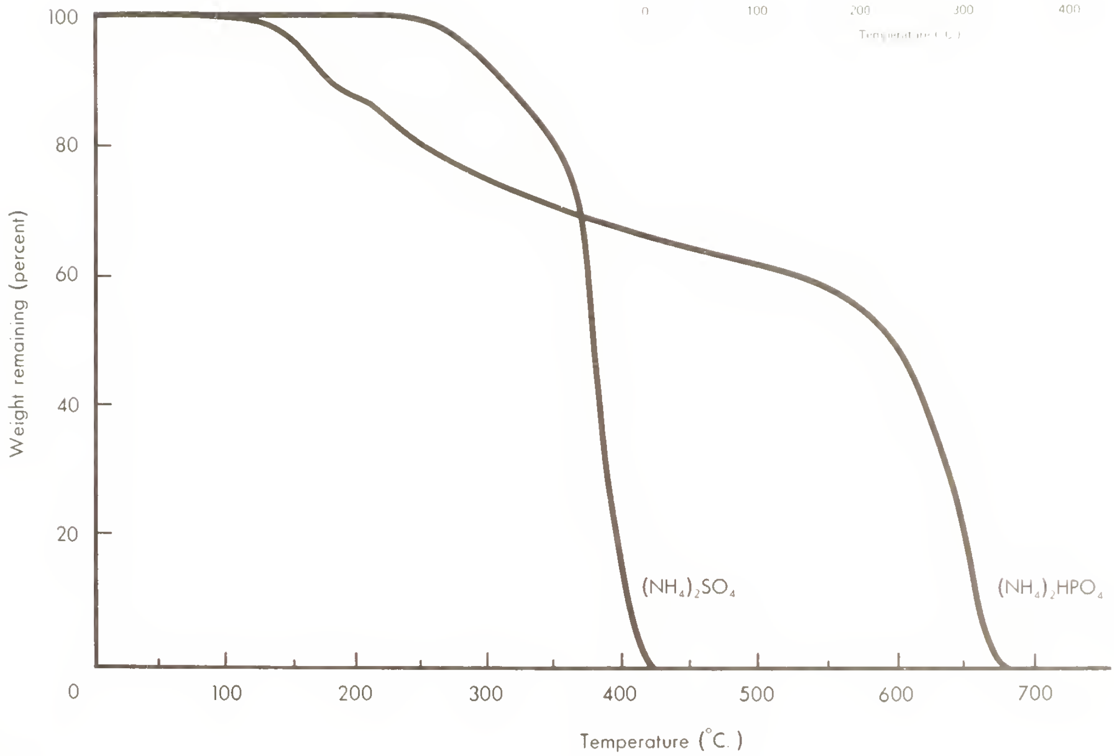
An important conclusion demonstrated by this study is related to the effect of treatment level on pyrolysis and combustion. A direct comparison or classification of inorganic chemicals on the basis of the effects these chemicals have on pyrolysis and combustion at one treatment level may often be misleading and lead to erroneous conclusions concerning other levels of treatment.

Correlation of the results of this study with actual fire test data will be required to fully characterize the relationships. Further studies including quantification of volatile products as a function of chemical quantity will help to indicate the reactions involved.

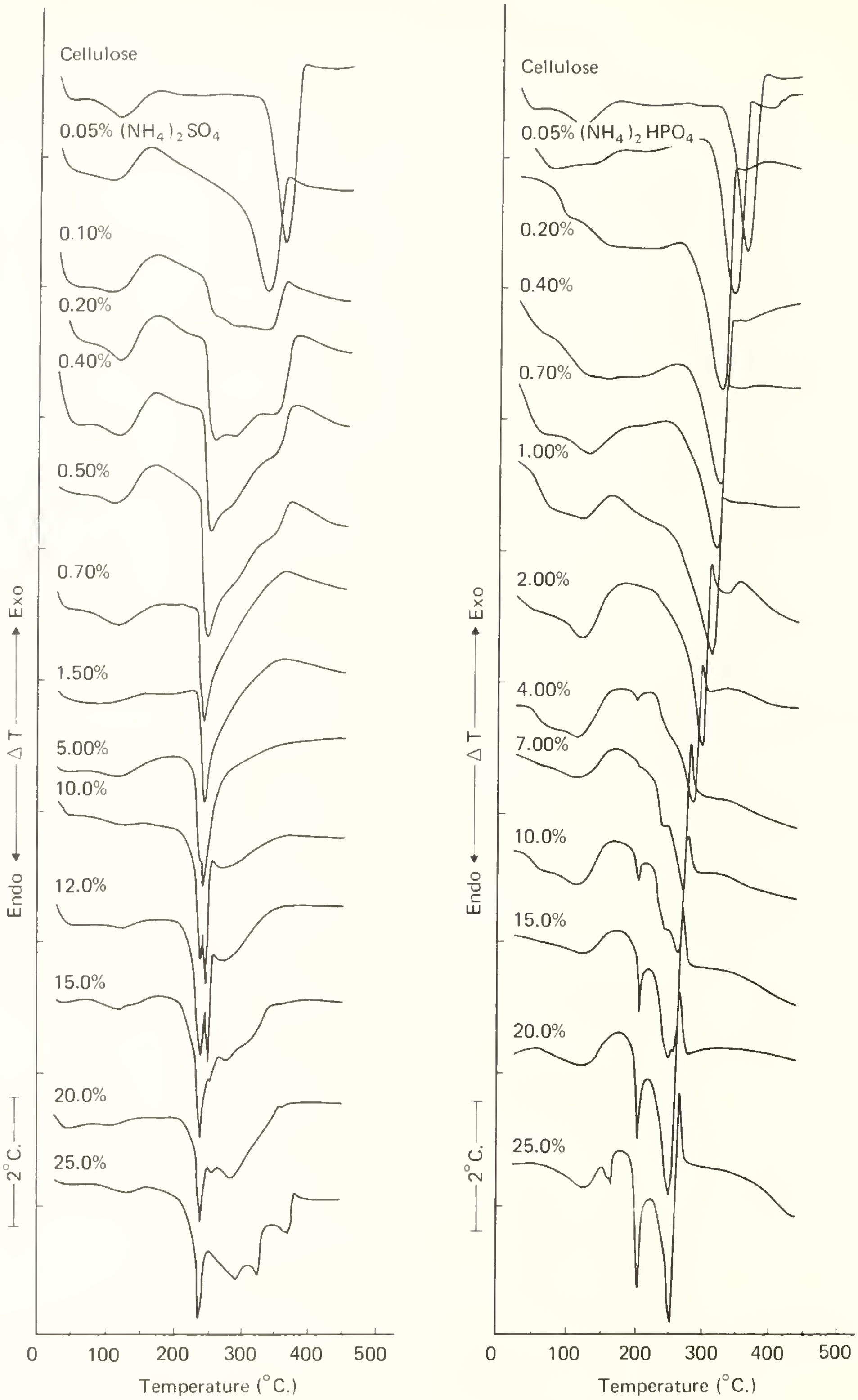
THERMOGRAMS

A--DTA thermograms of $(NH_4)_2HPO_4$, $NH_4H_2PO_4$, and $(NH_4)_2SO_4$ when heated at 25° C. per minute in a flow of 1 liter per minute air.

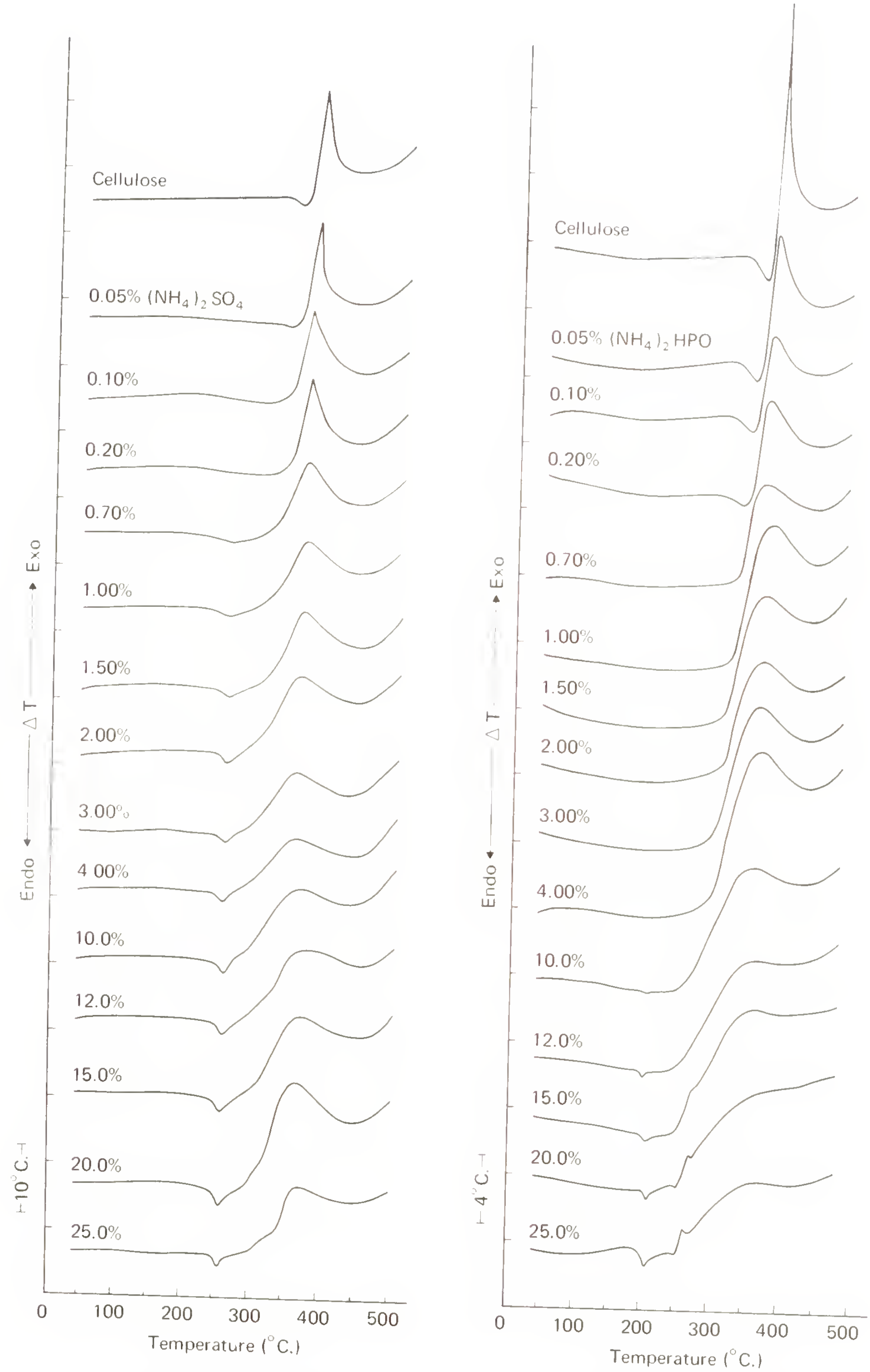




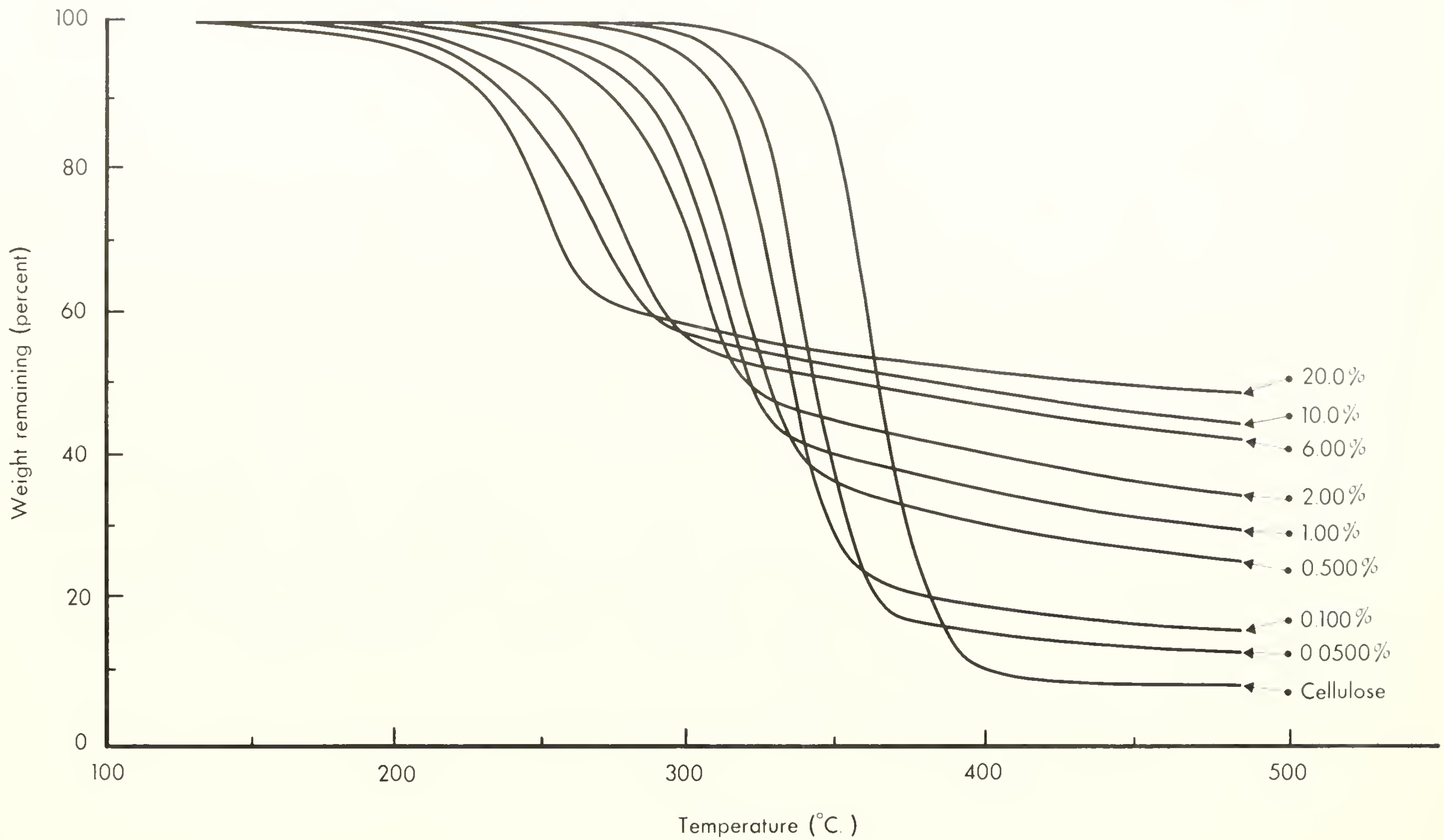
B--TGA thermograms for $(NH_4)_2HPO_4$ and $(NH_4)_2SO_4$ heated at 25° C. per minute in a flow of 1 liter per minute air.



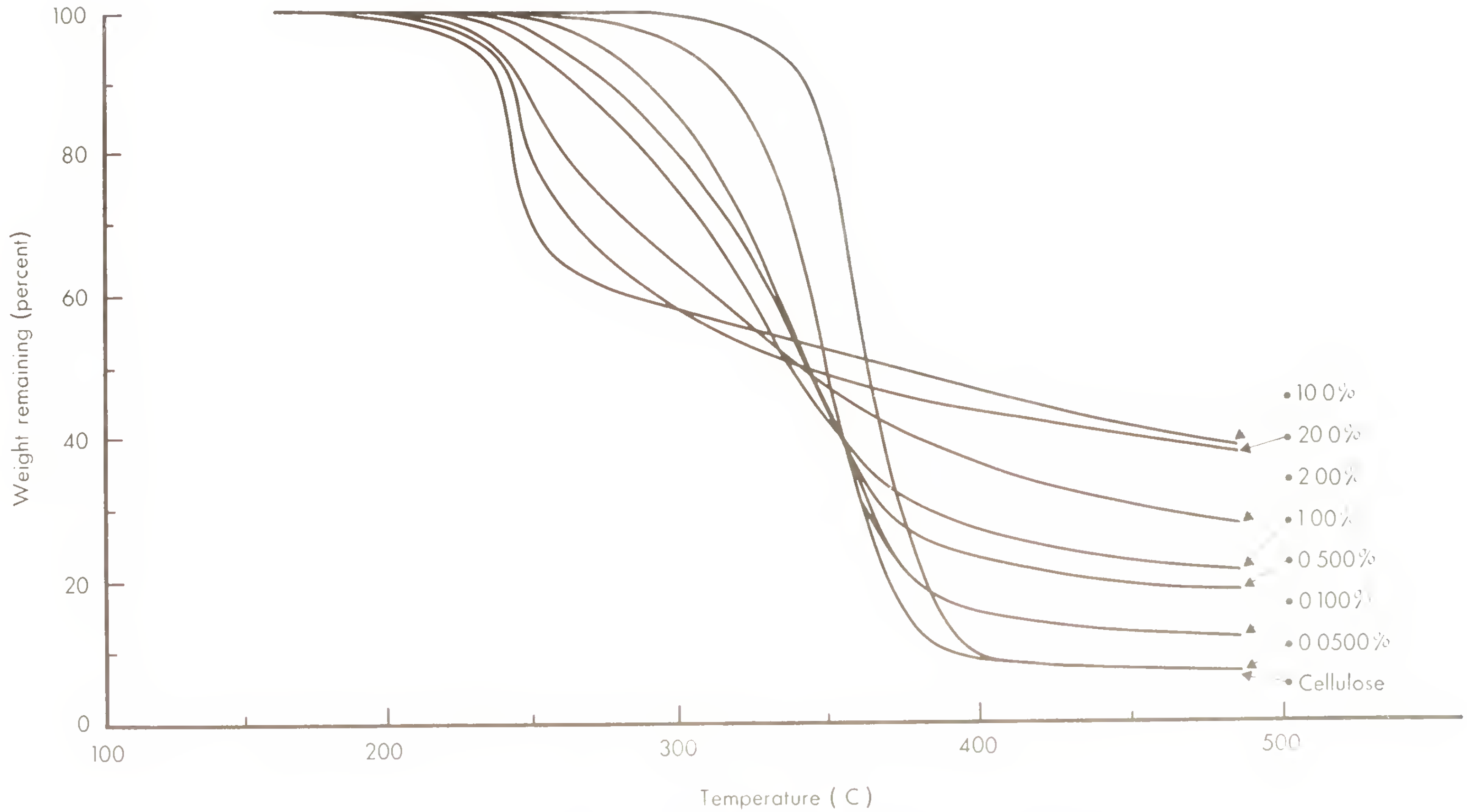
DTA thermograms of cellulose and treated cellulose heated at 25° C. per minute in a flow of 1 liter per minute nitrogen.



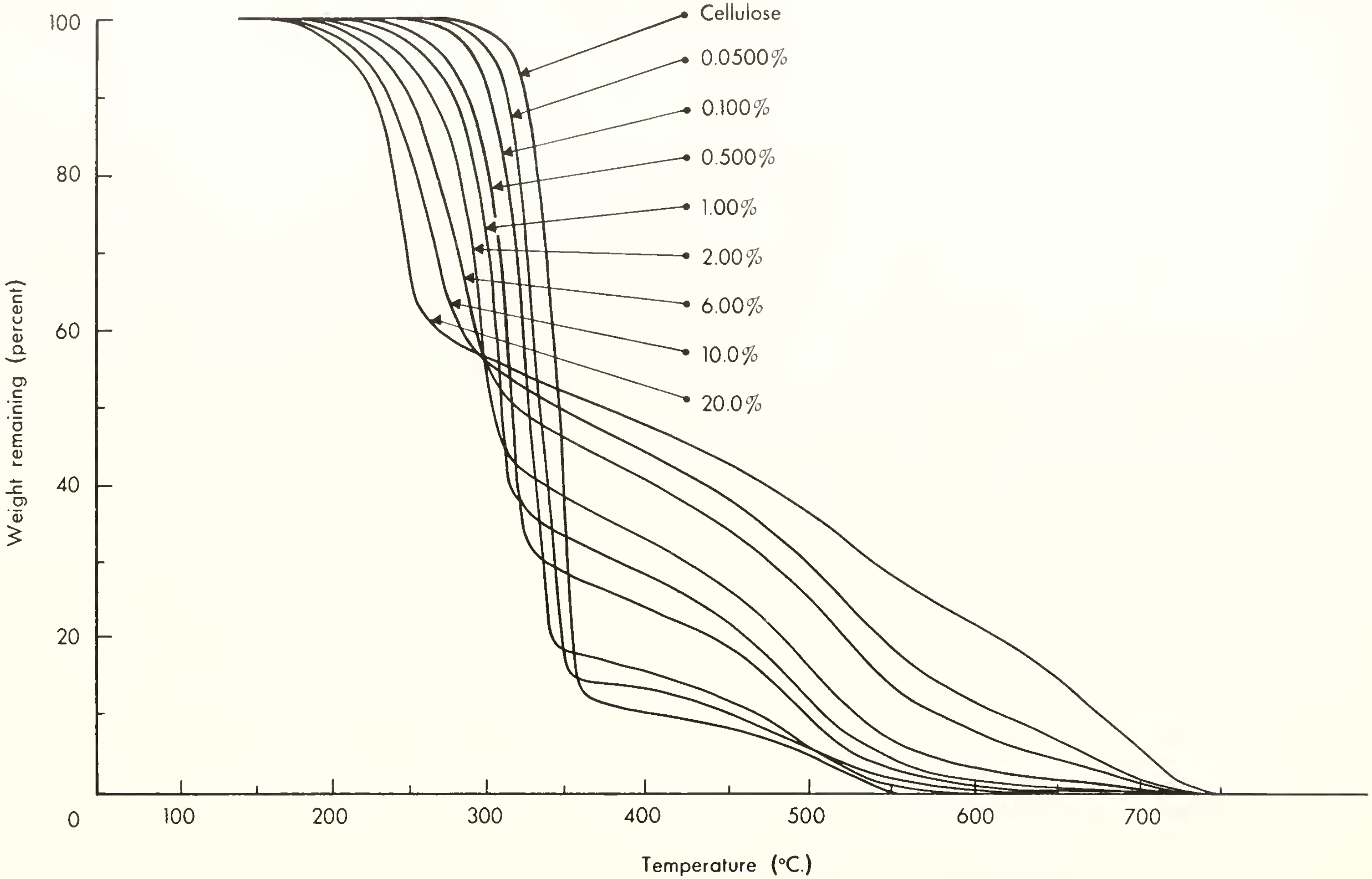
DTA thermograms of cellulose and treated cellulose heated at 25° C. per minute when fluidized with 100 cc. per minute air.



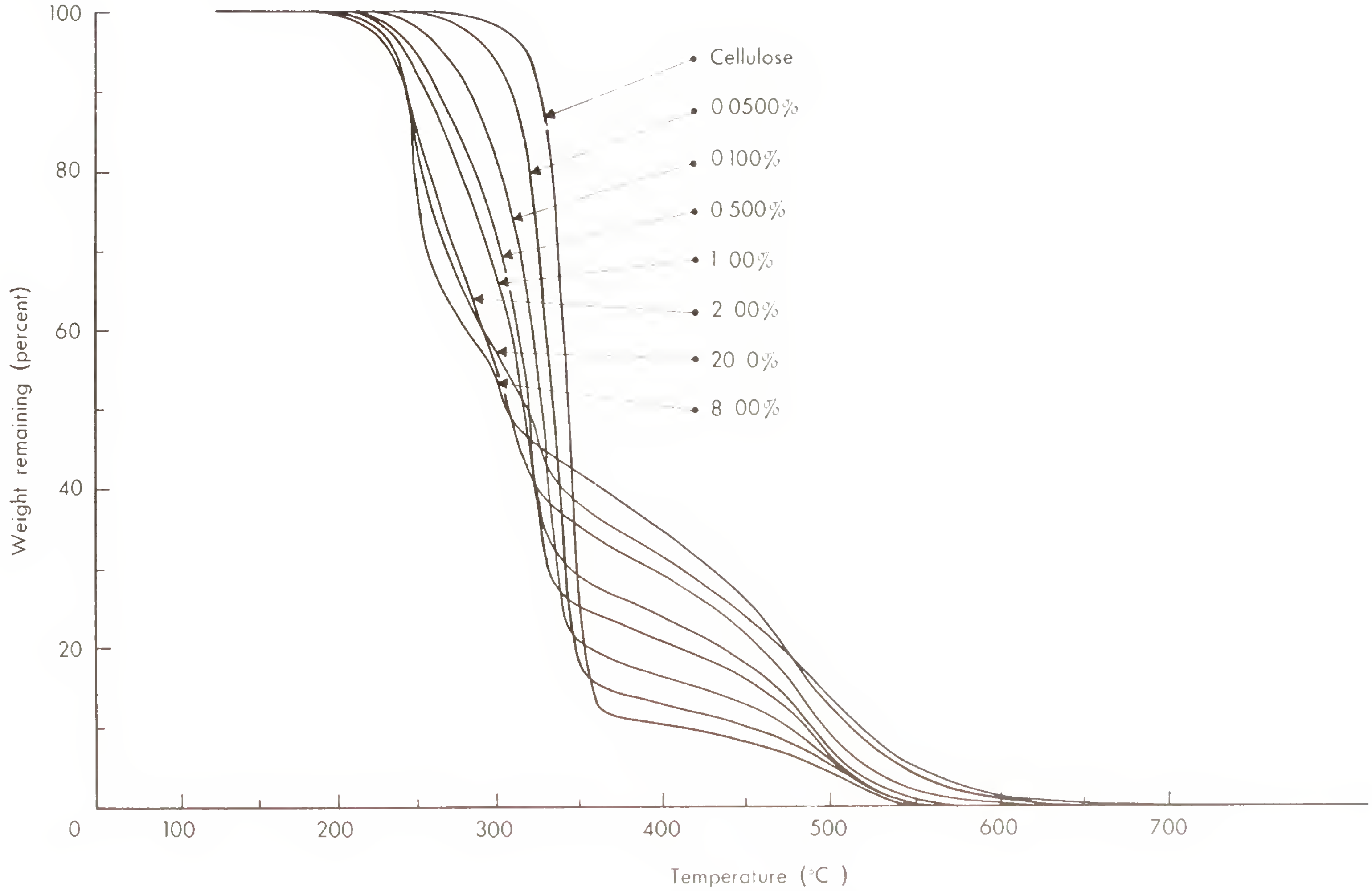
TGA thermograms of cellulose and $(NH_4)_2HPO_4$ treated cellulose heated at 25° C. per minute in a flow of 100 cc. per minute nitrogen.



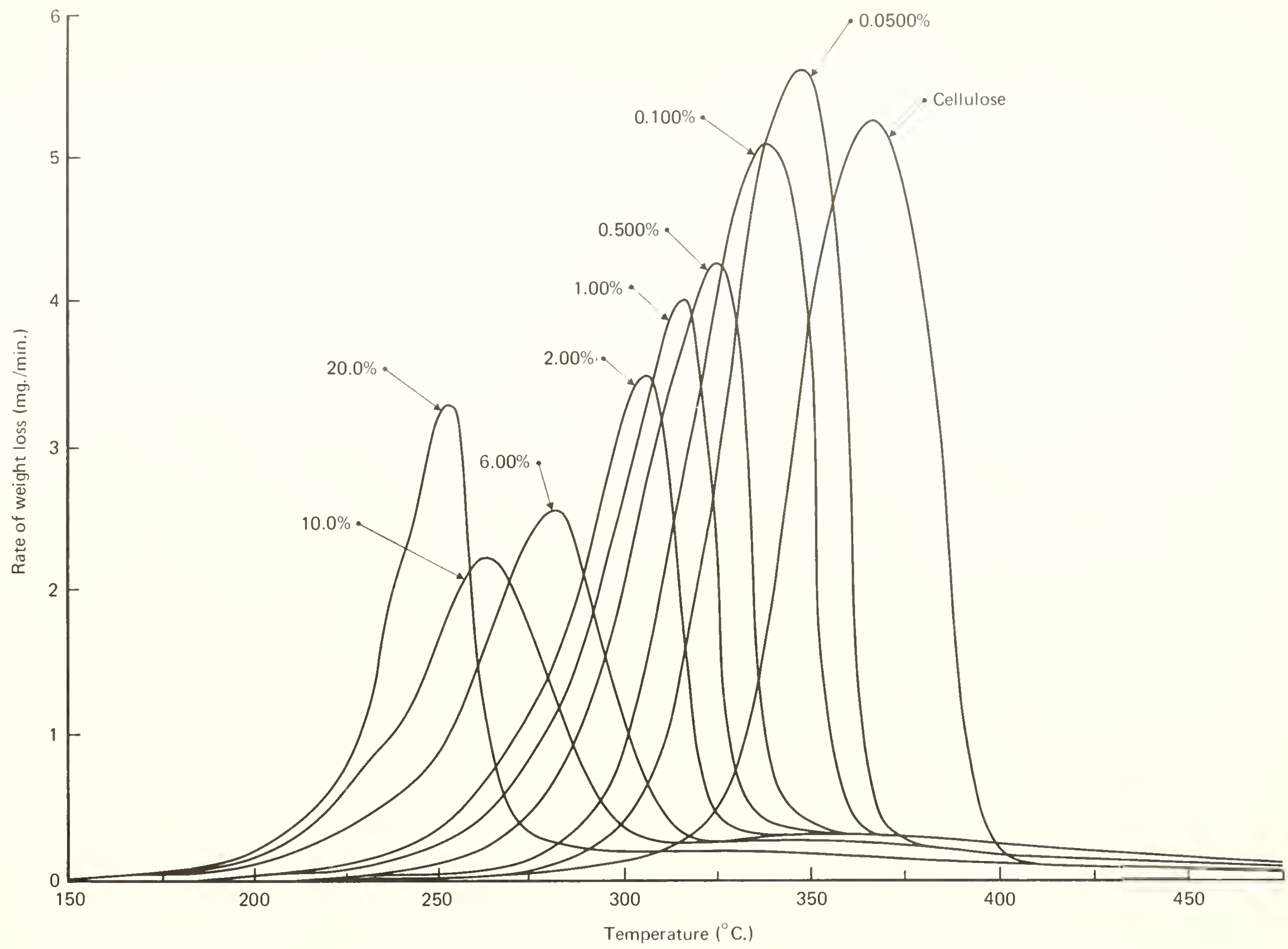
TGA thermograms of cellulose and [illegible] cellulose [illegible] at 25° C. per minute in a flow of 100 cc. per minute nitrogen.



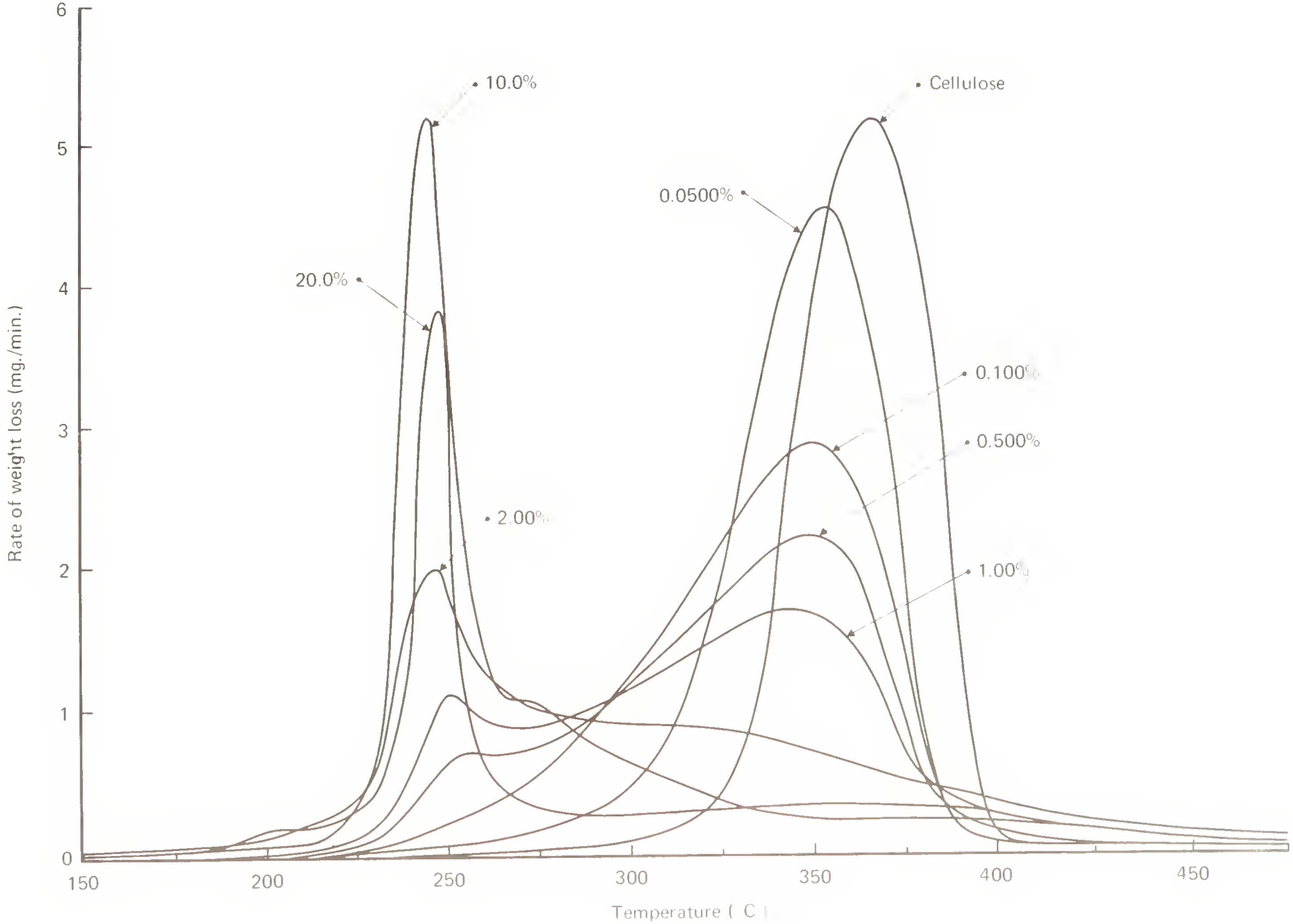
TGA thermograms of cellulose and $(NH_4)_2HPO_4$ treated cellulose heated at 25° C. per minute in a flow of 100 cc. per minute air.



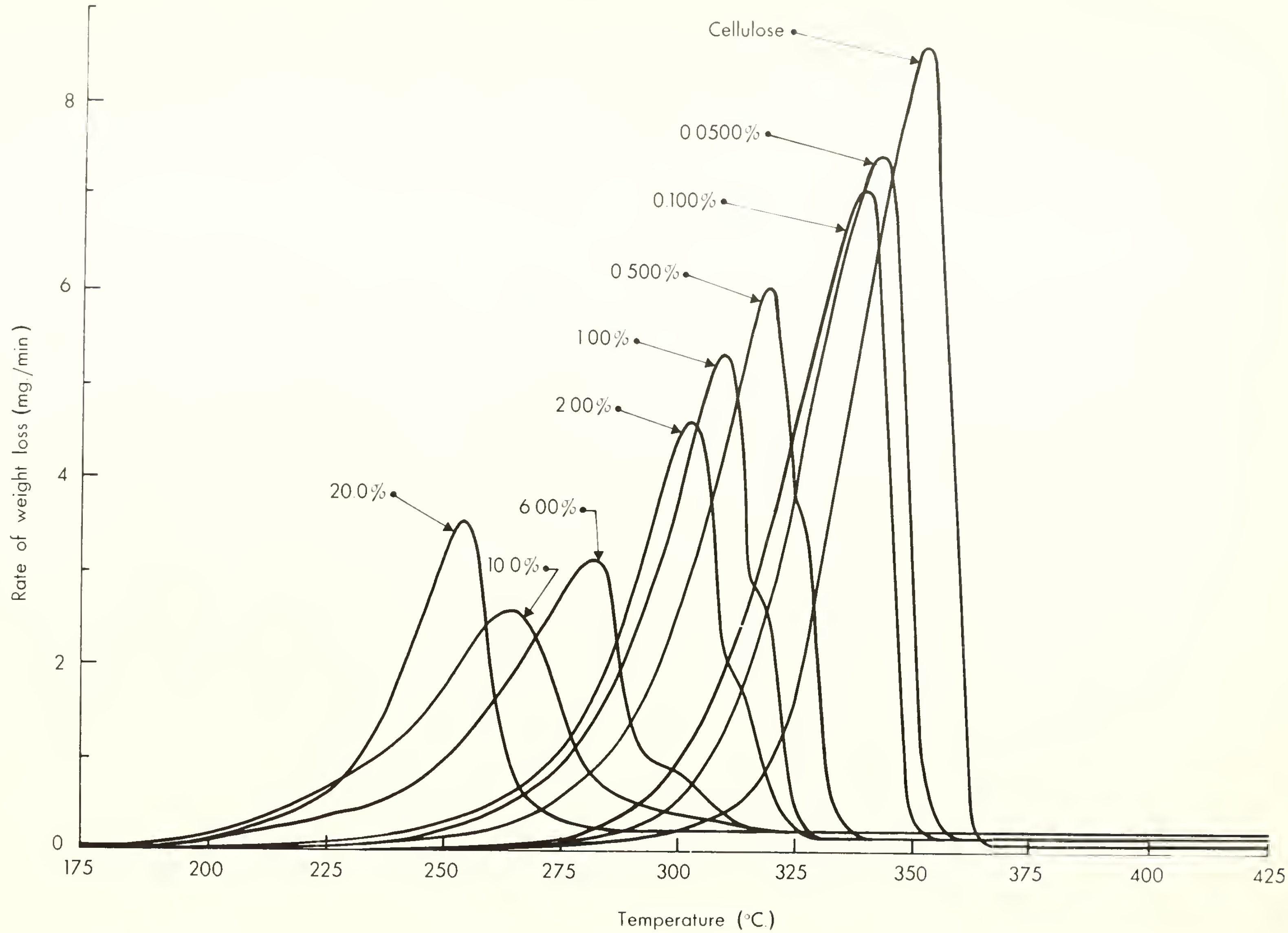
TGA thermograms of cellulose and $(NH_4)_2SO_4$ treated cellulose heated at 25° C. per minute in a flow of 100 cc. per minute air.



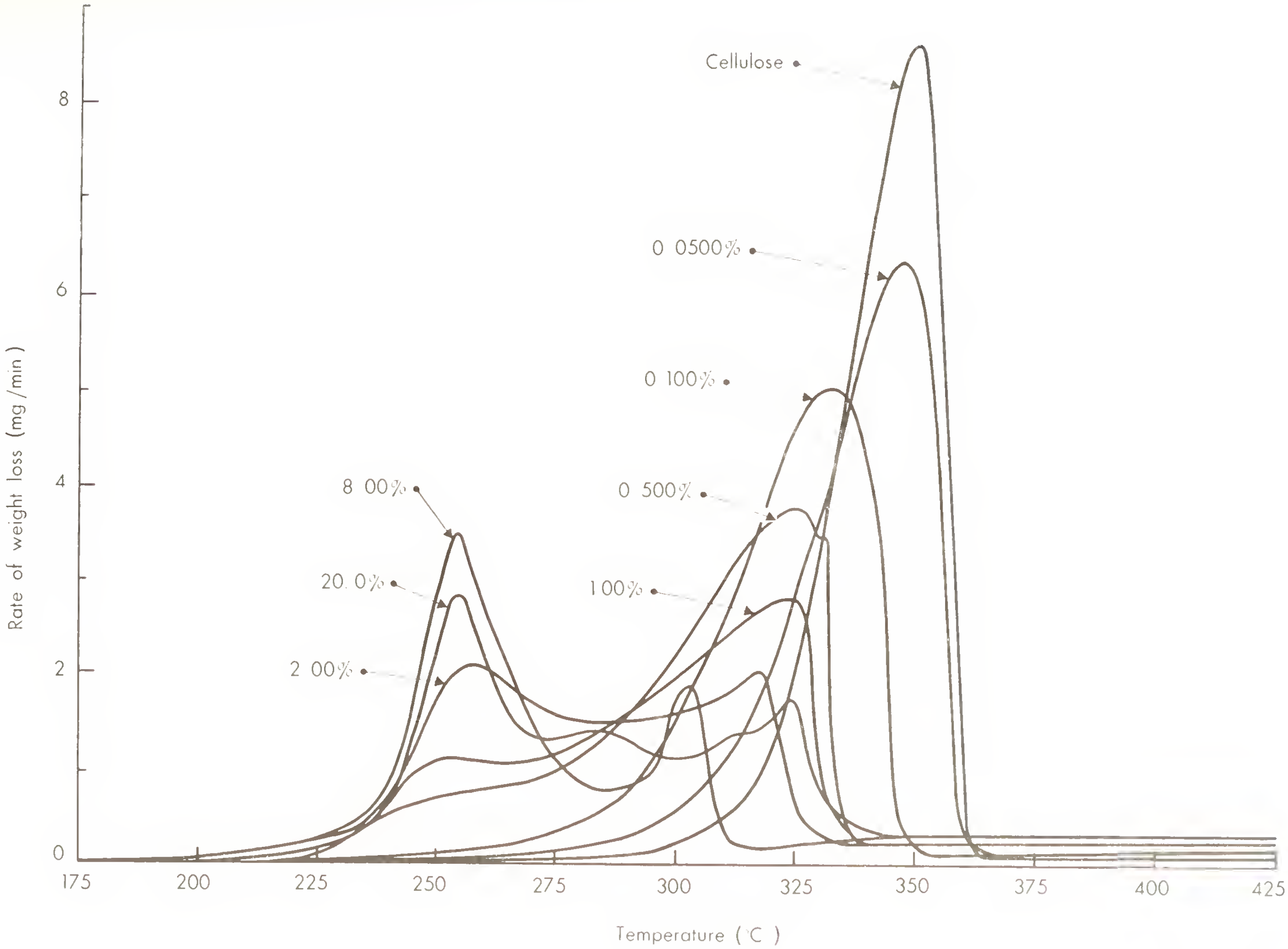
DTG thermograms of cellulose and $(NH_4)_2HPO_4$ treated cellulose heated at 25° C. per minute in a flow of 100 cc. per minute nitrogen.



DTG thermograms of cellulose and $(NH_4$ [illegible] treated cellulose heated at 25° C. per minute in a flow of [illegible] cc. per minute nitrogen.



DTG thermograms of cellulose and $(NH_4)_2HPO_4$ treated cellulose heated at 25° C. per minute in a flow of 100 cc. per minute air.



DTG thermograms of cellulose and $(NH_4)_2SO_4$ treated cellulose h[illegible] at 25° C. per minute in a flow of 100 cc. per minute air.

LITERATURE CITED

Browne, F. L., and W. K. Tang.
1963. Effect of various chemicals on thermogravimetric analysis of ponderosa pine. U.S. Forest Serv. Res. Pap. FPL-6, 24 p., illus.

Kilzer, F. J., and A. Broido.
1965. Speculations on the nature of cellulose pyrolysis. Pyrodynamics 2:151-163, illus.

Shafizadeh, F.
1968. Pyrolysis and combustion of cellulosic materials. P. 419-474, *In:* Advances in Carbohydrate Chemistry, vol. 23. Ed. by Melville L. Wolfrom and R. Stuart Tipson. New York and London: Academic Press.

Tang, Walter K.
1967. Effect of inorganic salts on pyrolysis of wood, alpha-cellulose, and lignin determined by dynamic thermogravimetry. U.S. Forest Serv. Res. Pap. FPL 71, 16 p., illus.

________, and Herbert W. Eickner.
1968. Effect of inorganic salts on pyrolysis of wood, cellulose, and lignin determined by differential thermal analysis. U.S. Forest Serv. Res. Pap. FPL 82, 30 p., illus.

Truax, T. R., C. A. Harrison, and R. H. Baechler.
1956. Experiments in fireproofing wood, fifth progress report. U.S. Forest Serv., Forest Prod. Lab. No. 1118, 23 p.

Van Wazer, John R.
1958. Phosphorus and its compounds. 954 p., illus. New York: Interscience Publishers, Inc.

APPENDIX

Table 1.--DTA *thermal behavior of cellulose and* $(NH_4)_2HPO_4$ *treated cellulose*

Treatment	Nitrogen				Air			
	Thermal effect	Peak temperature °C.	Thermal effect	Peak temperature °C.	Thermal effect	Peak temperature °C.	Thermal effect	Peak temperature °C.
Untreated cellulose			endo	364	endo	354	exo	377
Treated cellulose[1]								
0.0500			endo	347	endo	342	exo	372
.100			endo	340	endo	337	exo	367
.200			endo	329	endo	327	exo	363
.300			endo	330	endo	322	exo	367
.400			endo	327	endo	317	exo	362
.500			endo	324			exo	357
.700			endo	321			exo	363
1.00			endo	316			exo	367
1.50			endo	308			exo	361
2.00			endo	303			exo	360
3.00			endo	293			exo	358
6.00			endo	275			exo	355
10.0	endo	210	endo	269	endo	202	exo	353
12.0	endo	210	endo	265	endo	201	exo	360
15.0	endo	211	endo	263	endo	206	exo	363
20.0	endo	211	endo	257	endo	208	exo	370
25.0	endo	212	endo	262	endo	209	exo	375

[1]Percent by weight chemical.

Table 2.--*DTA thermal behavior of cellulose and* $(NH_4)_2SO_4$ *treated cellulose*

Treatment	Nitrogen				Air			
	Thermal effect	Peak temperature °C.	Thermal effect	Peak temperature °C.	Thermal effect	Peak temperature °C.	Thermal effect	Peak temperature °C.
Untreated cellulose			endo	364	endo	354	exo	377
Treated cellulose[1]								
0.0500			endo	339	endo	339	exo	378
.100			endo	339			exo	372
.200	endo	263	endo	347			exo	370
.300	endo	259					exo	364
.400	endo	258					exo	363
.500	endo	255			endo	258	exo	365
.700	endo	248			endo	258	exo	367
1.00	endo	248			endo	255	exo	368
1.50	endo	249			endo	256	exo	366
2.00	endo	246			endo	256	exo	363
3.00	endo	245			endo	254	exo	360
4.00	endo	243			endo	254	exo	358
5.00	endo	243			endo	254	exo	362
6.00	endo	243			endo	254	exo	357
8.00	endo	243			endo	254	exo	357
10.0	endo	244			endo	257	exo	367
12.0	endo	245			endo	256	exo	378
15.0	endo	244			endo	256	exo	370
20.0	endo	245			endo	256	exo	365
25.0	endo	245			endo	256	exo	367

[1]Percent by weight chemical.

Table 3.--Effect of [illegible] threshold temperature [illegible].[1]

Treatment	$(NH_4)_2HPO_4$ treated cellulose		$(NH_4)_2SO_4$ treated cellulose	
	Pyrolysis (N_2)	Combustion (air)	Pyrolysis (N_2)	Combustion (air)
Untreated cellulose	290	298	290	29[illegible]
Treated cellulose[2]				
0.0500	286	294	257	280
.100	274	285	239	250
.200	264	272	234	242
.300	255	266	230	239
.400	253	262	231	231
.500	250	254	229	229
.700	243	252	228	231
1.00	234	249	224	230
1.50	230	241	229	225
2.00	216	237	213	228
3.00	212	221	210	221
4.00	209	213	202	217
5.00	207	210	201	215
6.00	199	209	200	212
8.00	196	208	199	211
10.0	189	206	196	208
12.0	190	202	195	210
15.0	187	200	194	208
20.0	190	199	195	207
25.0	186	193	190	205

[1] The threshold temperature is arbitrarily denoted as the temperature required to produce a weight loss rate of 0.09 milligrams per minute (~ 1 percent of the maximum weight loss rate).
[2] Percent by weight chemical.

Table 4.--TGA-DTG thermal behavior of cellulose and $(NH_4)_2HPO_4$-treated cellulose in nitrogen

Treatment	Residue at 450° C.	Normalized cellulose residue at 450° C.	Peak rate of weight loss	Normalized peak rate of weight loss	Peak temperature
	Percent	*Percent*	*Mg./min.*	*Mg./min.*	*°C.*
Untreated cellulose	7.6	7.6	5.13	5.13	367
Treated cellulose[1]					
0.0500	12.2	12.2	5.50	5.50	348
.100	15.0	14.9	5.00	5.00	340
.200	19.6	19.5	4.48	4.49	334
.300	22.2	22.1	4.38	4.39	329
.400	24.4	24.3	4.26	4.28	328
.500	25.8	25.6	4.20	4.22	326
.700	28.6	28.4	4.05	4.08	321
1.00	30.2	29.9	3.96	4.00	316
1.50	34.4	34.0	3.52	3.57	311
2.00	35.8	35.2	3.43	3.50	306
3.00	39.4	38.4	2.90	3.02	298
6.00	42.8	41.4	2.52	2.68	281
10.0	45.2	43.2	2.19	2.43	264
12.0	46.0	43.6	2.33	2.65	261
15.0	47.4	44.6	3.05	3.59	259
20.0	48.4	44.8	3.23	4.04	253
25.0	49.2	44.5	3.66	4.88	250

[1] Percent by weight chemical.

Table 5.--*TGA-DTG thermal behavior of cellulose and $(NH_4)_2SO_4$ treated cellulose in nitrogen*

Treatment	Residue at 450° C.	Normalized cellulose residue at 450° C.	Low temperature peak: Rate of weight loss	Low temperature peak: Normalized rate of weight loss	Low temperature peak: Peak temperature	High temperature peak: Rate of weight loss	High temperature peak: Normalized rate of weight loss	High temperature peak: Peak temperature
	Percent	*Percent*	*Mg./min.*	*Mg./min.*	*°C.*	*Mg./min.*	*Mg./min.*	*°C.*
Untreated cellulose	7.6	7.6	--	--	--	5.13	5.13	367
Treated cellulose[1]								
0.0500	7.6	7.6	--	--	--	4.49	4.49	354
.100	12.4	12.4	--	--	--	2.84	2.84	351
.200	14.2	14.2	--	--	--	2.64	2.65	349
.300	15.0	15.0	0.49	0.49	254	2.61	2.62	349
.400	16.8	16.9	.53	.53	253	2.45	2.46	348
.500	18.8	18.9	.71	.71	252	2.22	2.23	348
.700	21.8	22.0	1.01	1.02	251	1.77	1.78	346
1.00	22.1	22.3	1.11	1.12	249	1.70	1.72	345
1.50	24.6	25.0	1.39	1.41	248	1.44	1.46	340
2.00	28.5	29.1	2.12	2.16	247	--	--	--
3.00	32.8	33.7	2.53	2.61	248	--	--	--
4.00	35.4	36.9	2.95	3.07	247	--	--	--
5.00	35.8	37.6	3.20	3.37	246	--	--	--
6.00	36.8	39.0	3.38	3.60	246	--	--	--
8.00	38.6	41.7	3.97	4.32	247	--	--	--
10.0	40.0	44.2	5.19	5.77	245	--	--	--
12.0	40.4	45.7	4.90	5.57	248	--	--	--
15.0	40.8	47.6	4.17	4.91	248	--	--	--
20.0	39.2	48.5	3.83	4.79	248	--	--	--
25.0	36.4	47.9	3.55	4.73	248	--	--	--

[1]Percent by weight chemical.

Table 6.--*TGA and DTG thermal behavior of cellulose and $(NH_4)_2HPO_4$ treated cellulose in air*

Treatment	Residue at 450° C.	Cellulose residue at 450° C.	Peak rate of weight loss	Normalized peak rate of weight loss	Peak temperature
	Percent	*Percent*	*Mg./min.*	*Mg./min.*	*°C.*
Untreated cellulose	7.7	7.7	8.41	8.41	349
Treated cellulose[1]					
0.0500	10.2	10.2	7.43	7.43	341
.100	12.0	11.9	7.06	7.07	339
.200	15.5	15.4	6.34	6.35	331
.300	17.4	17.3	6.15	6.17	325
.400	18.8	18.6	5.82	5.84	322
.500	19.0	18.8	6.07	6.10	318
.700	21.4	21.1	5.60	5.64	313
1.00	22.9	22.5	5.35	5.40	316
1.50	24.8	24.2	4.90	4.97	308
2.00	26.8	26.1	4.63	4.72	302
3.00	29.2	28.1	4.04	4.16	296
4.00	30.1	28.7	3.91	4.07	291
5.00	33.3	31.7	4.50	4.73	279
10.0	37.2	34.3	2.69	2.99	265
12.0	38.3	34.9	2.65	3.01	257
15.0	40.7	36.8	3.61	4.25	254
20.0	43.2	38.3	3.56	4.45	250
25.0	46.3	40.7	4.08	5.44	244

[1]Percent by weight chemical.

Table 7.--*TGA-DTG thermal behavior of cellulose and $(NH_4)_2SO_4$ treated* [illegible]

Treatment	Residue at 450° C.	Cellulose residue at 450° C.	Low temperature peak: Rate of weight loss	Low temperature peak: Normalized rate of weight loss	Low temperature peak: Peak temperature	High temperature peak: Rate of weight loss	High temperature peak: Normalized rate of weight loss	High temperature peak: Peak temperature
	Percent	*Percent*	*Mg./min.*	*Mg./min.*	*° C.*	*Mg./min.*	*Mg./min.*	*° C.*
Untreated cellulose	7.7	7.7	--	--	--	8.41	8.41	349
Treated cellulose[1]								
0.0500	10.4	10.4	--	--	--	6.29	6.29	344
.100	13.2	13.2	--	--	--	5.00	5.01	332
.200	13.8	13.8	--	--	--	4.56	4.57	332
.300	14.3	14.3	0.46	0.46	255	4.11	4.12	330
.400	15.0	15.1	.60	.60	251	4.01	4.03	326
.500	16.0	16.1	.71	.72	252	3.71	3.73	325
.700	18.3	18.4	1.02	1.03	257	2.93	2.95	330
1.00	18.8	19.0	1.12	1.13	255	2.90	2.93	327
1.50	19.6	19.9	1.43	1.45	253	2.72	2.76	324
2.00	22.6	23.1	2.13	2.17	256	1.75	1.78	318
3.00	24.1	24.7	2.69	2.77	251	1.37	1.41	311
4.00	24.8	25.7	3.22	3.35	251	1.90	1.98	306
5.00	25.2	26.4	3.38	3.56	255	1.66	1.75	310
8.00	26.9	29.0	3.45	3.75	256	1.75	1.90	309
10.0	27.0	29.8	4.13	4.57	255	.96	1.06	308
12.0	26.4	29.7	3.69	4.19	257	2.11	2.39	307
15.0	26.3	30.6	3.50	4.12	257	1.48	1.74	312
20.0	25.7	31.6	2.88	3.60	255	--	--	--
25.0	25.8	33.7	3.00	4.00	257	--	--	--

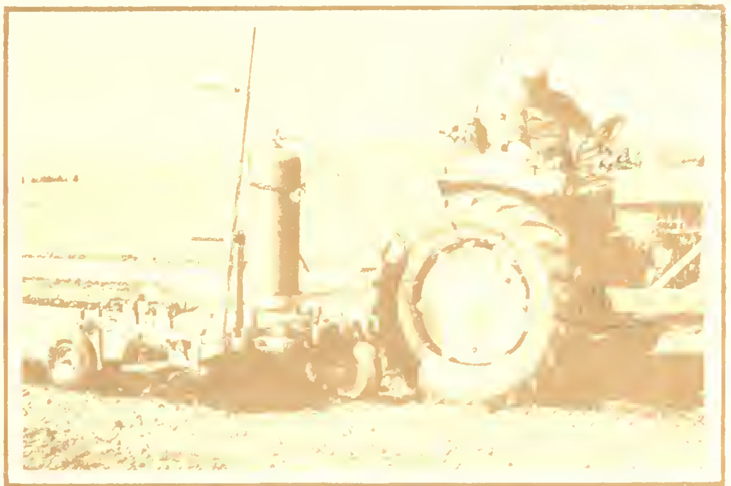
[1]Percent by weight chemical.

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

EFFECTS OF SOIL FUMIGATION ON PRODUCTION OF CONIFER NURSERY STOCK AT TWO NORTHERN ROCKY MOUNTAIN NURSERIES

R. J. Boyd



USDA FOREST SERVICE RESEARCH PAPER INT-91
INTERMOUNTAIN FOREST & RANGE EXPERIMENT STATION
Ogden, Utah 84401

USDA Forest Service
Research Paper INT-91
April 1971

EFFECTS OF SOIL FUMIGATION ON PRODUCTION OF CONIFER NURSERY STOCK AT TWO NORTHERN ROCKY MOUNTAIN NURSERIES

R. J. Boyd

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

The Author

RAY BOYD received his B. S. in general sciences from Colorado State University in 1949 and his master of forestry degree in 1951. From 1949 to 1953 he did silvicultural research for the Rocky Mountain Forest and Range Experiment Station. Since 1953 he has been an Associate Silviculturist, assigned to the Station's silviculture of western white pine work unit now at Moscow, Idaho.

CONTENTS

Abstract

Soil fumigation has improved production of Douglas-fir, western white pine, Engelmann spruce and ponderosa pine stock at two northern Rocky Mountain nurseries. The better fumigation treatments substantially reduced weeds, losses from diseases and insects, and generally resulted in larger stock with improved survival potential. These benefits more than compensated for the cost of fumigation. Fumigation has also resulted in greater operational efficiencies by providing more predictable and more uniform seedling stands. Late summer fumigation with methyl-bromide based fumigants has provided the most dependable overall improvement in nursery operation.

PESTICIDES PRECAUTIONARY STATEMENT

This publication reports research involving pesticides. It does not contain recommendations for their use, nor does it imply that the uses discussed here have been registered. All uses of pesticides must be registered by appropriate State and/or Federal agencies before they can be recommended.

CAUTION: Pesticides can be injurious to humans, domestic animals, desirable plants, and fish or other wildlife--if they are not handled or applied properly. Use all pesticides selectively and carefully. Follow recommended practices for the disposal of surplus pesticides and pesticide containers.

INTRODUCTION

Research personnel of the Intermountain Forest and Range Experiment Station have been experimenting since 1961 with soil fumigation as a means of improving conifer nursery stock and reducing production costs. These experiments have been in cooperation with nursery personnel of the Northern Region of the USDA Forest Service, the Dow Chemical Company, and Stauffer Chemical Company[1] and were conducted at the Forest Service's Coeur d'Alene nursery, near Coeur d'Alene, Idaho, and at the Savenac nursery, located at Haugen, Montana.

Until 1964 soil fumigation was conducted at the above nurseries on an experimental basis only. By then it was obvious that, in spite of the high cost of fumigation, the benefits generally exceeded the cost by a wide margin. Since 1964, most of the Coeur d'Alene seedbeds have been fumigated on an operational basis prior to the sowing of each conifer crop.

---

[1]The assistance of the following personnel is gratefully acknowledged: Nurserymen James W. Augenstein (retired) and Lee L. Mason; Assistant Nurserymen David A. Gibney, Frank Salomonsen, and Steven McDonald; Nursery Technicians Mrs. Bea Fisher and John Isaacson; Mr. Jack Fisher, Dow Chemical Co.; and Mr. Graham Randall, Stauffer Chemical Company.

CONDITIONS, MATERIALS, FUMIGATION METHODS

Soils of the Coeur d'Alene nursery, where most of the trials were conducted, are well-drained sandy loam underlain by water-sorted sands and gravels. Surface-soil pH averages 6.2; organic matter content ranges from 2.6 to 4.2 percent. The site is located at an elevation of 2,500 feet and was previously forested with ponderosa pine (*Pinus ponderosa* Laws.)[2]

Savenac nursery soils involved in fumigation studies are well-drained loams and silt loams derived from stream and glacial outwash deposits. The original vegetation of this site was a mixed conifer type, Douglas-fir [*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco], grand fir [*Abies grandis* (Dougl.) Lindl.], western larch (*Larix occidentalis* Nutt.), and lodgepole pine (*Pinus contorta* Dougl.). Surface soil pH averages 6.6 with an organic matter content of about 2 percent.[2]

After some promising trials of soil fumigation at both Savenac and Coeur d'Alene in 1960, serious experimentation was started at the Coeur d'Alene nursery in the fall of 1961. By 1962, it was obvious that a more complete evaluation was needed. Consequently, in 1963 a major fumigation test was initiated. This included both spring and fall fumigation, a number of additional promising fumigants, varied rates of application for some, and applications at both the Coeur d'Alene and Savenac nurseries (table 1). Soils treated with each fumigant at these two nurseries were broadcast sown with stratified, but otherwise untreated, western white pine (*Pinus monticola* Dougl.), Douglas-fir, ponderosa pine, and Engelmann spruce (*Picea engelmannii* Parry).

Since the 1963 trials, all of the operational fumigation areas have been closely observed, usually with some unfumigated check areas incorporated into the program, to provide continued monitoring of fumigation effectiveness. Additional species have been grown in fumigated soils including grand fir, western larch, and lodgepole pine.

---

[2]R. C. McConnell and M. G. Klages. Forest nursery soils of northern Idaho and western Montana. Mont. Agr. Exp. Sta. Bull. 63, 33 p., illus. 1969.

All fumigants were applied according to the manufacturer's recommendation. Fumigants containing methyl bromide (Brozone, Trizone, and MC-33; see table 1, footnote 2) were covered with polyethylene tarpaulins immediately after injection. Vidden-D, M-2441, and M-2467 were injected in the same manner as the methyl bromide-containing fumigants, but were sealed with sprinkler application of water. Most of the Vapam was applied with a gravity-flow dribble applicator, and the soil immediately rototilled, roller-packed, and water-sealed. In the 1963 spring fumigation, the 40-gallon-per-acre rate of Vapam was sealed with polyethylene. All fumigants were applied at soil temperatures above 55°F. with soil moisture near field capacity. In the 1961 fall and 1963 spring trials, each replication contained one unfumigated control plot. Alternate beds were fumigated in the 1963 fall fumigation so that each fumigated bed had an unfumigated check bed adjacent to it. Soil fumigation after 1963 has been on an operational basis with entire "sections" (the area between overhead sprinkler pipes spaced at 50-foot intervals) fumigated and results compared with unfumigated "sections." Either Trizone or a 2:1 mixture of methyl bromide and chloropicrin have been used in these operational-scale fumigations.

Table 1.--*Summary of conditions represented in soil fumigation studies conducted at the Coeur d'Alene (CdA) and Savenac nurseries*

Location	Species sown[1]	Fumigation time	Fumigant[2]						
			Brozone	Trizone	MC-33	Vapam	Vidden-D	M-2441	M-2467
			lb./acre			gal./acre			
CdA	WWP,PP DF,ES	Fall, 1961	170	140	--	--	--	--	--
			340	180	--	--	--	--	--
CdA	GF,DF, PP,ES	Spring, 1963	110	140	170	40[3]	50	50	50
			170	200	300	80	--	--	--
			340	--	--	--	--	--	--
CdA & Savenac	WWP,DF, PP,ES	Fall, 1963	110	140	170	40	50	50	50
			170	200	300	80	--	--	--
			340	--	--	--	--	--	--

[1]For the fall 1963 fumigation, all species were sown only in the spring at both nurseries except for western white pine, which was sown both in the spring and the fall at Coeur d'Alene and only in the fall at Savenac. WWP = western white pine; PP = ponderosa pine; DF = Douglas-fir; GF = grand fir; and ES = Engelmann spruce.

[2]Brozone = Methyl bromide (68.6%); Chloropicrin (1.4%); inert (30%) - Dow Chemical Co.
Trizone = Methyl bromide (61%); Chloropicrin (30%); 3-Bromopropyne (6.8%) - Dow Chemical Co.
MC-33 = Methyl bromide (66.7%); Chloropicrin (33.3%) - Dow Chemical Co.
Vapam = Sodium N-methyldithiocarbamate - Stauffer Chemical Co.
Vidden-D = 1,3-dichloropropene, 1,2-dichloropropene; 2,3-dichloropropene; 3,3-dichloropropene and related chlorinated hydrocarbons (100%) - Dow Chemical Co.
M-2441 = Vidden-D (80%); Chloropicrin (20%) - Dow Chemical Co.
M-2467 = Vidden-D (90%); 3-bromopropyne (10%) - Dow Chemical Co.

[3]Sealed with polyethylene tarp; all other Vapam treatments water sealed.

WEED CONTROL

METHODS

The effects of fumigation on weed control have been evaluated by periodic sample counts of weeds on three or four randomly selected 1-square-foot plots during the first growing season and the early part of the second. Weed counts were followed by hand weeding. When possible, time studies of hand weedings were conducted to relate labor cost to weed density. Greenhouse germination of weeds from soil samples taken at various soil depths provided information on the residual weed-seed population and its control by fumigation. Experimental design and statistical analyses were obtained by standard randomized block layouts and analysis of variance, by paired-sample t-test procedures, or by regression analysis.

EFFECTS ON WEED POPULATIONS

Weed control has been an outstanding, readily visible feature of the benefits of soil fumigation (figure 1). Most of the fumigants consistently resulted in substantial reductions in subsequent weed populations; this was especially apparent during the early part of the first growing season following fumigation (table 2). Fumigants that did not show a positive control of weeds were: (1) Vapam applied 40 gallons per acre and not covered by tarpaulins; (2) Brozone applied 110 pounds per acre; and (3) Vidden-D applied 50 gallons per acre.

In general, those products containing 1,3 dichloropropene and related hydrocarbons (Vidden-D, M-2441, and M-2467) were not as effective in controlling weeds as were the methyl bromide-based fumigants or Vapam. In the 1963 spring fumigation, which was less influenced by a post-fumigation influx of windblown weed seed than any of the fall fumigations, weed control was roughly proportional to the amount of methyl bromide and 3-Bromopropyne (propargyl bromide) in the fumigant. Vapam applied at 40 gallons per acre and sealed with a polyethylene tarpaulin was as effective as the water-sealed material at twice this application rate.

Periodic weed counts showed that the effects of fumigation on weed populations tended to diminish during the summer. By September 1963, there were no significant differences in weed population which could be attributed to fumigation; nor was there any carry-over effect into the second growing season. Apparently weeds germinating on the treated plots in late summer and the following spring originated from windborne seed.

Table 2.--*Effects of soil fumigation on weed density, Coeur d'Alene and Savenac nursery soil fumigation trials, 1961-1963*

Trial	Fumigant (amount applied/acre)	Weeds per square foot[1]
1961 (Fall)[2]	Brozone (170 lb.)	1
Coeur d'Alene	Brozone (340 lb.)	2
(counted 6/25/62)	Trizone (140 lb.)	10
	Trizone (180 lb.)	11
	Unfumigated	20
1963 (Spring)	Vapam (40 gal.)	3
Coeur d'Alene	Brozone (340 lb.)	4
(average of four	MC-33 (300 lb.)	5
counts during 1963	Vapam (80 gal.)	5
growing season)	Brozone (170 lb.)	7
	Trizone (200 lb.)	7
	M-2467 (50 gal.)	8
	MC-33 (170 lb.)	10
	Trizone (140 lb.)	11
	Vidden-D (50 gal.)	13
	M-2441 (50 gal.)	14
	Brozone (110 lb.)	17
	Unfumigated	22
1963 (Fall)	Trizone (200 lb.)	8
Coeur d'Alene	Brozone (170 lb.)	8
(counted 6/24/64)	MC-33 (170 lb.)	8
	Brozone (340 lb.)	14
	Vapam (80 gal.)	14
	M-2467 (50 gal.)	15
	Vidden-D (50 gal.)	16
	Trizone (140 lb.)	17
	M-2441 (50 gal.)	18
	MC-33 (300 lb.)	21
	Brozone (110 lb.)	22
	Vapam (40 gal.)	34
	Unfumigated	37
1963 (Fall)	Brozone (170 lb.)	5
Savenac	Brozone (340 lb.)	8
(counted 6/17/64)	Trizone (200 lb.)	11
	Vapam (80 gal.)	11
	MC-33 (170 lb.)	12
	MC-33 (300 lb.)	14
	M-2467 (50 gal.)	26
	Trizone (140 lb.)	27
	M-2441 (50 gal.)	30
	Vidden-D (50 gal.)	44
	Brozone (110 lb.)	45
	Vapam (40 gal.)	66
	Unfumigated	80

[1]Vertical lines indicate those population estimates that are not significantly different at the 95% probability level.
[2]No statistical test made.

There was some long-range weed control resulting from a single fumigation. Following the 1963 fall fumigation, soil samples were taken in selected plots, both fumigated and unfumigated, to a depth of 6 inches. The surface inch of soil was discarded to eliminate weed seed which had blown in since fumigation. Samples of the remainder of the soil were then spread on containers in the greenhouse, and weeds counted as they germinated. A total of only six weeds germinated on 37 samples of fumigated soils; in contrast, 33 samples from unfumigated soils supported a total of 425 weeds. Fumigation virtually eliminated viable residual weed seed to a depth of at least 6 inches. Many of these weed seeds have a prolonged viability and might eventually be brought to the surface by cultivation where they could germinate; thus, the treatments should provide some long-range weed control benefits.

A similar test of weed control was made in the fall of 1965 comparing soils operationally fumigated with Trizone at 200 pounds per acre with unfumigated soils. Soil samples were collected on October 10 after an early September fumigation. The soil had not been disturbed in the period between fumigation and sampling. Twenty-four randomly selected locations were chosen in both fumigated and unfumigated areas. At each location a sample was obtained from each of three levels beneath the soil surface: 1 to 2 inches; 4 to 5 inches; and 8 to 9 inches. Weeds were then germinated from measured subsamples in the greenhouse with the following results:

Soil depth	*Number of weeds per sample*	
(Inches)	*Fumigated*	*Unfumigated*
1 - 2	6.9	44.9
4 - 5	7.4	46.0
8 - 9	5.4	29.6

Differences in weed population between fumigated and unfumigated soils were highly significant (99% probability level).

The deep-action effect of fumigation on residual weed seeds, as demonstrated in these two tests, promises to provide a reduction in weed population for future crops.

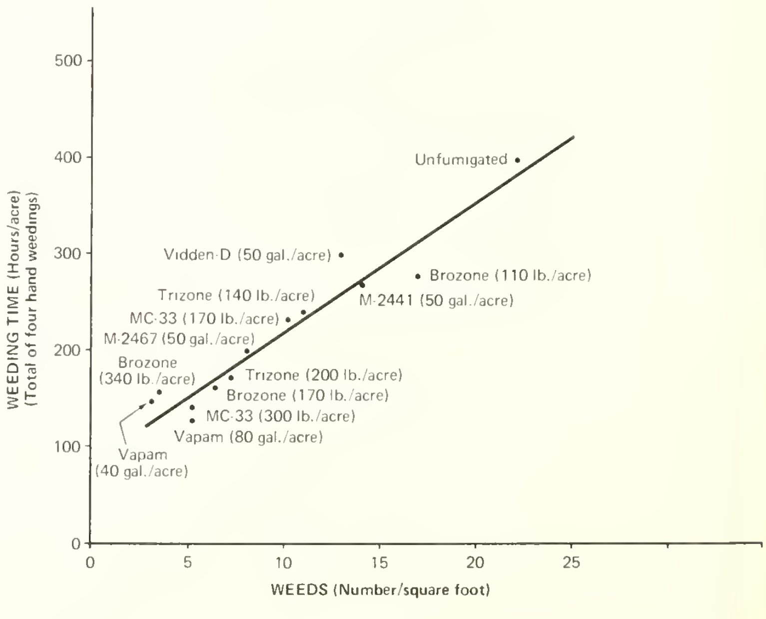


Figure 1.--Weeding time as related to the weed densities resulting from various fumigant treatments in the 1963 spring trials at Coeur d'Alene nursery.

None of the fumigation treatments tested have eliminated weeds. Some hand weeding has been required to control deep-rooted perennials, weeds from windblown seed, and, no doubt, weed seed which escaped fumigation due to imperfect application techniques. Much of the effort spent in fumigation can be lost if weeds, which become established in spite of the best fumigation efforts, are not removed or killed prior to their seed maturation and dispersal.

EFFECTS ON WEED CONTROL COSTS

Hand-weeding time studies were made during the 1963 spring and fall fumigation trials at Coeur d'Alene. A range of weed densities provided by fumigation treatments were correlated with weeding time and cost. Figure 1 shows the relationship between number of weeds, weeding time, and fumigant treatment for a total of four hand weedings during the first growing season in the 1963 spring fumigation trials. Unfumigated beds with approximately 22 weeds per square foot required nearly 400 hours of hand-weeding time per acre; weeding time was below 300 hours per acre on fumigated beds. The better fumigants reduced weed populations to less than 10 weeds per square foot and weeding times to under 200 hours per acre.

For seedbeds fumigated in the fall of 1963, time records were obtained for a single hand weeding in late June of the following year (figure 2). Weeding time for given weed densities ran higher than those for spring fumigation because the weeds were larger and greater care had to be used in removing them to keep from damaging tree seedlings. Unfumigated beds, and those fumigated with Brozone at 110 pounds per acre and Vapam at 40 gallons per acre (not covered by tarpaulins), had two to three times as many weeds as the more effective fumigants. Weed populations were generally higher in this test than in the 1963 spring tests due to the accumulation of windborne seed during the fall and winter following fumigation.

These two analyses (figures 1 and 2) indicate that, on the average, 10 fewer weeds per square foot should result in a reduction of 137 to 155 hours per acre in weeding

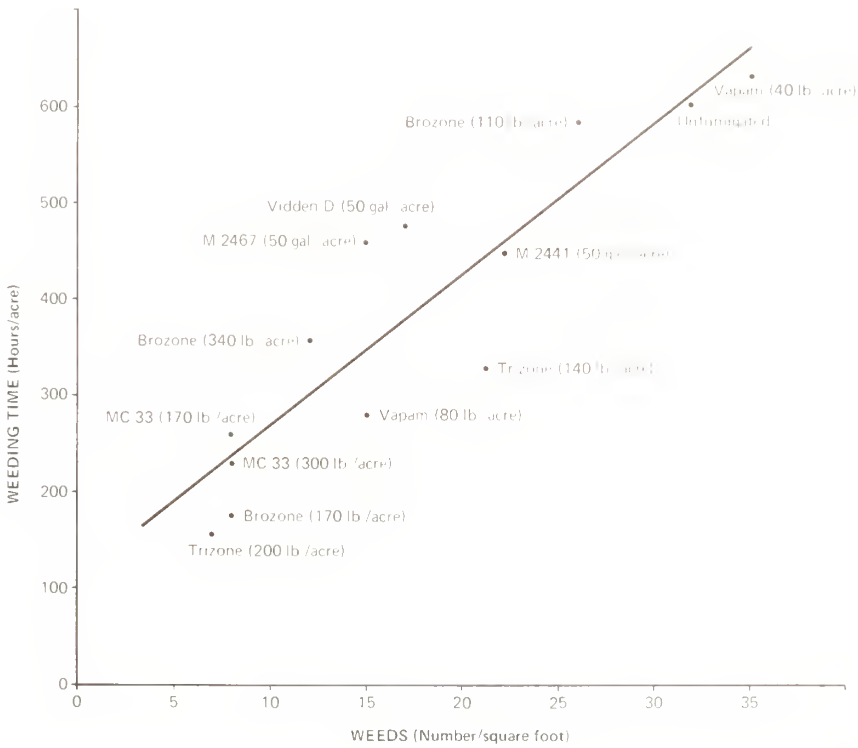


Figure 2.--Weeding time and weed density relationships, 1963 fall fumigation (four blocks, June 24 hand weeding).

time within the density ranges sampled. At a labor cost of $2.50 per hour, this would represent a savings of $342 to $387 per acre. For the more effective fumigants, which reduced weeds by over 20 per square foot, the savings in labor were generally over $700 per acre and ranged as high as $1,000 per acre.

Hand weeding is not, however, the only alternative to weed control. Herbicides, including the aromatic oils, and mechanical cultivation are successfully used at many nurseries to reduce weed populations and minimize hand work. Aromatic oils are successfully used on most species at Savenac, but have never been a dependable weed control measure at Coeur d'Alene without the risk of damage to the conifer crop. As yet, none of the synthetic herbicides has been useful except on non-crop areas such as fence lines and irrigation pipelines. Mechanical cultivation between drill rows has been abandoned because of the danger of soil splash on small seedlings. However, fumigation as a weed control measure alone is financially justified at Coeur d'Alene where conditions are characterized by: high residual weed seed population; weeds resistant to selective herbicides; crop species for which there is no suitable selective herbicide; and soil conditions which prevent mechanical cultivation.

DISEASE CONTROL

METHODS

Sample plots sown with known numbers of seed, nursery inventory data, and periodic counts of dead and dying seedlings were used to evaluate the effects of soil fumigation on the control of seedling diseases. Differences in germination and seedling survival were judged to be caused primarily by treatment effects on pathogenic fungi, but effects on nematodes and insects may have contributed to these differences. Plot design and statistical analysis used in the disease control evaluation were the same as those used in evaluating weed control.

EFFECTS ON SEEDLING PRODUCTION

In the 1961 tests, fumigated seedbeds had from 20 to 150 percent more seedlings than unfumigated beds, based on a September inventory of the 1-0 stock. Average increases were greatest for Douglas-fir (66%), followed by western white pine (57%), Engelmann spruce (39%), and ponderosa pine (32%). Germination and post-emergence mortality patterns indicate that fumigation reduced pre- and post-emergence mortality about equally well in Douglas-fir, ponderosa pine, and Engelmann spruce. Western white pine stand increases in fumigated soils, however, must be attributed largely to control of pre-emergence mortality since post-emergence mortality was greatest in the fumigated beds. Brozone applied at 340 pounds per acre produced the greatest average yield increase (98%), followed by Trizone at 180 pounds per acre (48%), Trizone at 140 pounds per acre (32%), and Brozone at 170 pounds per acre (17%).

A number of the 1963 fall fumigation treatments at Coeur d'Alene provided substantial and significant increases in seedling production of 2-0 stock (table 3). The production of western white pine was significantly increased by all of the methyl bromide-based fumigants, except the lowest rates of Trizone and Brozone, and by both application rates of Vapam. Increases in the 2-0 seedling stand, for effective treatments, ranged from 50 to 97 percent, with Trizone at 200 pounds per acre providing the largest increase.

Douglas-fir production results were similar except that neither the highest rate of Brozone (340 lb./acre) nor the 40 gallon per acre Vapam treatments were effective in increasing production. The effective treatments provided increases in Douglas-fir production of 23 to 144 percent. MC-33 at 300 pounds per acre was outstanding with a 144 percent increase in the 2-0 stand.

Engelmann spruce production was increased significantly by two fumigants (Trizone at 140 lb./acre and Brozone at 170 lb./acre). Other production gains probably were present although they are not statistically significant. Replications may have been inadequate to remove the effect of the great variability in disease incidence in the nursery fields. Percentage increases in spruce production ranged from 115 to 133 percent.

Table 3.--*Differences in density per square foot of 2-0 stock grown in fumigated and unfumigated seedbeds at Coeur d'Alene nursery, 1963 fall fumigation*

Fumigant (amount applied/acre)		Western white pine			Douglas-fir			Engelmann spruce			Ponderosa pine		
		Fum.	Unfum.	Diff.	Fum.	Unfum.	Diff.	Fum.	Unfum.	Diff.	Fum.	Unfum.	Diff.
		Seedling density per square foot											
Trizone	(140 lb.)	38	30	8	34	32	2	43	20	23*	60	52	8
	(200 lb.)	45	23	22**	39	26	13*	30	23	7	60	51	9
Brozone	(110 lb.)	36	29	7	29	19	10	29	13	16	52	57	-5
	(170 lb.)	48	29	19*	58	47	11*	42	18	24*	66	60	6
	(340 lb.)	42	28	14*	47	49	-2	24	21	3	54	51	3
MC-33	(170 lb.)	39	26	13*	47	32	15*	20	7	13	58	51	7
	(300 lb.)	52	32	20*	39	16	23**	39	25	14	52	54	-2
Vidden-D	(50 gal.)	29	18	11	20	20	0	22	22	0	57	58	-1
M-2441	(50 gal.)	32	31	1	27	28	-1	21	19	2	45	53	-8
M-2467	(50 gal.)	30	21	9	27	29	-2	16	23	7	60	51	9
Vapam	(40 gal.)	46	28	18*	34	35	-1	13	9	4	51	48	3
	(80 gal.)	43	25	18*	39	19	20*	29	28	1	46	33	13*

*Differences significant at 95% probability level.
**Differences significant at 99% probability level.

Ponderosa pine production was, in general, the least affected by fumigation. Only Vapam at 80 gallons per acre provided a significant increase (39%) in 2-0 seedling production. None of the dichloropropene base compounds (Vidden-D, M-2441, or M-2467), nor the lowest rate of Brozone, resulted in any significant changes in plant production.

In seedbeds fumigated in the fall of 1963, the post-emergence mortality during the first growing season was generally only slightly greater in unfumigated than in fumigated seedbeds. Also, the magnitude of differences in the 1-0 stands in fumigated and unfumigated beds was about the same as the 2-0 stand differences. Thus the treatment effects on overall plant production seem to have been primarily the result of reductions in pre-emergence losses.

The effects of fumigation on the ultimate production, and therefore, by inference, on the incidence of disease losses, were highly variable with significant block effects as well as significant treatment effects. A particular treatment tended to look effective or ineffective depending on whether it happened to fall in an area of high disease incidence and virulence or in an area where conditions were naturally unfavorable for the pathogen. The design of the trials was generally not adequate to remove the effect of such differences and provide good statistical information on the relative effectiveness of the various fumigants.

The effects of the 1963 fall fumigation at the Savenac nursery were similar to those at Coeur d'Alene. Production of 3-0 Engelmann spruce stock was increased from 21 to 35 percent by MC-33 at 300 pounds per acre, Trizone at 200 pounds per acre, and Brozone at 170 pounds per acre. Although sampling of other species was not sufficient for a good statistical test, it was obvious that western white pine production was greatly benefited by MC-33 at both rates, Trizone at 200 pounds per acre and by Vapam. Savenac ponderosa pine was least benefited by fumigation but did display increases in production with the better fumigants such as Trizone at 200 pounds per acre.

Spring fumigation, unlike the fall fumigations, provided no detectable control of disease losses. Neither post-emergence damping-off nor the 1-0 stand densities were significantly different on fumigated and unfumigated soils. In fact, seedlings growing in fumigated soils were often stunted and chlorotic. If fumigation provided some disease control, it was masked either by fumigant toxicity or unknown secondary detrimental effects. While there may be some advantage to sowing as soon after fumigation as possible, Coeur d'Alene spring weather is generally not warm enough to bring the soil temperature up to suitable fumigation levels until mid-May, which is generally several weeks beyond the optimum sowing date. This delay in sowing, plus the additional delay imposed by allowing time for the chemicals to dissipate from the soil, makes spring fumigation impractical.

SEED COST SAVINGS

The higher seedling survival promoted in the nursery beds by fumigation can result in appreciable savings through lower seed costs. The amount of savings depends not only on the effectiveness of disease and insect control, but also upon the desired seedbed density and upon seed costs.

Using a final density goal of 40 seedlings per square foot, savings in seed cost have ranged as high as $1,100 per acre for a fumigation investment of approximately $400 per acre. This occurred in Douglas-fir seedbeds at Coeur d'Alene which have been particularly subject to disease losses. Seed cost savings have been highest with Douglas-fir, western white pine, and ponderosa pine. Savings with Engelmann spruce and western larch have been relatively small due to the low cost per unit count of seed.

SEEDLING GROWTH

METHODS

The effects of soil fumigation on seedling development have been evaluated by observation and by measurement of the following characteristics on three to four randomly selected groups of 10 seedlings from both fumigated seedbeds and their paired, unfumigated controls:

Height of shoot
Weight of shoot (ovendry basis)
Stem diameter (at root collar)
Shoot-root ratio (by weight)
Weight of roots (ovendry basis)
Root area index[3]

Most of the results are based on the 1963 fall fumigation trials at Coeur d'Alene and Savenac. Only those fumigation treatments which seemed to have provided the most effective pest control and the best growth responses were included in the sample measurements.

EFFECTS ON SEEDLING SIZE

Soil fumigation at Savenac and Coeur d'Alene has caused a variety of seedling growth responses ranging from a definite depression of growth to substantial increases in seedling size. In the 1963 spring fumigation, for instance, a number of treatments caused reduced growth and seedling chlorosis. There were no obvious increases in seedling growth resulting from spring fumigation.

In the 1963 fall-fumigation trials, measured seedlings provide results ranging from "no-effect" to substantial and significant increases in the size characteristics of 2-0 and 3-0 seedlings (figure 3 and table 4). In general, seedlings grown in fumigated soils were larger than those from unfumigated soil. In about 22 percent of the individual comparisons which were made, this difference proved significant at the 95-percent level of probability or greater. There were not enough differences in the

[3]A technique (similar to the "root titration" measurement used by many nursery workers) in which the relative surface areas of root systems are determined by dipping the roots in a dilute water-india ink suspension, draining, washing the roots in water, and colorimetrically measuring the amount of ink transferred. The recorded difference in light transmittance is the "root area index."

Table 4.--*Effect of soil fumigation on size attributes of 2-0 stock grown at Coeur d'Alene and Savenac nurseries, 1963 fall fumigation*

Nursery & treatment (amount applied/acre)	Top height Fum.	Top height Unfum.	Top height Diff.	Stem diameter Fum.	Stem diameter Unfum.	Stem diameter Diff.	Root area index Fum.	Root area index Unfum.	Root area index Diff.	Top weight[1] Fum.	Top weight[1] Unfum.	Top weight[1] Diff.	Root weight[1] Fum.	Root weight[1] Unfum.	Root weight[1] Diff.	Shoot/root ratio[2] Fum.	Shoot/root ratio[2] Unfum.	Shoot/root ratio[2] Diff.
	- - -	cm. - - -		- - - -	mm. - - - -					- - - -	g. - - - -		- - - -	g. - - - -				
WESTERN WHITE PINE																		
Coeur d'Alene																		
Trizone (200 lb.)	7.5	5.7	1.8	2.6	2.5	0.1	8.4	7.8	0.6	0.88	0.72	0.16	0.37	0.42	-0.05	2.35	1.71	0.64
MC-33 (300 lb.)	10.3	6.2	4.1*	3.3	2.6	.7*	13.2	10.9	2.3	1.62	.81	.81*	.58	.48	.10	3.03	1.70	1.33*
Vapam (80 gal.)	6.7	6.6	.1	2.3	2.3	.0	8.3	13.1	-4.8**	.67	.77	-.10	.35	.53	-.18	1.95	1.45	.50
Savenac																		
Trizone (200 lb.)	7.7	5.6	2.1	2.4	2.1	.3*	6.2	4.6	1.6	.74	.48	.26	.29	.23	.06	2.60	2.08	.52
MC-33 (300 lb.)	6.6	5.5	1.1	2.0	1.9	.1	4.8	4.9	-.1	.53	.42	.11	.25	.22	.03	2.32	2.00	.32
Brozone (340 lb.)	5.8	4.0	1.8*	2.2	1.8	.4*	5.6	3.5	2.1*	.59	.34	.25*	.28	.18	.10*	2.14	1.92	.22**
Vapam (80 gal.)	6.1	4.8	1.3	2.1	2.0	.1	4.8	4.3	.5	.51	.38	.13	.22	.22	.00	2.43	1.77	.66**
DOUGLAS-FIR																		
Coeur d'Alene																		
Trizone (200 lb.)	9.8	7.8	2.0**	2.9	2.4	.5*	7.9	4.7	3.2**	1.08	.60	.48**	.46	.29	.17**	2.35	2.03	.32**
MC-33 (300 lb.)	9.0	6.9	2.1*	2.4	2.3	.1*	8.0	7.0	1.0	.81	.55	.26	.33	.32	.01	2.40	1.72	.68**
Brozone (170 lb.)	11.0	10.8	.2	3.0	2.9	.1	12.2	11.9	.3	1.16	1.15	.01	.54	.48	.06	2.21	2.46	-.25
ENGELMANN SPRUCE																		
Coeur d'Alene																		
Trizone (200 lb.)	8.9	8.1	.8	3.2	2.9	.3	10.8	10.3	.5	1.35	1.25	.10	.51	.47	.04	2.69	2.65	.04
Savenac[3]																		
Trizone (200 lb.)	13.7	8.9	4.8**	2.9	2.6	.3**	--	--	--	1.24	.88	.36*	.42	.45	-.03	2.98	1.90	1.08**
MC-33 (300 lb.)	16.6	9.0	7.6*	3.6	2.8	.8	--	--	--	2.22	.98	1.24	.68	.44	.24	3.26	2.19	1.07
Brozone (170 lb.)	14.5	9.5	5.0*	3.4	2.7	.7	--	--	--	1.63	.80	.83*	.52	.38	.15	3.11	2.26	.85
PONDEROSA PINE																		
Coeur d'Alene																		
Trizone (200 lb.)	22.1	22.0	.1	3.1	3.2	-.1	9.6	10.5	-.9	2.17	2.09	.08	.61	.67	-.06	3.57	3.14	.43
MC-33 (300 lb.)	21.9	23.6	-1.7	2.9	3.6	-.7	8.7	12.5	-3.8	1.82	2.66	-.84	.50	.78	-.28	3.73	3.47	.26
Brozone (340 lb.)	22.7	22.2	.5	3.2	3.2	.0	8.9	8.8	.1	1.97	2.04	-.07	.58	.57	.01	3.56	3.61	-.05
Savenac																		
Trizone (200 lb.)	22.4	20.7	1.7	3.0	3.0	.0	8.2	6.3	1.9	1.87	1.78	.09	.36	.38	-.02	5.26	4.61	.65
MC-33 (300 lb.)	20.2	18.6	1.6**	2.8	2.5	.3	8.6	7.6	1.0	1.38	1.05	.32**	.36	.32	.04*	3.80	3.24	.56**
Brozone (170 lb.)	18.7	18.0	.7	2.5	2.3	.2	10.1	7.3	2.7*	1.00	.85	.15**	.33	.30	.05	2.93	2.81	.12

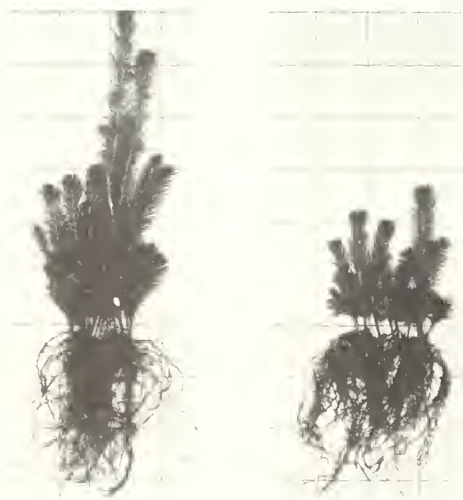
[1]Ovendry basis.
[2]Shoot/root ratio computed from ovendry weights of tops and roots. Each sample = 10 trees.
[3]Engelmann spruce at Savenac nursery was measured as 3-0 stock.
*Differences significant at 95% probability level.
**Differences significant at 99% probability level.

Fumigated Unfumigated
Ponderosa pine (2-0)
Coeur d' Alene nursery

Fumigated Unfumigated
Ponderosa pine (2-0)
Savenac nursery

Fumigated Unfumigated
Douglas-fir (2-0)
Coeur d' Alene nursery

Fumigated Unfumigated
Western white pine (2-0)
Coeur d' Alene nursery



Fumigated Unfumigated
Engelmann spruce (3-0)
Savenac nursery

Figure 3. — Some representative samples of the effects of soil fumigation with MC-33 at 300 pounds per acre on the size of conifers grown at Coeur d'Alene and Savenac nurseries. (Background grid = 2-inch squares.)

effects of individual fumigants to warrant a preference for any of the methyl bromide-based formulations. The effects of Vapam were measured only on western white pine and are inconclusive. None of the fumigants caused any significant changes in the measured characteristics of ponderosa pine at Coeur d'Alene. Douglas-fir had the largest proportion of significant increases of seedling size, followed by spruce, western white pine, and ponderosa pine.

Most of the estimates of the effect of fumigation on seedling size are probably conservative since the higher densities, typical of most fumigated seedbeds, tended to independently reduce most seedling size characteristics. The growth of western white pine seedlings at Savenac in thinned and unthinned beds demonstrates these relationships (table 5). Although fumigation generally resulted in larger stock at both high and low densities, the high-density seedlings grown in fumigated soil were

Table 5.--*Size characteristics of 2-0 western white pine seedlings grown at low (55/sq.ft.) and high (153/sq.ft.) seedbed densities in fumigated and unfumigated soil*

Characteristic	Seedbed density	Fumigated[1]		Unfumigated[1]
Top height (cm.)	Low	6.0	**	4.9
		--	**	**
	High	7.1	**	5.0
Stem diameter (mm.)	Low	2.4	**	2.2
		**	*	**
	High	1.9	*	1.7
Root-area index (units)	Low	7.1	*	5.5
		**	*	**
	High	3.5	--	3.2
Top dry weight (g.)	Low	0.93	**	0.50
		**	--	**
	High	0.45	**	0.31
Root dry weight (g.)	Low	0.35	**	0.28
		**	**	**
	High	0.17	--	0.15
Shoot/root ratio (dry weight basis)	Low	2.08	*	1.82
		*	**	*
	High	2.66	**	2.06

[1]Asterisks between any horizontal or vertical pair of the four means given for each characteristic indicate a significant difference at the 95% (*) or 99% (**) probability level. Dashed lines (--) indicate no significance. Symbols within the diagonal lines mean that the test applies only to the means connected by the diagonal line.

generally smaller than seedlings grown at low density in unfumigated soil. Thus, in this extreme case, the density effects have completely concealed the true fumigation effects. If all of the size comparisons could have been made at common densities, both the magnitude and number of significant differences in seedling size would probably have been greater.

In general, the increases in seedling size characteristics associated with soil fumigation can be considered beneficial. Seedlings grown in fumigated soil are generally large enough to outplant at an earlier age than those from unfumigated soils. Even ponderosa pine, which showed no increase in size in the 1963 fall-fumigation tests at Coeur d'Alene, has responded to subsequent operational fumigation with improved growth and a higher percentage of trees developing fascicled needles during the first growing season. This improved growth has permitted the shipment of 1-0 ponderosa pine stock. Production time for Engelmann spruce stock has been shortened by 1 year, and some 1-0 Douglas-fir may be plantable. A 1-year reduction in time to produce seedling stock is equivalent to a cost savings of $3 to $4 per thousand or $3,000 to $4,000 per acre.

In one respect, however, the increased seedling growth may be detrimental. Seedlings from fumigated soils consistently have higher shoot-root ratios than those from unfumigated soil (table 4), indicating a poor "balance" of tops to roots. This has resulted not from a decrease in root weight, but rather from a proportionately greater increase in top weight than root weight. It seems that this effect may be, at least partially, an artifact resulting from standard lifting depth and root-pruning lengths, regardless of seedling size. Just how high the shoot-root ratio can go before it reduces field survival and growth is not known. To limit the development of high ratios in fumigated soils, nurserymen might wish to place greater emphasis on cultural practices such as root pruning in place or "root wrenching."

The reasons for improved seedling growth in fumigated soils are not clear. It is unlikely that the improvement can be attributed to reduced weed competition since both fumigated and unfumigated beds were kept relatively weed free. Reduced populations of soil organisms may have resulted in better nutrition of seedlings--or in a reduction of sublethal infections which could reduce growth without killing the seedlings.

OUTPLANTING SURVIVAL

METHODS

The survival potential of nursery stock grown in fumigated soil has been tested by a nursery-based "moisture-stress-plot" procedure rather than by field planting tests.[4] Stock (2-0) from the 1963 fall-fumigated test was used in this phase of the work. Seedlings from the same treatments used in the evaluation of growth (those shown in table 4) and from adjacent unfumigated beds were lifted in late April of 1966, stored until late May, and planted in the moisture-stress plots. All test seedlings were kept well-watered until July 1. The seedlings were then subjected to three moisture-stress regimes during the remainder of the growing season. Three random samples of 24 seedlings were tested for each species-fumigant-moisture stress combination. Survival was determined at 2-week intervals during the first growing season.

---

[4]Raymond J. Boyd and others. Moisture-stress-plot evaluation of nursery stock survival and growth potential. Western Forest Nursery Counc. Proc. 1968: 34-39, illus.

EFFECTS ON SURVIVAL

Except for the Coeur d'Alene ponderosa pine, and western white pine grown at very high densities, soil fumigation seems to have increased the survival potential of the stock (table 6). Differences were not great and the results were quite variable. Particularly notable were the 9 and 16 percent average increases in survival of Douglas-fir grown in fumigated soils and tested under severe and moderate moisture-stress levels, respectively. Fumigation significantly reduced the survival potential of ponderosa pine grown at Coeur d'Alene and tested at the moderate moisture stress level. In western white pine, both at Coeur d'Alene and at Savenac, there was no significant effect of fumigation on survival potential at any moisture stress level.

Although there is evidence that fumigation may reduce the survival potential of 2-0 ponderosa, this may not be a problem under the current practice of planting 1-0 rather than 2-0 stock. Fumigation, by stimulating early growth, may bring about severe competition at an earlier age. Thus 2-0 stock grown in fumigated soil may be suffering from rather severe competition which could be reflected in reduced survival capabilities. In contrast, the 1-0 stock is still relatively free growing in the nursery beds. Some recent field tests show that there is very little, if any, difference in field survival of 1-0 and 2-0 ponderosa pine grown in fumigated nursery soils.

Table 6.--*Effects of moisture stress on survival of outplanted 2-0 stock grown in fumigated and unfumigated soils*

Nursery and species	Low stress			Moderate stress			Severe stress		
	Fum.	Unfum.	Diff.	Fum.	Unfum.	Diff.	Fum.	Unfum.	Diff.
	Percent survival[1]								
Coeur d'Alene									
Ponderosa pine	96	97	-1	86	92	-6*	60	70	-10
Douglas-fir	92	89	3	71	55	16*	46	35	9*
Western white pine	94	97	-3	92	91	1	0	1	-1
Savenac									
Ponderosa pine	96	96	0	95	86	9	62	53	9
Western white pine									
Low density[2]	96	94	2	97	89	8	1	0	1
High density[2]	83	93	-10	81	84	-3	0	0	0

[1]Percent of survival converted to arcsin $\sqrt{\%\text{ survival}}$ for statistical analysis.
[2]From fumigation-seedbed-density interaction study (see table 5).
*Differences significant at 95% probability level.

DISCUSSION, CONCLUSIONS

Several years of trials have demonstrated that soil fumigation at the Coeur d'Alene and Savenac nurseries is a practical operation from the standpoint of pest control, growth stimulation, and increased survival potential.

Weed and disease control have been best with methyl bromide-based fumigants and with Vapam, applied at medium to high rates. The dichloropropene-based fumigants were not effective enough to be considered practical. Late August or early September fumigation has proven more effective and more practical than spring fumigation. Fumigation at this time of year gives plenty of time to prepare the soil and to fumigate at the optimum temperature and moisture content. The nursery workload is relatively low at this time, so the extra job of fumigation is not a great hardship to the nurseryman. Most important, however, when conditions for sowing are favorable the following spring, the soil can be worked and the seed sown at the earliest possible date to gain the advantage of early germination and a long growing season. Spring fumigation proved operationally difficult and resulted in stunted seedlings and no observable disease control.

Both spring and fall fumigation substantially reduced weed populations during the first growing season, and reduced potential weeds by killing seed to a depth of at least 9 inches. When compared to hand weeding, the more effective fumigants provided substantial savings in weed control costs.

Production was greater in effectively fumigated seedbeds, reflecting primarily the control of pathogenic fungi. Control of white grubs was observed 1 year and may have played a part in the observed effects in other years. Although nematodes were not abundant enough to be considered a problem, reduction of their population by fumigation could have contributed to the good results. Fumigation, by providing more plants per pound of seed, reduced the seed cost by substantial amounts, often exceeding the $300 to $400 per acre fumigation expense.

Soil fumigation with the methyl bromide-based fumigants has generally increased the size of seedling stock of Douglas-fir, western white pine, Engelmann spruce, and ponderosa pine. These effects of fumigation on the size of planting stock are, for the most part, beneficial since they have helped to reduce the time required to produce stock which is suitable for planting. A reduction of 1 year in production time is roughly equivalent to $3 to $4 per thousand seedlings or $3,000 to $4,000 per gross nursery acre. Since fumigation increases the plant density from a given amount of seed, a reduction in sowing rates is required to capitalize on the full effects of fumigation on plant size.

Survival of 2-0 stock from fumigated seedbeds when "outplanted" into semi-controlled soil-moisture-stress levels was generally equal to or better than that of stock from unfumigated soil. Douglas-fir survival under moderate and severe soil moisture stress was significantly improved by fumigation. In contrast, the survival potential of Coeur d'Alene grown 2-0 ponderosa pine was reduced by fumigation. However, fumigation has made it possible to raise suitable 1-0 ponderosa pine planting stock which survives field planting well and is probably not as severely affected by competition in the nursery beds as is the 2-year-old stock used in testing field survival of stock from the fumigation tests.

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

USDA Forest Service
Research Paper INT-92
1971

SOME ECONOMIC CONSIDERATIONS OF WATERSHED STABILIZATION ON NATIONAL FORESTS

Alan W. Green

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Ogden, Utah 84401

THE AUTHOR

Alan W. Green began his Forest Service career in 1955 at the Central States Station office in Carbondale, Illinois, as a Research Forester in silviculture and regeneration. From 1958 until 1961 he was superintendent of the Amana Experimental Forest in Iowa. In 1961 he was assigned to the Foreign Forestry Services branch in the Washington Office as an analyst of timber resources and industries on an international basis. He joined the Timber Production and Multiple Use Economics Project at the Intermountain Station in Ogden, Utah, in 1964 and is currently the Project Scientist in Research Work for Evaluation of Timber Growing Opportunities and Forestry Program. In addition to a degree in economics, he also holds both Bachelor and Master of Science degrees in forestry from Purdue University.

USDA Forest Service
Research Paper INT-[illegible]
April [illegible]

SOME ECONOMIC CONSIDERATIONS OF WATERSHED STABILIZATION ON NATIONAL FORESTS

Alan W. Green

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

CONTENTS

ABSTRACT

The Forest Service is responsible for protecting and managing nearly half the major watersheds in the high mountain areas of the Western States. By 1985, water demands of people in the Western States probably will have doubled. Sites for storage and distribution facilities to assure adequate and timely delivery of water are limited, and in many areas alternate sites are nonexistent. Consequently, the Forest Service must look ahead in its watershed management planning to assure that such projects are given every opportunity for continued efficient operation.

Appropriate long-term planning means that use damaging to watersheds must be stopped, damaged watersheds repaired, and control of use gained before water storage projects are undertaken, not afterward. The kind and level of land use on watersheds must have protection as the primary goal rather than predicating protection and rehabilitation activities on desired land use patterns.

Limited budgets demand a careful evaluation of stabilization and rehabilitation activities in terms of costs, probable results, and accomplishment of basic goals and objectives. Alternative measures must be considered in relation to effectiveness and overall efficiency of water management.

INTRODUCTION

For many years the Forest Service has been conscious of its watershed responsibilities in the Western States. The high mountain country in the 11-State area from New Mexico to Montana and westward provides the water necessary for the survival and well-being of some 32 million persons. About 18.5 percent of the land area in these States is administered by the Forest Service and nearly 50 percent of the major water producing areas fall within National Forest boundaries. Acting as managers of watersheds that supply the needs of so many people is indeed a grave responsibility.

The Forest Service, throughout its history as a public land management agency, has given special attention to problems of water production and quality in conjunction with its management and protection of other land resources and within the framework of its land stewardship commitment. A major consideration in regulating timber harvest, range use, and the general development of forest land has been to maintain or improve watershed and streamflow conditions. The concern for these critical watersheds is reflected in the policy to rehabilitate, as promptly as funds permit, those watersheds damaged by fire or past management practices.

Damage to watersheds is not a problem the Forest Service alone faces, nor is it a problem peculiar to the West. Moreover, not all such damage can be called "historical." Although it is true that before National Forests were established the millions of sheep and cattle that roamed the open ranges did irreparable damage, overgrazing continued long afterward on the Forests and on other public lands. Although the Taylor Grazing Act and actions by the Forest Service have succeeded in substantially reducing the impact of heavy grazing, there have been many instances where public land agencies, including the Forest Service, have permitted a level of grazing that has since proved far too heavy.

Overgrazing cannot, however, be blamed for all watershed damage either past or present. Careless logging operations, poorly-constructed road systems, mining activities, and excessive concentrations of big game in small areas, coincident or subsequent to depletion of larger game-range areas, also contributed to many of the current watershed problems.

During the time the Forest Service has been attempting to conquer its watershed management and rehabilitation problems, the rapidly developing West has placed even greater demands on watersheds. These demands are both for water production and other onsite uses at levels that are potentially damaging. As the development of the land and communities moved out of the valley bottoms, there was a need for increasing numbers of storage and distribution facilities. As a result, such facilities were often constructed before the land use and land management problems on the watersheds could be brought under control. Consequently, many small reservoirs filled with sediment at such rates that they virtually had no chance to function as designed.

These pressures for more water and increased onsite uses likely will continue. Current projections of population growth indicate that by 1985 about 45 million persons will be relying on the same watershed areas for a water demand that could double. Consequently, an increasing number of water development projects are being undertaken, and they are expensive. In the West the precipitation is highly seasonal over most of the region where water is most needed. Providing adequate water at desired times requires large storage facilities in areas where alternative storage sites are very limited, if they exist at all. Limited sites and few alternatives make it imperative that completed storage and distribution projects be given every chance for long-term effective operation. A reservoir that is rapidly filling with sediment cannot be useful for very long.

In the past, construction of many water development projects has been established under the assumption that the Forest Service, or other responsible agency, would be able to stop all but "natural erosion" immediately to assure maximum benefits from such projects. While such an assumption is not inconsistent with the desires of the Forest Service, such control is very difficult and rarely has been achieved. This general lack of control stems from several reasons and their economic implications are important and point to one fact: water development projects are more expensive in the long run when the normal erosion and sedimentation rate is not achieved.

In the first place, the extremely complex patterns of land use and their attendant socio-economic institutions have often resulted in damaging use of watershed resources. Changing these patterns so that they are compatible with environmental and biological constraints of the watershed is a slow and most difficult task. In many cases, communities have developed far beyond the capacity of the land and resources to sustain them.

In addition, greater public interest in environmental quality and resource protection is being expressed today; however, there remains a real lack of understanding by the public of the environment-resource use relationship as it applies to watersheds. Unfortunately, it is only when the public understands these relationships that they are willing to finance needed watershed work. The willingness to finance depends on the value seen in such work, but the simple fact is that value is a social expression and water has value in relation to a watershed only to the extent that society understands such relationships. Because the concepts of value in relation to environment are only now beginning to materialize, they cannot be adequately considered in feasibility analyses of watershed improvement opportunities.

Somewhat related to the two situations mentioned above, there seems to be a general lack of knowledge about the capacity of watersheds to withstand use. Such information is basic to the determination of watershed use level, rehabilitation needs and opportunities, techniques, and probable success. Again, the lack of public understanding has seriously limited the financing of the research necessary for managers to learn how to deal with watershed problems.

The fourth factor, land ownership patterns, makes control of watershed conditions difficult if not impossible. Seldom is all the land on a large watershed under the jurisdiction of a single government agency. More commonly, private land is intermingled with public lands administered by one or more federal agencies. Adequate and coordinated watershed management and use is hard to achieve under this situation.

All generations face decisions involving consumption of certain resources in favor of economic growth. They must either set resource use limits or define a desired economic growth rate. If the present course is continued with regard to watersheds, it is doubtful that this generation will look any better to its descendants than do our ancestors to us. While all generations are willing to make some sacrifices in the name of resource protection, they do look for some indication of parity between generations so that no one generation becomes unduly burdened because of the mistakes or foolishness of their predecessors.

This resource-decision dilemma leads to two kinds of economic considerations--economic efficiency for the current generation and some kind of economic resource ethic for the next. The current generation can do its part in support of parity by doing foolish things with our resources less frequently and by being more efficient in achieving our own shortrun desires. As far as water development projects are concerned, the last sites available (such as Grand Canyon and Yosemite Park) will cost dearly in terms of other things that will have to be given up. Therefore, taking steps to assure some longevity to current and future water projects is imperative.

Watersheds differ in so many respects that it is difficult to say what is an "average" watershed. Yet the situation at Joes Valley Reservoir on the Manti-LaSal National Forest in north central Utah typifies many of the problems the Forest Service has to deal with in the present and in the future.

The purpose of this discussion is to examine some of the economic factors (relating to public needs and influences described above) that must be considered when planning for watershed stabilization and rehabilitation. Although data from a portion of the Joes Valley watershed will be used for purposes of discussion, this is not an after-the-fact evaluation of the desirability of the Joes Valley (Emery County) Project or the feasibility of stabilization and rehabilitation of that watershed. Rather, it is a look at some typical factors that should be emphasized in planning similar future projects.

Data from the North Dragon Creek subwatershed which drains into Joes Valley Reservoir will be used to illustrate specific points about the typical problems discussed. The area is heavily grazed, is a heavy producer of sediment, and the data on the watershed are more complete than for any other watersheds serving the reservoir.

IMPORTANT CONSIDERATIONS

There is seldom doubt about the worth of establishing water projects; however, for particular locations there may be great disagreement as to the propriety of this use of resources. But once a project has been approved and installed, the conclusion would have to be drawn that society as a whole deemed it worthwhile; certainly the provision for meeting increasing water demands would seem wise. However, water storage and distribution facilities are not cheap, either in terms of dollars or in total resource use, and there is no reason to expect the cost of such projects not to go up in the future.

Preplanned Project Life

A conservative cost estimate of the Joes Valley Reservoir construction and distribution system attendant to that storage is about $7.5 million, which provided 62,500 acre-feet of storage capacity:

Component	*Volume (acre-feet)*
Dead storage (sediment pool)	8,500
Inactive storage (conservation pool)	4,000
Active storage	50,000
Total	62,500

The installation of this system was approved on the basis of a 100-year expected life. This life expectancy was provided by creating the 8,500 acre-feet of dead storage to accommodate the sedimentation which was estimated at a rate of 85 acre-feet per year.

This points up an element of illusion in an analysis that assumes some specified life span such as 50, 100, or 120 years for a reservoir. If the sediment pool is expected to fill within a specified period either due to natural erosion and sedimentation rate or to an accelerated rate caused by damaging use, then it must be assumed that the site either will be abandoned or removal of silt will be necessary to provide additional years of service. But what is the reasoning that makes abandonment more acceptable than dredging? Dredging is expensive, but so is the construction of a dam; therefore, if we accept the idea that water is becoming an increasingly coveted commodity, then regardless of the investment, the stating of a life expectancy for the reservoir is open to criticism. This criticism is even more justified if alternative project sites are limited or nonexistent.

From this standpoint, Joes Valley is not typical because, if necessary, the dam that now cuts off a deep, narrow canyon could be raised and thus would provide additional storage area. The cost would include loss of established recreation and administrative facilities, grazing land and roads.

The main point, however, is that planning a specified project life for critical projects such as water development is questionable considering the surety of increasing water needs, limited project sites, high and rising costs in resources required, and increasing public concern over environmental stewardship.

But there is a more important consideration than preplanning effective reservoir life. It is precisely because water projects are expensive, sites are limited, water is critical, and society is concerned for the environment, that protection and control of management on the critical watersheds must be obtained before, not after, the dams are built. This is vital not only to the success of the water development project, but to the overall goals set by society for natural resource and environment protection.

The responsibility of the Forest Service to provide "post construction" assurance of water project success is not an enviable burden, especially considering the extent of demands upon many of the critical watersheds.

Grazing, a Major Problem

With few exceptions, on watersheds in the western mountains where high intensity summer storms are common, if not frequent, some erosion must be considered normal. The amount of erosion and the deposition of sediment into streams, lakes, reservoirs, and valleys depends on many factors, among which are terrain, geology of the area, character of the soil, and vegetative cover, in conjunction with intensity, duration, and frequency of storms. This "geologic" erosion and subsequent sediment deposit must be dealt with as a part of any water project. The amount of sedimentation that cannot be economically or feasibly stopped must be designed into the capacity of the storage facility as was done in Joes Valley.

The abnormal sediment produced by damaging intensities of land use on watersheds is not so easily dealt with. The single most damaging use of watersheds in much of the Intermountain West has been overgrazing by domestic livestock. Unfortunately, our ancestors grazed the range down to the bare soil on many critical watersheds that were at best unstable. This has the appearance of a sort of capital borrowing against the future in order to develop an economy of more substantial and lasting quality for their descendants. Even if we assume their thinking was along this line, it takes a great deal of charity for many in this generation to accept such motives, although in some instances this same outlook persists.

It is fortunate that the current generations have sufficient funds for correcting the situations we inherited; this money should be spent wisely if the commitments to resource development and protection are to be met.

Unfortunately, the social institutions of public grazing lands and subsidies are still with us, and there remain far too many watersheds being grazed to a degree that is damaging. And, here again, there is an element of illusion in the land use associated with watershed or environmental management. The real cost in resources is <u>not</u> met by incomes paid to the responsible agency or generally by incomes received by the user if the resource is utilized to the extent it is damaged. While it is a general economic truth that the cost of any resource use is measurable in terms of the alternative uses foregone, it makes little sense to sacrifice the resource, as well as the option to use the resource in the future, by being wasteful or damaging now. This is precisely what happens when watersheds are used at a damaging intensity. When alterna-tive project sites are too few or lacking, such use not only fouls the existing project, it also makes the future installation of as yet unplanned projects more expensive and more risky.

Still another illusion, therefore, exists concerning analyses related to stabiliza-tion and rehabilitation. The value of keeping sediment out of a reservoir is usually weighed against the cost of physically removing it once deposited, or against the cost of creating storage. However, this ignores the real cost of site deterioration on the land from which the sediment came. It is obviously false to assume that uncontrolled erosion caused by misuse of land does not have a cost to society. [illegible] rangeland deteriorates, erosion increases, reservoirs and streams [illegible] and the results are expensive to repair, if indeed they can be repaired within a reasonable time.

In Joes Valley, the grazing intensity on North Dragon was about 1,200 to [illegible] AUM's (animal-unit-months) before the dam was built, and continued for several years. The extent to which such use is damaging is reflected, though not precisely determined, by two other figures. First, it is estimated that the potential safe grazing intensity is about 550 AUM's. Second, the natural rate of sediment production on North Dragon is estimated to be about 22 acre-feet per year; however, past grazing practices have resulted in delivery of some 32 acre-feet of sediment per year. The natural, or geolog-ic rate, can be achieved when reduced grazing intensity, better range management, and rehabilitation are effected.

It is doubtful that income from grazing at Joes Valley in excess of 550 AUM's would ever equal the cost of removing sediment at some future time to keep the reservoir operating at designed capability. Grazing reductions and better range management alone (without rehabilitation treatments) would reduce sedimentation by about [illegible] acre-feet per year. The estimated cost of removing sediment from the reservoir would be between $1,326 and $3,978 per acre-foot; consequently, an additional 500 AUM's of grazing resulting in 5 acre-feet of sedimentation, would need to be worth approximately $6,630 to $19,890 to compensate for only the cost of handling the sediment created--a value most difficult, if not impossible, to achieve. In simpler arithmetic, this amounts to between $13 and $40 per cow month. This assigns no cost to the loss of soil that, because of the deposition of soil on lands between erosion location and the reservoir, exceeds 5 acre-feet per year.

The public pressure for grazing is an important consideration in Joes Valley as in other areas. In fact, water project benefits to ranchers downstream were predicated partially on the use of the watershed for summer grazing. There is a question as to whether even nondamaging grazing is economical, or in the best interests of society; the answer depends on the investment of all the resources required to provide a given amount of grazing.

The cost of fencing required for the management of a rest-rotation program on North Dragon is estimated at $25,000. It is assumed that the 550 AUM's planned for the area is a nondamaging level for the range and watershed resource. The annual receipts from grazing fees would be less than $550, hardly enough to cover the administrative cost of providing the grazing. The $25,000 would be largely subsidy to ranchers. On areas where more than dollar resources are expended (i.e., soil loss from grazing) the real cost of grazing is even more. The conclusion is obvious: utilizing forage on critical watersheds, even when it can be done safely, often is a costly operation because of the high cost of the developments needed to assure proper use and control.

Obviously, balancing dollar costs of providing grazing with grazing receipts is not the only consideration for public land management decisions relative to grazing. There may, or may not, be other benefits, tangible or intangible, to consider. However, a comparison of dollar costs and grazing receipts affords a point at which to start an evaluation; and if costs exceed receipts, or other dollar incomes, such a comparison indicates the real cost of providing any intangible benefits. Total costs are a basic consideration in any decision regarding provision of intangible benefits.

It cannot be assumed that the tangible and intangible benefits associated with the provision of grazing are worth, to the community or nation, the total cost measured in dollars, physical consumption, or resource deterioration. Society has placed an undetermined but not unlimited value on the provision of grazing and other resource use and protection programs. In land management planning, it is inconsistent to consider only the intangible benefits associated with grazing and ignore the actual costs in dollars and resources. Actual costs must include the total values lost through resource consumption or deterioration as well as dollar costs. Multiple use is a land stewardship principle, not a license to provide a consumptive subsidy in order to get a particular use at any price.

This is not to say that grazing should be eliminated from the plans for watershed management. The point is that land use has a cost and the real cost of any use should be considered in the management of the area, and control of the land use should be achieved before, not after, water projects are undertaken. To assume control will be gained afterward is no guarantee of project success. Therefore, it makes no sense to tolerate a kind and level of use that consumes or damages resources vital to the success of a water project thought desirable for the well-being of society. If water projects are vital enough to justify their high cost, any sediment not kept out of the reservoir by the most judicious management must eventually be hauled out; an expensive alternative at best.

Establishing Priorities

The Forest Service has always recognized the importance of prudent watershed management. As previously stated, the guiding policy for watersheds damaged by fire or past management practices has been to rehabilitate them as promptly as funds permit. Because funds are always limited, priorities for treating watersheds must be established and money available for a given watershed project must be carefully used.

Because of the inherent variations in soil and ecological conditions on most watersheds, there are many ways in which rehabilitation goals can be realized.

Opportunities for natural recovery are present on all watersheds and they should always be given full consideration. The natural restoration of adequate vegetative cover may require elimination of use and varying degrees of biological or physical help. Later, some use may be tolerated on some areas. On other parts of the watershed, conditions of soil and capacity to provide adequate vegetative cover may preclude any direct use. The choice of more intensive and costly rehabilitation techniques such as one of several forms of mechanical stabilization requires an equally serious and thorough examination.

The hydrologic situations (hydrologic types[1]) encountered on a watershed must be evaluated in terms of cost of treatment, probable treatment response, available funds or the likelihood of obtaining adequate financing, land use constraints, and the basic goals and objectives of managing and using the watershed. Land use should be tailored to the effective operation of the watershed rather than tailoring the watershed management and rehabilitation to the use of the land.

---

[1]A hydrologic type or unit is an area which, considering soil, slope, and vegetation, will react similarly to a given amount of water in terms of runoff, erosion, absorption, and so on.

Some parts of a watershed may require such costly treatments for stabilization that their application for sediment reduction is not feasible; it would be far less expensive to dredge out an equivalent amount of deposit. Other parts of a watershed may feasibly be trenched, furrowed, ripped, or harrowed at reasonable cost. The costs and benefits of various treatment schedules must be evaluated in order to rank treatable areas by priority for treatment.

When grazing opportunities are included in the evaluation, priorities might change. With good cost-treatment response data coupled with information on consequences of grazing intensity, a Linear Program solution to optimize some objective function, subject to budget and land use constraints, would indicate different priorities depending on the levels of use and money specified as available. The data for North Dragon indicated that using a given budget, sediment reduction could be increased 15 acre-inches per year (from 117 to 132) by dropping grazing from 500 to 100 AUM's. The areas designated for treatment (priorities for treatment) also changed. This simply means that the kind and level of any land use affect not only the final results of treatment, but also influence the preferred ranking of treatments and selection of areas to treat in order to meet objectives and stay within the bounds of the constraints. These influences must be taken into account early in the planning of watershed projects.

Budget Levels

Establishing a budget level for a particular watershed project is a most difficult task; many factors must be considered and good cost-response data are mandatory. Also, some definite goals or objectives must be set--how much erosion is to be stopped or sediment delivery reduction to be achieved. The "Let's git 'er!" approach to stabilization and rehabilitation implies at least two things, both of which are untrue. First it implies that given enough money, all erosion on the watershed could be stopped. Second, it implies that stopping as much erosion as is physically possible is worth whatever it will cost.

It is unreal to assume that all erosion and sedimentation can be stopped. On North Dragon, only about 10 acre-feet of sediment can be kept out of the reservoir annually by the best and most appropriate treatment of areas where treatment is feasible; geologic erosion cannot be stopped.

It is equally unreal to assume that whatever it would cost to achieve the minimum erosion and sediment delivery would be worth it. For North Dragon, the marginal cost of reducing sediment skyrockets after the use of treatments costing up to about $30 per acre-inch reduction (for hydrologic type 1P) as the data for furrowing illustrate (table 1). (The same is also true for trenching on North Dragon.) By treating hydrologic types 9C through 1P, costs of $30,840 result in a total sediment reduction of 1,743 acre-inches (145 acre-feet) over an 80-year period. Treating the remaining hydrologic areas resulted in a total furrowing cost of $37,980 and a total sediment reduction of 1,819 acre-inches (151 acre-feet). That means that the last 76 acre-inches (6 acre-feet) cost $7,140, or about $94 per acre-inch (or an average of $1,128 per acre-foot). The sediment reduction on hydrologic type 4C costs $133 per acre-inch ($1,596 per acre-foot) by furrowing, and on hydrologic type 5E a treatment cost of $225 resulted in no additional sediment reduction. (It might well be cheaper to haul out the last 6 acre-feet of sediment after it is deposited.)

As in all spending situations, beyond some point the marginal cost of additional benefits becomes excessive. That is, an infinite amount of money will buy virtually no additional benefits. In this case it appears that no more than $32,000 could be justified on furrowing (fig. 1).

Table 1.--*Furrowing costs and 80-year sediment reduction by hydrologic types*

Hydrologic type	Total treatment cost	Sediment reduction	Cost/AI	Cumulative cost	Cumulative sediment reduction
	Dollars	*Acre-inches*	*Dollars*	*Dollars*	*Acre-inches*
9C	75	27.91	2.69	75	28
9B	120	20.36	5.98	195	48
9A	195	30.20	6.45	390	78
4L	450	36.67	12.27	840	115
1E	1,200	85.77	13.99	2,040	201
1XX	6,345	441.27	14.38	8,385	642
6N	345	23.84	14.47	8,730	666
4H	450	30.83	14.60	9,180	697
4D	11,970	659.72	18.14	21,150	1,357
1F	1,170	59.50	19.66	22,320	1,416
4P	300	14.23	21.08	22,620	1,430
1-0	7,545	289.18	26.10	30,165	1,719
1CB2	150	5.72	26.22	30,315	1,725
4F	75	2.55	29.41	30,390	1,728
1P	450	15.10	29.80	30,840	1,743
1CB3	825	16.52	49.94	31,665	1,759
1F3	975	14.50	67.24	32,640	1,774
1YY	150	1.65	90.91	32,790	1,776
4K	1,545	16.63	92.90	34,335	1,792
4E	1,095	10.23	107.04	35,430	1,802
4C	2,325	17.48	133.01	37,755	1,819
5E	225	0	0	37,980	1,819

For the hydrologic types on which furrowing was appropriate, ranking the types in ascending order of cost of achieving an acre-inch of sediment reduction, the total cost of treatment, and the total sediment reduction can be cumulatively added (table 1) to provide a total cost-sediment reduction curve (fig. 1). By spending $1,000, about 125 acre-inches of sediment can be kept out of the reservoir. For an additional $1,000, another 75 acre-inches can be stopped. Each additional $1,000 results in less and less sediment reduction until finally, after about a $35,000 expenditure, there is virtually no additional sediment reduction achieved regardless of how much money is spent. Even understanding the relationship between costs and expected treatment response gives no indication as to whether any level of expenditure is worth the money. Such an understanding can, however, keep the managers out of the area of obvious foolish spending.

For purposes of determining a budget, the planner-manager must come to a decision as to how far to go in treatments once it has been determined that the stabilization and rehabilitation goals have been set and achievement has been judged feasible. Where the marginal cost of a particular treatment exceeds the estimated benefits from the treatment, or where total costs for the treatment become excessive, less expensive means for reducing sediment delivery or erosion should be sought. This could mean evaluating other treatments on a particular area, the same treatment on other areas, or sediment removal schedules. Where the prescription approach to stabilization is used, the marginal cost, and total cost data, must be used to indicate the point beyond which additional spending is inefficient.

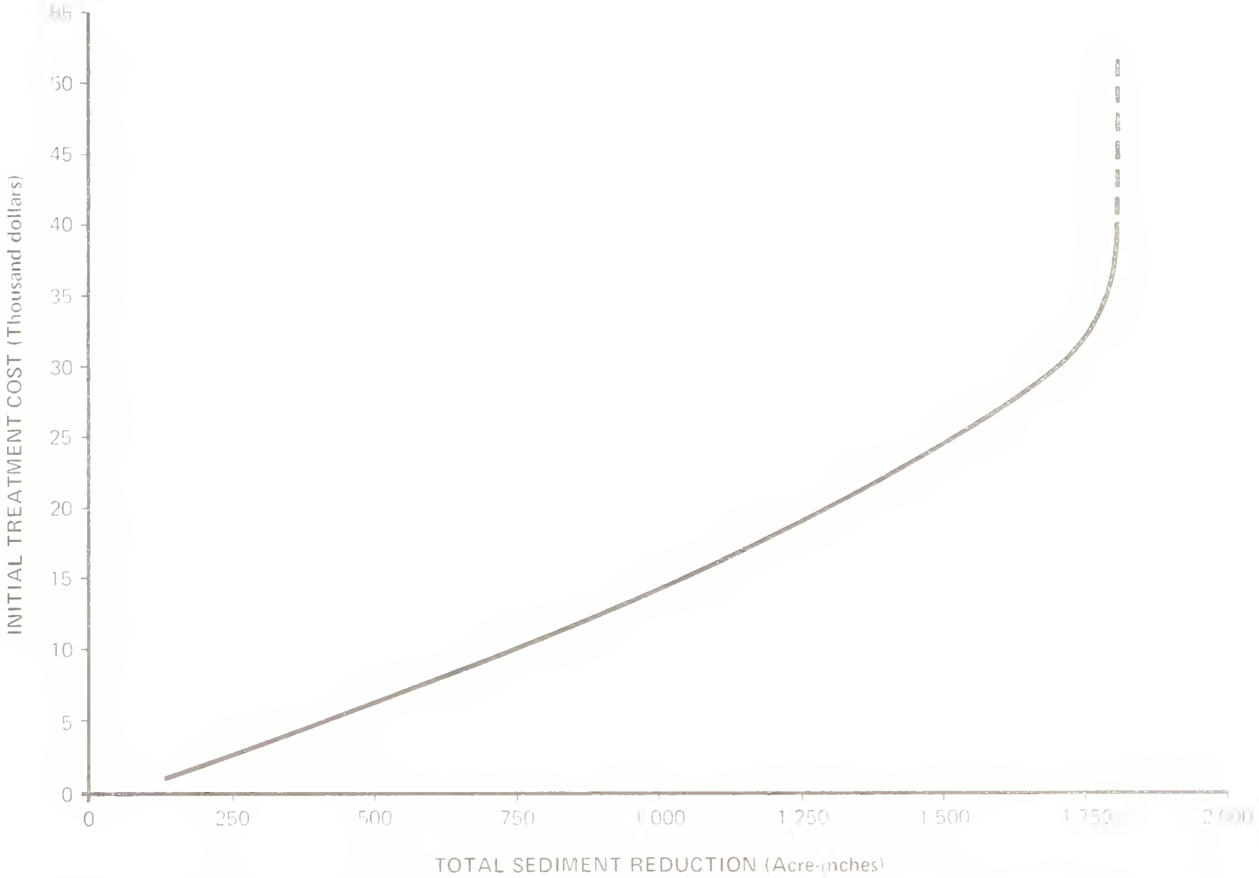


Figure 1.--Total cost-total sediment reduction for 30-year period on areas furrowed.

While economic analysis is an important tool in determining the budget required to achieve given goals and objectives, it is also important in allocating provided funds for a specific project or program. Managers have no choice but to be critical of their own spending proposals. The most difficult job is to guard against negating the benefits of spending by accommodating public pressures for certain types of land use that can either act counter to the goals of watershed management or increase the management cost of rehabilitation activity. The public land manager is no less responsible for fiscal integrity than he is for biological, ecological, and physical concern for the resource.

"Resource stewardship" is the phrase usually used to describe this obligation to the public, and it should be used as a guideline for management rather than a license to spend. The additional costs necessary to accommodate kinds and levels of uses that are generally local in scope and of limited value are direct subsidies to the user when the marginal costs exceed the marginal benefits for those who pay for them. It is presumptuous to assume society is willing to pay for something for which it has not recognized a value.

SUMMARY

Nearly half the major water producing areas in the high mountain areas of the Western States lie within National Forest boundaries. Presently, some 32 million people rely on water from these areas and by 1985 water demands will probably be double those of the present.

Sites for water development projects to assure timely and adequate water distribution are becoming limited and, in many cases, alternative sites are nonexistent. Such projects are not only expensive (and likely to become more so), they often are established in areas where they are served by watersheds damaged by past and current use and before adequate protection and control of the use and management of these watersheds is achieved.

The Forest Service is being put in a potentially untenable position regarding the use and management of critical watersheds by a public that needs increasing quantities of water and at the same time is making increasing demands as to land use and land use constraints. Because water development sites are limited and because future projects will be more and more expensive, the Forest Service must be able to look ahead through its watershed management planning to assure that such critical projects are given every chance to succeed.

Not only must watersheds damaged by past use and fire be stabilized and rehabilitated as present policy dictates, but also any use potentially damaging to fragile watershed areas must be eliminated. This means getting control of watershed management before, not after, water projects are established. The total cost of resources required for the use of watersheds must be evaluated in terms of the benefits generated from such use.

In addition, to meet the water needs for the future, money spent on the provision of adequate water must be spent efficiently in terms of priorities and the kind and extent of mechanical treatments required to provide a watershed condition that will assure the required performance of water storage and distribution systems.

Headquarters for the Intermountain Forest and Range Experiment Station are at Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

USDA Forest Service
Research Paper INT-93
1971

AIRBORNE INFRARED FOREST FIRE DETECTION SYSTEM: FINAL REPORT

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
NORTHERN FOREST FIRE LABORATORY
MISSOULA, MONTANA 59801

THE AUTHORS

RALPH A. WILSON is Principal Research Physicist, STANLEY N. HIRSCH is Project Leader, and FORREST H. MADDEN is Associate Research Engineer (Electronics) for the Project Fire Scan Research Program at the Northern Forest Fire Laboratory, Intermountain Forest and Range Experiment Station, Missoula, Montana.

B. JOHN LOSENSKY was the Research Forester in Project Fire Scan at the time this research was being conducted. He has since transferred to the Darby Ranger District of the Bitterroot National Forest, Darby, Montana.

ACKNOWLEDGMENTS

The authors gratefully acknowledge financial, technical, and cooperative assistance by several agencies and organizations in accomplishing the tasks included in this report. Among them are:

Bendix Corporation
Department of the Army, Office of the Secretary of the Army
Department of Defense, Advanced Research Projects Agency
The Electronic Command, U. S. Army Materiel Command
Litton Industries
Montana State Forestry Department
Texas Instrument Company
University of Michigan, Infrared Physics Laboratory, Institute of Science and Technology
USDA Forest Service, National Forest Administration

COVER PHOTOS

Front — Infrared imagery from patrol over Nezperce National Forest, Idaho. Lower fiducial mark in right margin is automatic target alarm on a wildfire in Granite Creek drainage.

Back — Photos of target area and closeup of the Granite Creek fire — still burning in the end of a fallen snag, with very little smoke.

USDA FOREST SERVICE
RESEARCH PAPER INT-93, 1971

AIRBORNE INFRARED FOREST FIRE DETECTION SYSTEM: FINAL REPORT

(Work Unit 2521A)

SUMMARY

A mathematic-functional representation of airborne infrared line scanners is used for development of an effective forest fire detection system. Conventional statistical descriptions of forest backgrounds are found to be useless for predicting detection probabilities. In situ fire detection probability measurements in 13 timber types representing the major forested areas of North America are presented. Detection probabilities approach 100 percent in the open-grown, shade-intolerant timber types; but the probabilities are marginal (50 to 60 percent) in the more shade-tolerant types, such as Douglas-fir rain forests on the West Coast and dense hardwood forests around the Great Lakes.

Also presented are the operational procedures for the system and the aircraft navigational requirements that were developed on wildfire patrol test flights made during the 1967 forest fire season in the Northern Rocky Mountains. Results of these tests indicate that approximately 50 percent of all possible wildfire targets are detected using the system. Proposed are some real time autocorrelation techniques that will significantly improve the detection capability of the system.

USDA Forest Service
Research Paper INT-93
May 1971

AIRBORNE INFRARED FOREST FIRE DETECTION SYSTEM: FINAL REPORT

Ralph A. Wilson,
Stanley N. Hirsch,
Forrest H. Madden, and
B. John Losensky

THE EVALUATION OF AN AIRBORNE INFRARED MAPPER
AS A TOOL FOR DETECTING AND MEASURING FIRES
(Work Unit 2521A)
for
Department of Defense, Office of Civil Defense
Contract OCD-OS-62-174
and
Department of Defense, Advanced Research Projects Agency
ARPA Order No. 636, Program Code No. 5860

ARPA REVIEW NOTICE

This report has been reviewed by the Advanced Research Projects Agency and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of this Agency.

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
U. S. DEPARTMENT OF AGRICULTURE — FOREST SERVICE
Ogden, Utah 84401
Joseph F. Pechanec, Director

Northern Forest Fire Laboratory
Missoula, Montana 59801

CONTENTS

The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U. S. Department of Agriculture of any product or service to the exclusion of others which may be suitable.

INTRODUCTION

This work was undertaken because of a mutual interest of the Department of Defense, Advanced Research Projects Agency (ARPA), and the USDA Forest Service in the problems of detecting hot targets against natural terrain backgrounds using airborne infrared (IR) line scanning instrumentation. The study objectives were broadly defined in ARPA Order No. 544, which contains three specific task assignments that were modified from time to time during the course of the study. The basic problem was to examine the target obscuring effects of timber foliage or canopies on small charcoal fires in the forest cover types of North America. A concurrent objective was to develop an optimum system for airborne forest fire detection including the development of the operational patrol procedures.

Our work, beginning in 1962, is described in a series of three reports. This report, together with the Interim Report (1966), covers the development of the fire detection system. The third report, Fire Mapping 1968, supplements these two reports; however, it is limited to the development of the system's performance in mapping very large forest fires.

In 1962, we had planned a three-phase investigation of airborne IR fire detection problems to (1) develop the equipment; (2) measure fire detection probabilities of controlled targets in specific timber stands; and (3) develop operational patrol procedures.

The first year, 1962, was devoted primarily to acquiring and becoming familiar with the military IR line scanning equipment and adapting it to our needs. An AN/AAS-5 IR scanner was borrowed from the U.S. Army Materiel Command and installed in a Beechcraft AT-11 aircraft. We found that major modifications were needed in this hardware to accomplish the fire detection mission.

In the summer of 1963, we measured detection probabilities in only four timber types: ponderosa pine, lodgepole pine, larch–Douglas-fir, and Engelmann spruce. The idea was originated for estimating the target-obscuring effects of timber canopies using shade tolerance as a basis. We found that a standard dual-omni aircraft navigation system was inadequate for wildfire detection patrols. Also, we developed the following equipment requirements for operational patrol: (1) Rapid access to imagery; (2) a larger total field of view; (3) better optical resolution; (4) increased temperature sensitivity; and (5) more precise air navigation.

In 1964, we tried an operational test of the equipment and of navigational procedures that we had developed for wildfire patrols in a 6,000-square-mile area southwest of Missoula. Our tests failed because of IR equipment malfunctions.

The first 3 years of work are reported in the Fire Detection Interim Report (Wilson and

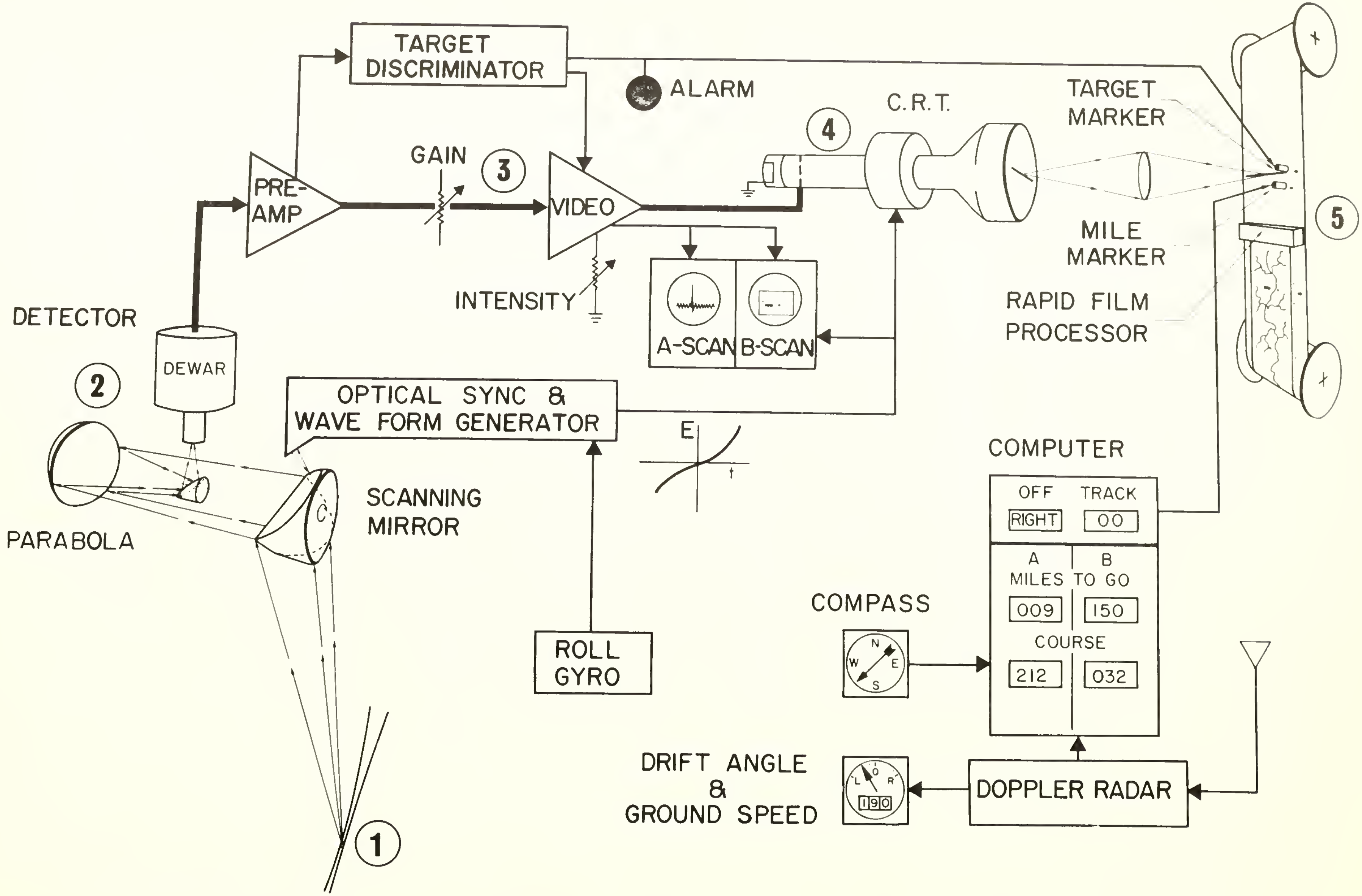


Figure 1. — Schematic of the 1967 IR detection system.

Noste 1966). From these early studies, we concluded that (1) the basic technique (i.e., airborne IR fire detection) was a sound approach; (2) detection probabilities in a wider range of timber canopies should be examined; and (3) an investment in more reliable equipment was necessary.

As a result of our 1964 work, we realized a very valuable spin-off of the detection program — the capability for mapping large wildfires. As a result, the fire mapping system was installed in an Aero Commander 500-B aircraft. In July 1966, this system was placed in operation in the Forest Service. A detailed description of the electronic signal processing required for fire surveillance is presented in Appendix V of the Fire Mapping Report.

During 1964, a Convair T-29B aircraft was obtained from the U.S. Air Force; in 1965, the fire detection instrumentation described in Appendix V was installed in this plane. This instrumentation was based on the concept illustrated in figure 1.

The study was expanded in 1965 and 1966 from the four timber types that were specified in the original ARPA task assignment to include 13 types; these were chosen to span the full range of canopy densities found in the north temperate zone of the Western Hemisphere. The Society of American Foresters (1956) recognizes approximately 150 timber types, of which about 75 types cover extensive geographic areas. Flights were made over test areas representing the 13 timber types in Louisiana, Illinois, Michigan, Montana, Idaho, Oregon, Washington, and Alaska. Figures 2 through 7 are samples of imagery of these test areas.

We realized that it was impossible to acquire enough flight data to predict reliably the detection performance at large aspect angles. As an alternative, a fixed platform was installed on a mountaintop within a larch - Douglas-fir timber stand, from which we were able to examine fire targets in detail. From the data, we developed a preliminary model for predicting detection probability based upon density differences in timber stands. In addition, recorded target signals from the mountaintop were used to develop the first automatic target alarm circuits.

The 1967 operational patrols (July 5 to September 1) encompassed the major portion of the forest fire season in the northern Rocky Mountains. The objective of these patrols was to scan as many natural wildfires as possible in order to gain operational experience and test the detection system.

While planning this report we felt that we had information to convey to three separate and distinct audiences. The first of these, of course, is the ARPA, whose support we gratefully acknowledge. That there are two other distinct audiences — forest land managers and systems design engineers — is symptomatic of the general lack of communication that often exists between systems development groups and systems user agencies which are particularly acute in forest fire detection.

In this report we have tried to show the forest land managers that small latent forest fires can be detected with reasonable probability using airborne infrared equipment. However, lookouts and visual air patrols will still find some fires that the IR scanners may miss and vice versa; and only lookouts can provide continuous surveillance of high hazard areas. On the other hand, IR systems provide new smoke penetration and nighttime detection capabilities. An integrated-combined systems approach will be necessary to achieve the most effective fire detection.

We have tried to demonstrate to the systems design engineers that forest fire detection is not a simple thermal mapping job. To be effective, this system must find the fire targets when they are very small and distributed over vast land areas. The fire targets must be precisely located to be of any use to fire suppression forces. In this report, we outline the basic requirements for a forest fire detection system and discuss the capability of the system to detect hot fire targets in natural forest backgrounds.

Our work prior to 1964 on detection probability and system development including the results of our early patrol tests is described in the Interim Report (Wilson and Noste 1966). This final report is concerned with the detection probability work we have conducted since 1965 when we adopted the detection equipment built to our specifications.

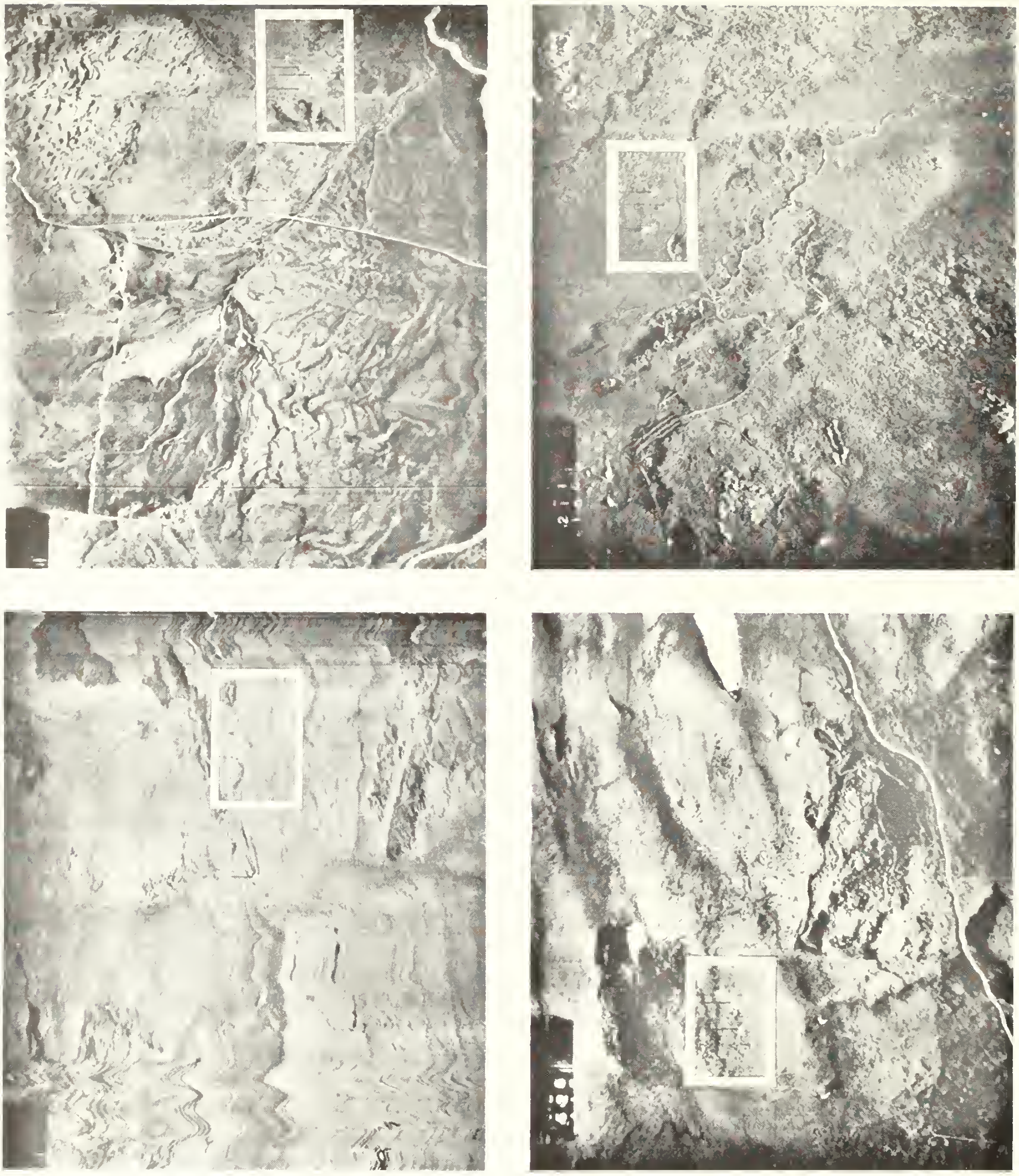


Figure 2. — Imagery shown above is from flights over ponderosa pine (932), lodgepole pine (135), Engelmann spruce (211), and larch—Douglas-fir (526) test areas. These were taken during the summer of June, July, and August 1963, using a Polaroid attachment to the AN/AAS-5 scanner. The Polaroid provided rapid access to the imagery for the detection tests, but would be inadequate for an extended patrol mission. The fire targets are observable and can be identified because we knew where to look (test areas are laid out within the white rectangles). Obviously, the targets would be difficult to discriminate from other background anomalies on a fire patrol mission because of the poor optical resolution (4 to 6 milliradians), the poor thermal resolution (3° to 5° C.), and the inadequate processing of the electronic signal.

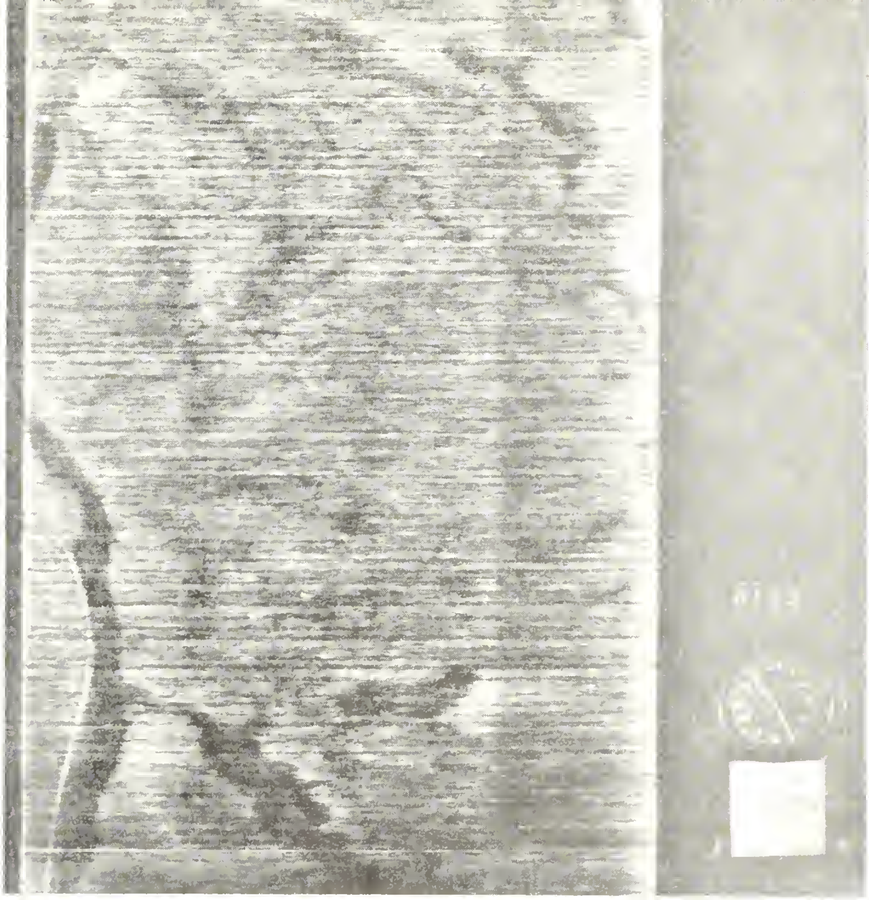


Figure 3. — Imagery of the western white pine test area on the Priest River in Idaho was made using the continuous strip camera. The excessive noise and improper response of the AN/AAS-5 system made the target difficult to locate on the imagery.

Figure 4. — Imagery of the western white pine test area was made in 1965 using the new Texas Instruments scanner and Litton electronic system. Although some instabilities are still evident in the imagery, the targets are much easier to discriminate from the background.

Figure 5. — These two pieces of imagery of the aspen test site of Michigan and the second-growth Douglas-fir in Washington, were made over terrain backgrounds having very low temperature contrast (the temperature differences measured on the ground were 4° to 7° C.). In both, the terrain detail is adequately mapped; the target signatures do not mask the surrounding background by oversaturating the electronics.

Figure 6. — This imagery was taken over the pin oak test area in 1966. Changes in the electronics improved the optical resolution and temperature resolution of this imagery over those shown in figs. 2 through 5. However, some sweep jitter and electronic instabilities are evident.

Figure 7. — The terrain adjacent to the white spruce test area along the Tanana River in Alaska is wet and boggy; it produces a flat thermal contrast. The horizontal bars are due to shifts in the electronic clamp of the CRT intensity level. Note that the bright specular reflection of the sun off the flat water surface does not affect the exposure of the surrounding terrain. The ability of the system to recover from saturation is one of the absolute requirements in fire surveillance.

DETECTION THEORY

Background and Targets

Timber provides the fuel for the fire target on the forest floor or in treetops or snags. The timber canopy attenuates the target radiance. And the timbered areas, together with grassy meadows, brush patches, barren rock faces and slides, and north-south slopes, provide the background radiant noise from which the target must be discriminated.

In addition to detection, we must locate the target relative to topographic features of the terrain background. In the sense of differentiating between desirable signals and undesirable noise, the terrain background is simultaneously a detection noise and a location signal.

Current state-of-the-art IR thermal mappers can produce imagery of background terrain with adequate resolution for the purpose of target location. Observable targets, of course, are printed in the background imagery. The detection of those targets is not a linear operation because the many possible inputs can produce only two outputs — a Yes-No dichotomy. However, IR mapping is a linear operation on orthogonal functions in the sense of superposition (i.e., the superposition of input signals provides a superposition of output signals).

No system is rigorously linear; however, the superposition requirement must hold over the dynamic range of the detection system — from significantly below the limiting background noise level up to a target signal level where the target detection probability approaches 100 percent.

We must recognize the photointerpreter (PI) as an integral part of any detection system because he makes the final decision. This decision function is also nonlinear, but the PI has an infinite advantage over an automatic line scan target discriminator (i.e., he has the facility for two-dimensional shape recognition).

Our concept of the ideal system includes an automatic target discriminator that sorts out all possible target signals. In such a system, the PI would simply review the automatic target alarms and eliminate those targets that he judged to be false alarms (campfires in campgrounds, bulldozer and construction equipment, and geothermal activity).

We should point out that false alarms may originate from two sources: (1) From thermal anomalies in the background scene, or (2) from internally generated noise in the system. Both of these types of false alarms are errors of commission. Missing a target that really exists is an error of omission that we must also avoid.

The choice of target threshold is an easy one if the automatic target discriminator can be set without concern for the relatively few false alarms caused by high peak signals. The unpredictable character of the peak signals is the major fault of statistical descriptions of non-Gaussian background noise.

Reliable estimates of minimum and maximum background temperatures can be made by judicious consideration of local meteorological data. These temperature estimates determine the peak-to-peak background contrast that is used to select the optimum detection threshold level for the automatic target discriminator. Such estimates provide a more useful criteria for threshold selection than would any conceivable statistical description of background noise.

The only remaining consideration for detection is the target radiance available at the entrance aperture of the IR system if given (1) an acceptable system capable of mapping the thermal background, (2) a realistic estimate of the peak-to-peak background radiance, and (3) a PI who can intelligently discriminate against false alarms by their unique extra-radiant character (slope, location, etc.).

The undetected, incipient forest fire has never been observed. However, the following generalizations of its character can be made:

1. It exists under a timber canopy, from which its fuels are derived.
2. For nonflaming, sustained combustion the temperature must range between 550° and 700° C.
3. In most fuels, combustion must exceed several inches in its least dimension to be self-sustaining.
4. Generally it will be located on an exposed air-fuel surface.

The typical target can be defined as not more than 5 square feet of glowing combustion.[1] This target is obscured to an unknown extent by the intervening timber canopy.

Theoretical treatments of detection probability start with a definition:

> **Detection probability is the probability that the target signal exceeds a threshold signal. The threshold signal is a signal level that the system operator may select by judicious consideration of the properties of the target, the background noise, and the IR system.**

The target signal is calculated by determining the system response to the target radiation (Wolfe 1965).The minimum acceptable threshold level is determined by fixing the maximum allowable false alarm rate. The false alarm rate is dependent on the characteristics of the background noise and the IR system's scanning function (Karr 1957; Genoud 1959).

Much has been published describing performance of IR search systems in "ideal" backgrounds (Hudson 1969; Jamieson 1963; Wolfe 1965). Almost invariably, system performance is described by a signal ratio — peak target signal (V_p) to root mean square (rms) noise (V_n) voltage ratio, V_p/V_n. Such descriptions assume that it is possible to determine the false alarm rate for any detection threshold level from incomplete statistical descriptions of the background noise (e.g., rms noise). Implicit in this assumption are the following: (1) The entire set of possible backgrounds have completely random properties (spatial and temporal); (2) these backgrounds have invariant statistical properties from one background to another; and (3) these statistical properties do not vary with the relative position of the observer (i.e., direction of view).

Robinson (1959) concludes:

> **. . . that these particular incomplete descriptions are only of value for a very restricted class of backgrounds. With most backgrounds and most systems, these methods are useless insofar as they can be used to predict performance.**

In other words, it would be very naive to consider wildland terrain backgrounds as having ideal, analytic statistical properties – they are not stationary, they are not ergodic, and they are not Gaussian.

Some have suggested more complete descriptions of backgrounds are needed (Robinson 1959; Holter and others 1962; Jamieson and others 1963). Obviously, a given background scene can be completely described by its spatial distribution of radiance, R(x). That is, R(x) is uniquely determined for every point (x) in the background. But, even a complete set of these detailed descriptions, R(x), does not meet the ergodic ensemble requirement for terrain background description (i.e., the value of a parameter — average peak radiance — is not the same when averaged over one scene or when averaged over the entire set of scenes).

The problem can be stated another way: A system should be capable of detecting targets against a wide selection of backgrounds. On any given mission, the detection threshold should be set with reference to the background that exists at that time in that locale. Thus set, the system will detect targets more reliably than if the threshold is set higher to miss false alarms for all possible backgrounds that might exist at any other time or place.

---

[1] *Reports on file at the Northern Forest Fire Laboratory indicate that five 1-square-foot combustion zones are found within a 30-foot perimeter in forest fires during the initial attack phase.*

Figures 8 through 15 show some of the effects of terrain backgrounds that are important in fire detection.

Figure 8. — An example of the spatial frequencies commonly found in the Bitterroot Mountains of western Montana is shown below. At least two distinct spatial frequency patterns are evident on this imagery. The first is the major drainage pattern of dark valley bottoms and warm exposed southern faces. The minor ridges and draws form a second distinct spatial frequency distribution.

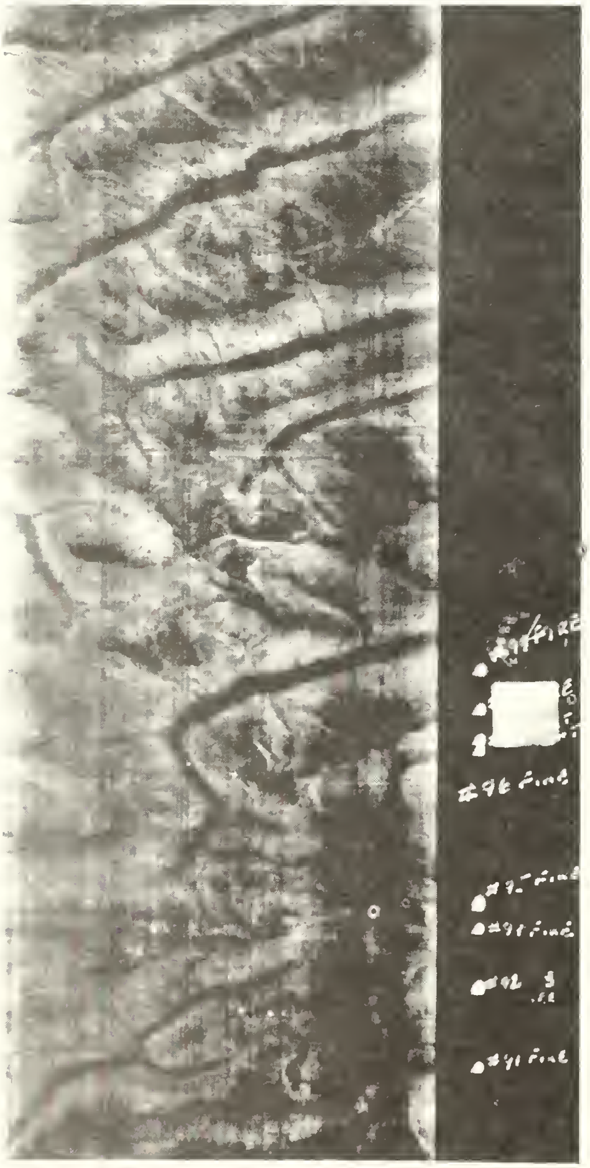


Figure 9. — The river bottom at the top of the imagery shown above has little terrain detail which is due to low frequency spatial contours of the background. The higher alpine terrain at the lower end of the picture has much higher spatial frequency distribution caused by the minor ridges and draws and exposed rock faces. Note also that the river bottom along the top of the frame is warm relative to the background, while the higher valleys are cool.

Figure 10. — The high plateau area of eastern Oregon has a peculiar spatial distribution of backgrounds which is caused by the eroded washed drainage pattern (below). The speckled high frequency distribution of vegetation is another discrete background phenomenon.

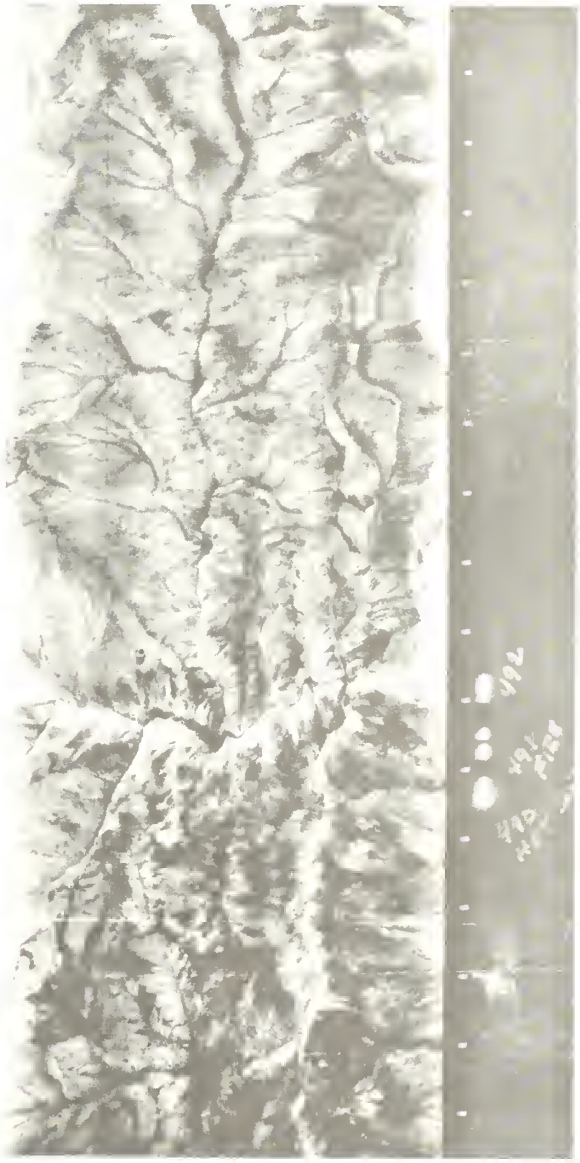
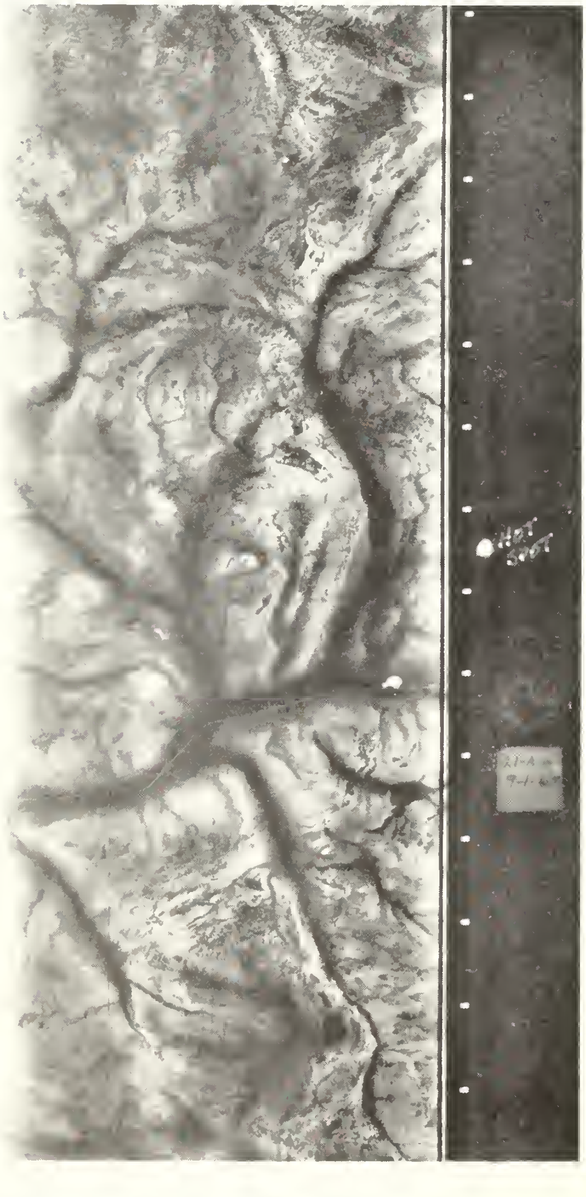


Figure 11. — The imagery shown above the exposed grassy slopes in the Salmon River country of Idaho shows the nighttime residual heat left by daytime solar radiation. The hot spring and creek can be seen in the center of the imagery just below the major river drainage pattern that runs horizontally across the frame.

Figure 12. — In the imagery below, the cool valley bottoms form a drainage pattern of low spatial frequency; the alpine meadows at the top and bottom form a spatial distribution of higher frequency.



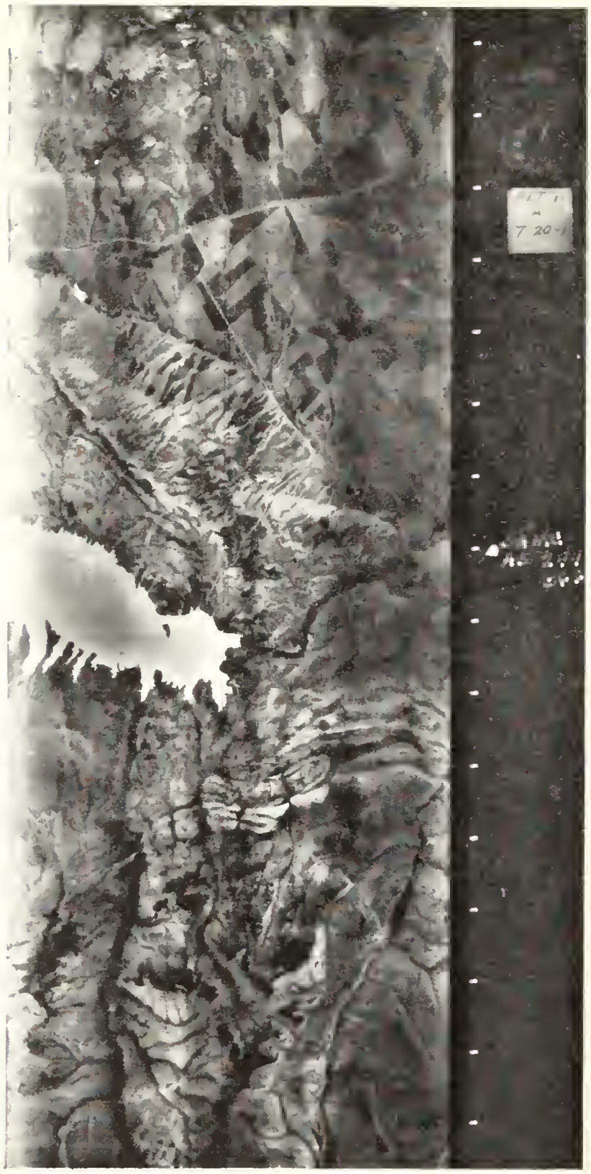


Figure 13. — Agricultural areas have a geometrical spatial pattern (above). Lakes and reservoirs are generally large; however, their shores have a sharp and discrete thermal contrast.

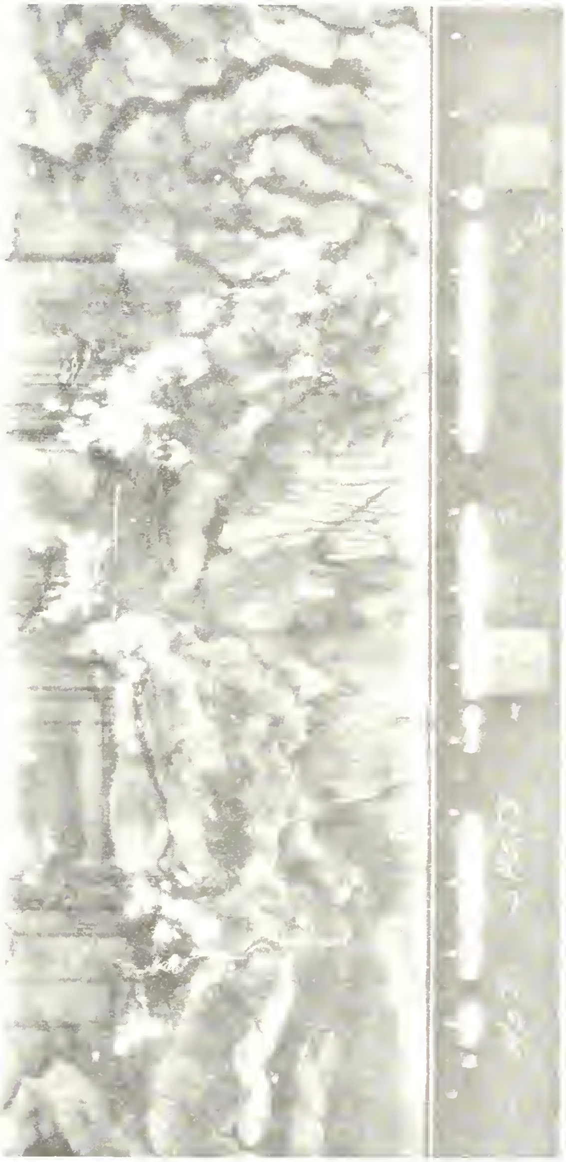


Figure 15. — This imagery is of the Gibbon Geyser Basin in Yellowstone National Park (above). Geothermal activity poses an obvious problem to fire detection.

Figure 14. — Rockslides on southern exposures form a discrete and significant class of backgrounds, which makes fire detection difficult (below).

Equipment Development

Designers of forest fire detection systems must recognize that (1) the purpose is to acquire and interpret certain information; (2) the equipment must process and reproduce the information without losing any significant detail; and (3) a well-designed system plays a major role in the decisionmaking process.

Initially, such information is a spatial distribution of cool, warm, and hot radiating surfaces. Thus, we first had to formulate a general expression for the radiant emittance distribution in the extended object plane of the terrain as Born and Wolf (1964-65) did for incoherent object illumination.

Let W(x, y) specify the radiant emittance for the point (x, y) in the object plane of the terrain. The properties of the imaging system may be characterized by a transform function, K(x,y; x',y'). K is defined by the photographic exposure per unit area of the x, y plane at the point (x', y') in the reconstructed image plane. This exposure is caused by radiant emittance of unit amplitude at the object point (x, y). Thus, the spatial distribution of photoexposure on the IR imagery is given by:

$$I\,(x',y') = \iint W\,(x,y)\; K\,(x,y;\, x',\, y')\; dx\, dy \qquad \text{Eq. 1}$$

K is the functional transformation of the total system. K is also the product of all response and transform functions of the individual components of the system. The calibration of this function for our feasibility tests is discussed on page 22.

The total system and each identifiable system component has a characteristic input-output relationship. For this analysis, each transformation function is separable into a modulation function and a response function. For example, the input to our scanner is a radiation difference, W(x, y), between adjacent terrain areas. The detector output is a time dependent voltage, S(t). The transformation, U, for this part of the system is a product of a response function, $R\left(\frac{\text{volts}}{\text{watts}}\right)$, and a modulation function, M(x, y, t). Thus $U = R\cdot M$ such that the scalar product $S(t) = W(x,y)\cdot U(x,y,t)$. The two functions, R and M, affect the "thermal resolution" and the "optical resolution" of the system, respectively.

The performance characteristics of airborne IR thermal mappers have been adequately covered in the literature (Institute of Science and Technology 1962, 1963, 1965, 1966, 1968; Wolfe 1965; Jamieson and others 1963; Holter and others 1962). However, fire detection systems have unique operational requirements. The scanning of the terrain and the reconstruction of its image in fire detection systems follows the numbered sequence shown in figure 1. The radiant power from the source (1) traverses an optical path to the airborne scanner (2) where it is sensed by the detector and electronically processed (3). The electrical signal is applied to the CRT (4) and the CRT spot is projected onto the film (5).

An equivalent blackbody temperature, T_{BB}, is usually defined as the temperature of an "ideal" radiation source that provides the same radiant power as the "real" source being observed in the spectral region, $\Delta\lambda$, of the observation.

The total radiance emitted from a small resolution element is averaged over the elemental area, $\Delta x \Delta y$ (see 1 in fig. 1). The elemental area must include the hot target, if it is present. The following equation serves as the definition and physical interpretation of "average, effective blackbody temperature, T_{BB}, of the instantaneous field of view (IFOV)."

$$W'(\lambda, T_{BB}, x, y) = \frac{1}{\Delta x \Delta y \Delta\lambda} \int_{y}^{y+\Delta y} \int_{x}^{x+\Delta x} \int_{\lambda}^{\lambda+\Delta\lambda} \epsilon(\lambda,x,y)\; W(\lambda,T,x,y)\; d\lambda\, dx\, dy$$

$$= \frac{1}{\Delta\lambda} \int_{\lambda}^{\lambda+\Delta\lambda} C_1 \lambda^{-5}\, (\exp(C_2/\lambda T_{BB}) - 1)^{-1}\, d\lambda \qquad \text{Eq. 2}$$

Note that the spectral dependence of $W'(\lambda, T_{BB})$ is not identical to that of $W(\lambda, T)$ within the element $\Delta\lambda$. Serious problems concerning T_{BB} arise when the hot target is included in the elemental area. There is always a T_{BB} that satisfies equation (2). However, T_{BB} does not approximate the true thermal temperatures of the source when the source significantly departs from the ideal blackbody conditions. When such is the case, we discard the simplified ideal blackbody assumption in favor of the actual spectral distribution (i.e., the real spectral character, $\epsilon(\lambda)$, of the source and/or the real spatial distribution of thermodynamic temperature).

From the source, the radiation traverses an optical path to the scanner's entrance aperture, A_a (at 2 in fig. 1). The spectral distribution of the transmission, $\Upsilon(\lambda)$, of radiation through the optical path is dependent on atmospheric composition. The scattering and obscuration effects of timber canopies are included in $\Upsilon(\lambda)$. The spectral responsivity, $R(\lambda)$, depends on the detector that is used. We include the spectral characteristics of the optical system in $R(\lambda)$.

The signal S_d, from the detector in response to radiant power, W, from the terrain is:

$$S_d(T_{BB},t) = \omega A_a \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} W'(\lambda, T_{BB}, r)\, \Upsilon(\lambda)\, R(\lambda)\, \delta(r-\dot{r}t)\, d\lambda\, dr \qquad \text{Eq. 3}$$

where

$$\omega = \left(\frac{\Delta x \Delta y}{h^2/\cos^3\theta}\right)$$

$= \alpha\cdot\beta$ is the lateral angular resolution times longitudinal angular resolution[2]

r = vector notation of coordinates x, y on the terrain object plane

t = time

$\dot{r}$ = scanning rate in the object plane

$\delta\ (r - \dot{r}t)$ is the scanner-receiver modulation function

From scanner geometry,[3] $\dot{r} = \dfrac{h}{\cos^2\theta}\dot{\theta}$

where

h = aircraft altitude

θ = scan angle

$\dot{\theta}$ = rotational speed of scanning IFOV.

δ performs the space-time convolution and has a maximum value of unity and a width equal to the effective size of the resolution element of the scanner. In principle, δ includes the transform (MTF) of the point spread function, which in theory depends on optical resolution, the time constant of the detector, scan rate, etc. In most well designed IR line scanners, those spread functions are made insignificant in comparison to the size of the field stop. The rectangular area, $\Delta x\Delta y$, of δ for a square field stop projected on the ground is

$$\Delta x \cdot \Delta y = \frac{\alpha h}{\cos^2\theta} \cdot \frac{\beta h}{\cos\theta} = \frac{\omega h^2}{\cos^3\theta}$$

and the dwell time, $\tau = \Delta x/\dot{r} = \alpha/\dot{\theta}$, is constant over the full width of the scan line. The size, $\Delta x\Delta y$, of the IFOV (the projection of the resolution element onto the terrain object plane) varies as the aspect angle, θ, along the scan line.

The thermal washout at the edges of the imagery of certain discrete classes of background objects (see figs. 8 to 15) is caused by the averaging of T_{BB} over the larger IFOV at the ends of the scan lines. At the same time, other size classes may be printed with good contrast. This observation supports our contention about the non-Gaussian character of forest backgrounds.

The time dependent electric signal from the detector is amplified and processed by well known techniques (3 in fig. 1). From a practical engineering standpoint, the processing through amplifiers, filters, etc., requires that we look in detail at the time-frequency transforms of individual components (see Appendix V). For this functional representation we will define the gain, G, of time-dependent signals from the electronic system such that

$$S_o(t') = G(t, t')\, S_d(t). \qquad \text{Eq. 4}$$

---

[2] *Longitudinal resolution is in the direction of the aircraft flight path; lateral resolution is in the direction along the scan line, perpendicular to the flight path*

[3] *Rigorously, θ is measured in the vertical plane of* **x** *(with no* **y** *component); $\dot{y}$ is the aircraft speed, and $\dot{x} = \dot{\theta}h/\cos^2\theta$ is the scanning sweep speed and $\dot{r} \approx \dot{x}$ because the ratio $\dot{y}/\dot{x}$ is very, very small.*

Note that G need not be linear. In fact, system requirements for adequate thermal resolution at low signal levels (terrain background) and large dynamic range (hot fires) suggest a highly nonlinear, electronic gain. The first stages of signal amplification are generally the source of the limiting system noise.

The signal, S_O, is applied to the Z input of a CRT (4 in fig. 1). Thus, emittance of the source is related to the visible output — spot intensity of the CRT — and is characterized by a response, I, (e.g., luminosity per volt) and a spatial distribution δ'. The spot is focused on a photographic emulsion moving normal to the scanning direction and results in an exposure.

$$E(r') = \int S_O(t')\, I\, \delta'\,(r' - \dot{r}'t')dt'. \quad \text{Eq. 5}$$

I is the photographic exposure per unit of signal for the CRT-camera system; and $\delta'(r' - \dot{r}'t')$ is the time-position transform of the writing CRT spot on the photographic film.

The photographic film (5 in fig. 1) is processed with a characteristic, γ.

$$D(r') = \gamma \log E(r') \qquad \text{Eq. 6}$$

is the film's optical density as a function of position, r′ on the film.

The limiting system noise may be printed on the film. Knowing the system transfer function, we can calculate the noise equivalent input. Noise equivalent power, NEP (or NET defined in equation 2), of the system is defined as the difference in input radiant power, $\Delta W(T_{BB})$, that will produce a film density contrast equal to the density contrast produced by the limiting system noise. To determine a value of NEP, we must explicitly define our noise measurement (i.e., peak-to-peak or RMS, bandwidth, etc.) and the equivalent radiation signal (shape, size, power, etc.).

The imagery is an exact reproduction of the thermal scene, and film density is functionally equivalent to terrain temperature, $D(r') \equiv W(r')$, only to the extent that:

1. The total transformation from equation (3) to equation (6) is linear and the principle of superposition holds. The radiant power must approximate an ideal radiator in the spectral range of the observation, and the radiation contrast must significantly exceed the equivalent system noise.

2. That the δ and δ' are properly synchronized and produce complete sets of orthogonal functions, S(t) and D(r′). Note that the image resolution is determined by the total "spread" in the product of all these transforms, including those, G(t,t′), within the electronic video chain.

PROCEDURES

Equipment

The equipment installed in the Convair T-29 aircraft is shown in figures 16, 17, and 18. This aircraft was an ideal flying laboratory in which equipment development and modifications were easily performed.

The IR receiver (including mechanical mount, optics, drive motor, and InSb detector) is a stripped down version of the RS-7 IR line scanner built by Texas Instruments, Inc.

Several preamplifiers have been built and tested in attempts to resolve the video problems, such as amplifier noise, target and background dynamic range, and low thermal contrast of backgrounds. A discussion of preamplifiers is given in Appendix V.

The electronic equipment for signal processing and CRT display was built by Litton Industries, Electronic Tube Division. Slant range correction (rectilinearization), electronic roll correction and good d.c. amplification of the video signal were designed into the equipment.

The imagery is reproduced on an Ansco rapid film processor — KD-14 camera system. This camera produces continuous strip imagery that is available for viewing within a few seconds after flying over an area.

The navigation system that was in the T-29 when we obtained it from the Air Force was an AN/APN-81 Doppler radar. We replaced it in 1967 with a more reliable Bendix DRA-12/CPA-24 Doppler radar navigation system. Both of these systems compute aircraft position from the track of the Doppler radar and the aircraft compass heading.

In 1967, we added the target discrimination module (TDM) to our system. The TDM provides a marker pulse for the imagery and a trigger for an external alarm. The target markers are shown in the imagery of figure 19. The down track mileage marks from the navigation system are also shown.

Auxiliary instruments that were necessary for these tests included an extra set of flight instruments — altimeter, groundspeed indicator, etc. — for the test observer, and electronic test equipment for monitoring, processing, calibrating, and recording of the video signals.

The operational goals for the fire detection system were arbitrarily established by considering three factors: economics of fire detection, performance of alternative detection systems, and the expected capabilities of IR line scanners. The goals were as follows:

1. Detect fires as small as 1-square-foot of burning material.
2. Locate these fires relative to the thermally mapped background terrain.
3. Patrol 5,000 to 10,000 square miles per patrol mission.

As suggested by Wolfe (1965), these goals reduce to a set of system performance parameters as follows:

1. Aircraft speed of 200 miles per hour and 10-mile-wide coverage gives 2,000 square miles per hour capability.
2. 15,000 to 18,00 feet altitude with 120° wide field of view will provide 10-mile-wide coverage with adequate overlap for navigation of adjacent patrol strips.
3. The thermal and optical resolution requirements reduce to a capability of observing 1° or 2° C. background temperature differences; 30- to 70-foot objects are resolved with 2-milliradian instantaneous fields of view.

Figure 16. — Convair T-29B aircraft.

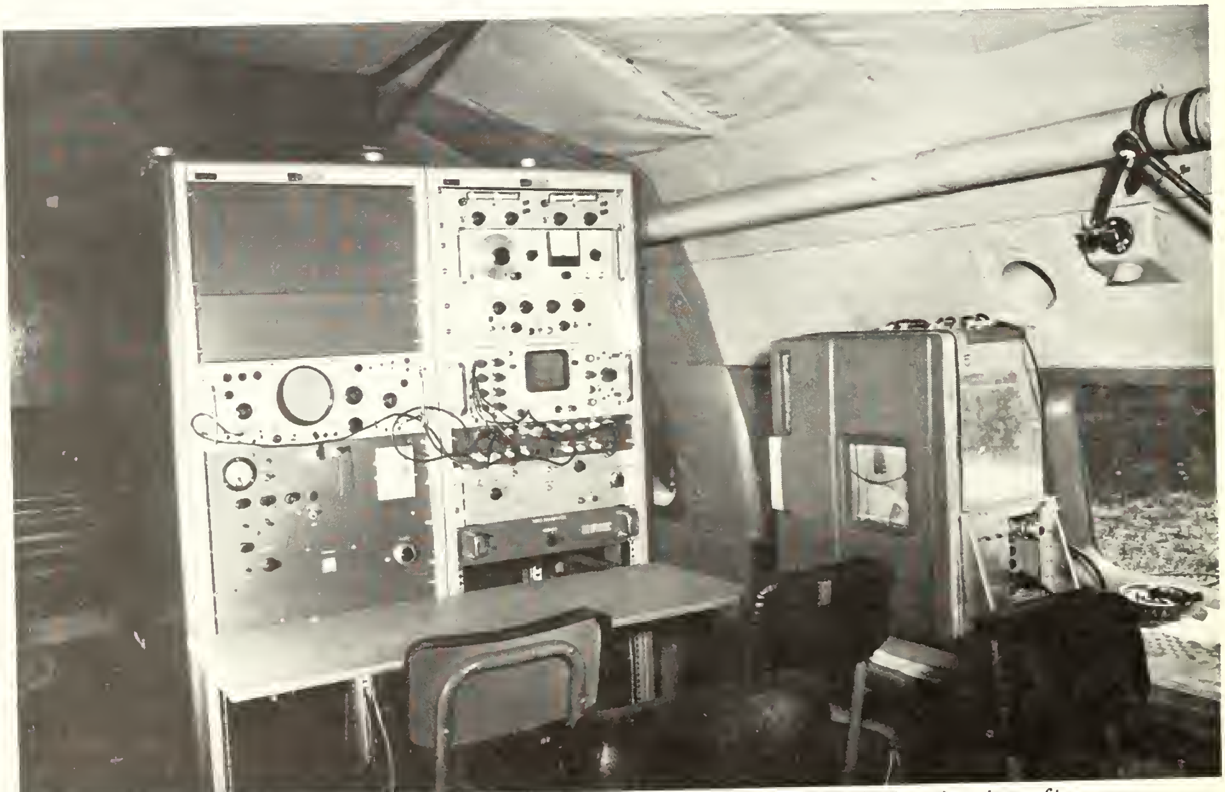


Figure 17. — Equipment racks and tape recorder installation in aircraft.

Figure 18.—Navigation and observation console containing Doppler radar and navigation computer.

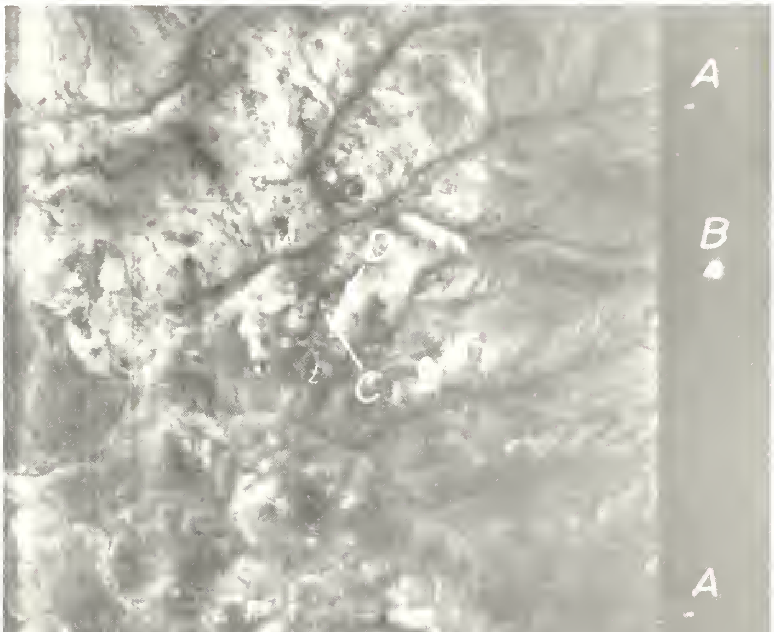


Figure 19. — This IR image, made at 12,000 feet above terrain, covers approximately 40 square miles. A, Inserted by the navigation system, these marks show 5-mile intervals along the track; B and C, automatically inserted by the TDM to indicate the presence of a fire target; and D, latent forest fire.

Airborne Detection Probability Tests

We used Baker's (1949) table for ranking tree species by shade tolerance as a qualitative indicator of crown density because species having dense crown foliage logically (1) would obscure fire targets, and (2) be more tolerant of shade. Thus shade tolerance was used as one scale of measurement for crown density. As a result of preliminary investigations, however, we found that a second scale of measurement for crown density was needed for insuring reliable prediction of detection probabilities. To do this better, we took field measurements of tree crowns in terms of height, diameter, and closure, as well as stems per acre, diameter at breast height, etc. (see Timber Cruise tables, Appendix II). These measurements were used to construct the prediction model as described in Appendix III.

The individual test areas were fully stocked. We preferred that the trees be confined to the early, mature stage and that the stands be of a basically pure type (Society of American Foresters 1954, p. 67) to allow explicit description of the composition of the test stands. These timber cruises were made in each test area using the variable radius Bitterlich plot technique (Grosenbaugh 1952, p. 32-37).

Each plot location was described according to slope, aspect, and basal area. These same plot locations were used as the test fire points.

In four of the test areas — second-growth Douglas-fir, western white pine, northern hardwoods, and lodgepole pine — the diameters and heights of each tree bole and tree crown that intercepted the scanner line of sight were measured for all aspect angles from 0° to 60°.

An analysis of 250 smokejumper reports indicated a typical spot fire consists of five 1-square-foot burning areas in a 30-foot-diameter circle. A typical spot fire spreads slowly along a broken perimeter, leaving a burned out interior and a large amount of cold or dead fire edge. Such fires in the dormant, or incipient state, maintain a fairly constant live burning area that disperses as hotspots burn apart. Therefore, we simulated these fires using five 1-square-foot buckets of burning charcoal equally spaced on the circumference of a variable radius circle. We termed these "test fire arrays." The circle radius was varied in 3-foot increments from 3 to 15 feet. Spacing of 300 feet between test fire arrays facilitated separation on the IR imagery. Fifteen to 20 test fire arrays were laid out in each of the 13 test areas.

The buckets of burning charcoal closely approximate Lambertian radiators. Temperatures of these range from highs between 850° to 900° C. 30 minutes after ignition to lows between 550° to 600° C. 5 hours after ignition. These temperatures were affected by meteorological conditions — the most apparent being the effect of wind.

During the flight tests, a ground crew monitored these target temperatures as well as terrain background temperatures. Meteorological records were kept of wind, air temperature, and relative humidity. These measurements were needed in data analysis to remove the variable effects of atmospheric water absorption and target temperatures. The ground crew also changed the radii of the test fire arrays upon instruction from the flightcrew.

In addition to the pilot, copilot, and crew chief, the flightcrew included a flight observer and an equipment operator. The flight observer monitored the IR imagery while the equipment operator adjusted system electronic controls so that terrain background contrast covered the lower half of the film gamma curve. On the film the upper portion of the gamma curve was reserved for fire target signatures. System settings corresponding to film exposure (cathode ray tube bias, or level) and temperature contrast (amplifier gain) were logged by the observer. These records proved invaluable for system development, but were inadequate for rigorous data analysis.

After 1965, most of the test data were also recorded on magnetic tape as well as film. The magnetic tape was used extensively for system development and performance checks. In addition, it provided precise data on target strength for comparison with the PI's subjective target measurements on the IR imagery.

Test flights were made at 8,000 feet over terrain. The aspect angle was varied in 10° increments. The scanner optical system was tilted in pitch angle for aspect angles from 0° to 40°. The aircraft flightpath was offset for aspect angles from 40° to 60°.

For cost reasons, we simplified this procedure and adopted a "rule-of-thumb" flight plan as follows:

1. Two passes were flown over the test area from opposite directions (i.e., 30 to 40 target observations), after which the flight observer counted the targets on the imagery. This pair of passes was made looking straight down (0° aspect angle) with the targets on a 9-foot radius (halfway between 3 and 15 feet). If near 100-percent detection was observed, the aspect angle was increased to 10° and the next pair of passes was flown. As long as percent detection "looked good," two passes were made at each succeeding 10° aspect increment to a maximum of 60°.

2. When, or if, the percent detection decreased significantly, two to six additional passes were made at each 10° increment until the flight observer had established a representative average percent detection. This procedure was continued out to an aspect angle of 60° or until the percent detection had fallen to less than one-half of its 0° aspect value.

3. If the target data were high (80- to 100-percent detection), we assumed the detection of fires over 9 feet also would be good and the ground crew was instructed to move the targets to a 3-foot radius. However, if the 9-foot data were low (less than 80-percent detection), the targets were enlarged to 15 foot radii and, the 10° angle increment procedure was repeated. Six-foot and 12-foot fire radii were tested only if it was necessary to fill in large differences of percent detection between the 3-, 9-, and 15-foot radii targets.

Figure 20. —Imagery of 20 target arrays in the aspen test area.

Imagery was recorded in flight on 5-inch film using a KD-14 rapid process camera and simultaneously on magnetic tape using an Ampex 1300 recorder. Figure 20 is sample imagery of a 20-target test area in the aspen test area. In this imagery, the test fires were placed on the circumference of a 3-foot-radius circle and viewed vertically (0° from the nadir). Forty to 100 pieces of imagery in each timber type were necessary to determine the capabilities of the detection system and to determine what fire size and aspect angle limited performance.

A simplified schematic of the test system and its associated response functions are shown in figure 21 to demonstrate our calibration technique. A density wedge was photographed on film and used to measure target strengths directly from the imagery. This wedge is the film record of calibrated signals introduced at the system input by a pulse generator. The wedge provides the PI with a scale 0 to 5 of target strengths for various background densities (fig. 21B, far right).

Figure 22 shows the video traces of individual target signals that were tape recorded simultaneously with the imagery shown in figure 20. The numbers in the upper left-hand corner of each set of traces identify individual targets. Signal strengths (0 to 5) are subjective evaluations of target intensity from filmed imagery — 0 represents no detectable target and 5 represents a saturated target. The PI's subjective measurements are well correlated with the actual signal strengths. Thus, we reliably read the target signals directly from the imagery. We then normalize these data to constant atmospheric path, target temperature, and aircraft altitude.

Adjustments made by the equipment operator proved to be a crude data normalization procedure in itself. For example, the flight observer made compensating adjustments of the imagery's thermal contrast in response to changes in environmental conditions (e.g., atmospheric H_2O absorption or target temperature). Thus, our hot target signatures as read from the imagery could not be used to determine optical attenuation coefficients of the timber canopy. This was disappointing. However, this did not seriously affect our primary objective of measuring the system's detection capability because we recognized that the calibration wedge is only a reference scale for target comparison.

The only system requirements for adequate data acquisition are (1) that the terrain background be easily observable above the system noise limit; and (2) that the flight observer must adjust the gain and level controls for optimized imagery, as described above.

It must be emphasized that the PI was always aware of the precise location of the targets in these tests; therefore, he was confident of his ability to identify targets that were hidden in the background. Actual detection of an individual fire is a yes-no dichotomy. Detection probability is the fraction of total fires that a PI observes on the output imagery. Detection probability should be related directly to the target signal strength. Even though we are primarily interested in the number of targets detected, the readings of target signal strength are better indications of system performance because we have more statistical confidence in a measure of target magnitude than we have in the yes-no dichotomy. In these tests, the PI was obviously biased by previous knowledge of target location. By requiring the observer to estimate target signal strength, a more objective measure of detectability is provided.

In the operational mode, detection performance will depend — in part — on the PI's ability to pick out submarginal targets, which in these tests were included as positive detections.

Each "piece" of imagery represents one pass over the test area and contains the target signatures of 15 to 20 test fire arrays. At least two pieces of imagery were made at each aspect angle and for each fire size in each timber type. Three different PI's read each piece of imagery; thus, each primary data point (average signal strength) represents the average of three readings of at least 30 individual target signatures. In cases where the flight observer determined "unusual" differences (number of targets on imagery or magnitude of target signals) between the first two passes, additional pairs of passes were flown until the differences were subjectively resolved. This procedure was a compromise (as we have already inferred) between statistical confidence in the data and economy of operation.

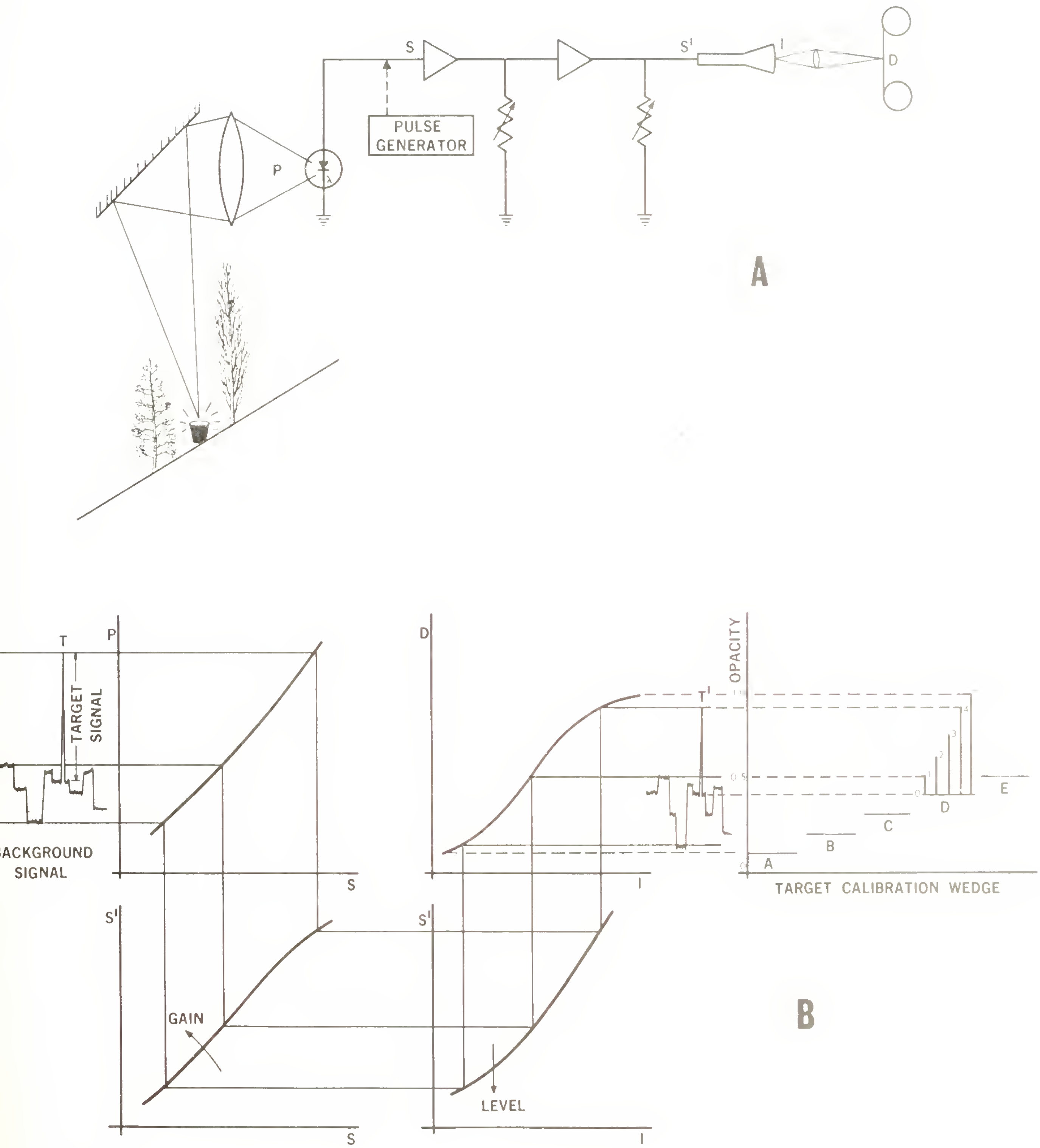


Figure 21. — A, Schematic of IR system; B, transfer function demonstrating target calibration technique.

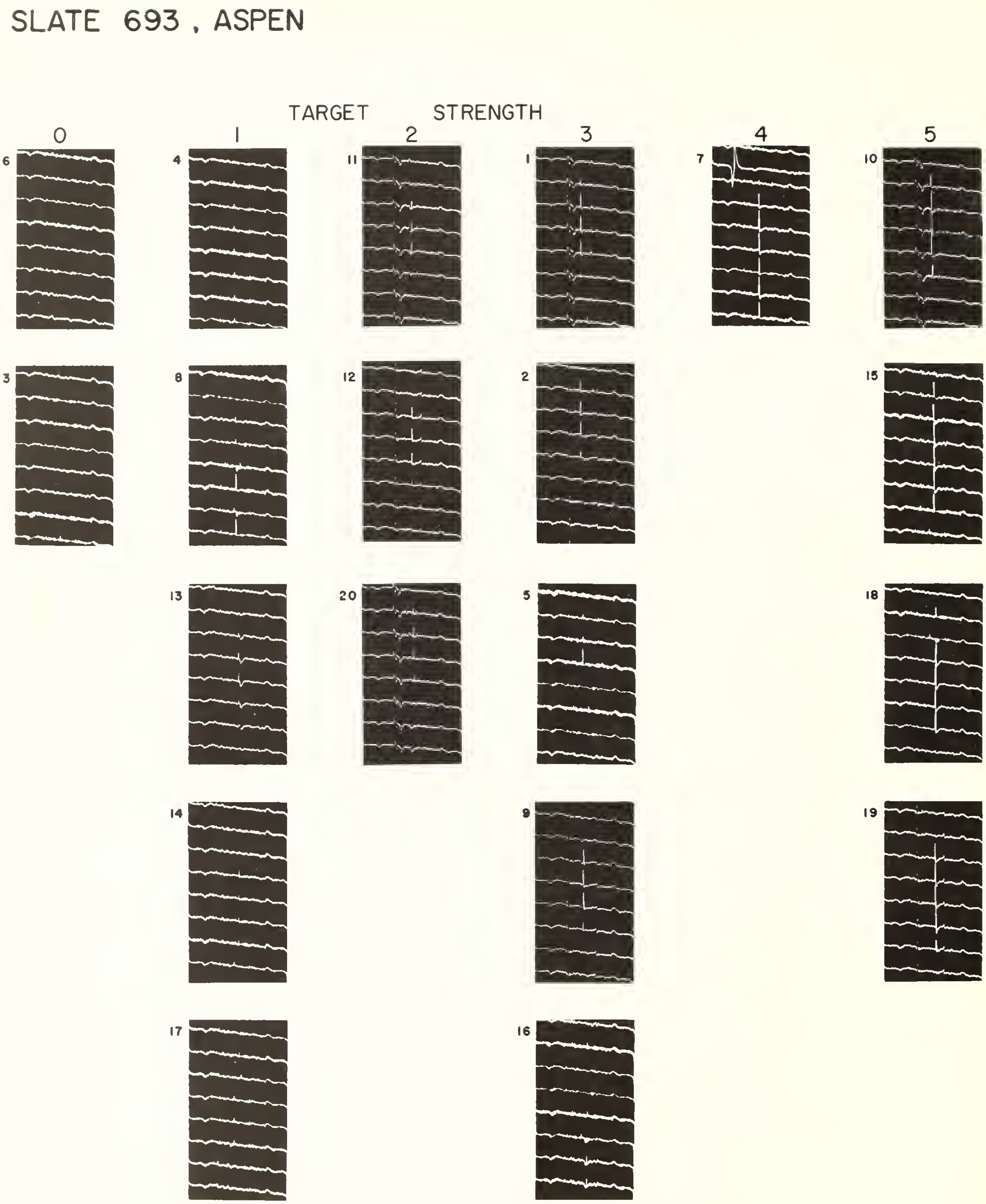


Figure 22. — Oscilloscope traces of target signals of typical test imagery (aspen, northern Michigan, August 2, 1965).

The flight observer monitored the IR imagery in "real time" for the primary purpose of directing the progress of the tests. In figure 23, his record of targets observed in flight are correlated with the later, more detailed recount by the PI's. The observer efficiency (ratio of flight observer's target count to the PI's target count) was 86 percent — average over 493 pieces of imagery from nine test areas.

Two types of error by the flight observer are possible: (1) Identification of targets that actually have no signature on the imagery (false alarms) — this error **(of commission)** occurred very seldom; or (2) missing or failing to count targets with identifiable signatures — this error **(of omission)** was far more common. Most of the missed targets (14 percent) had very weak, marginal signatures.

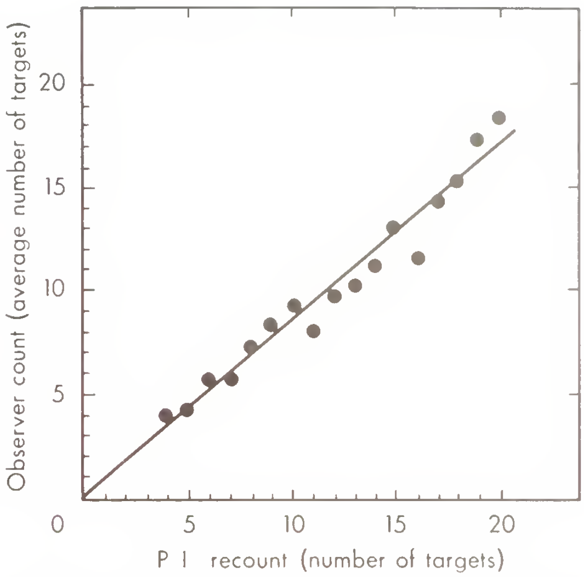


Figure 23. — Percent real time observer count versus PI recount.

Mountaintop Tests

The objective of the mountaintop tests was to measure detection probability at large vertical angles in one timber type.

The scanner was installed on a cliff overlooking the Bear Creek Drainage test area (fig. 24). This area is located west of Victor, Montana, in a well-stocked, mature larch — Douglas-fir stand associated with grand fir, Engelmann spruce, alpine fir, and lodgepole pine.

Test plots were established in the timber stand at 45°, 48°, 50°, 54°, 58°, and 60° aspect angles. Each test plot consisted of two lines 250 feet long and about 15 feet apart, oriented at right angles to the scanner line of sight. Slant ranges from the scanner to the test plots were between 2,000 and 3,600 feet.

The AN/AAS-5 scanner had been modified to improve its dynamic range and lower its noise level. The video signal was amplified by about 40 db. Target signals (A-scan traces) were recorded on Polaroid film from a Tektronix 535 oscilloscope (fig. 25). Electronic gain was periodically calibrated to compensate for drift caused by changes in environmental conditions.

A 1-square-foot burning charcoal target was moved in 1-foot increments along the test lines, providing approximately 500 individual target readings at each aspect angle (fig. 26). Radiometric tests in the laboratory wind tunnel had revealed that significant temperature fluctuations would occur as a result of wind and physical jostling of the fire bucket. Every possible precaution was taken in the field to minimize these fluctuations. Weather data, bucket temperatures, and background temperatures were recorded continuously.

Unobscured control targets were located at least 20 feet outside each end of the test line. These control targets provided an additional target calibration signal and aided the scanner operator in locating the test lines.

A detailed timber cruise was made of all trees located within 50 feet in front of each test line; each tree was identified by recording species, d.b.h., tree height, crown height, and crown width. Trees exceeding 5 inches d.b.h. also were measured that were growing between 50 and 100 feet in front of each test line. In earlier tests we had made a detailed timber crown study at the 45° test plot during which

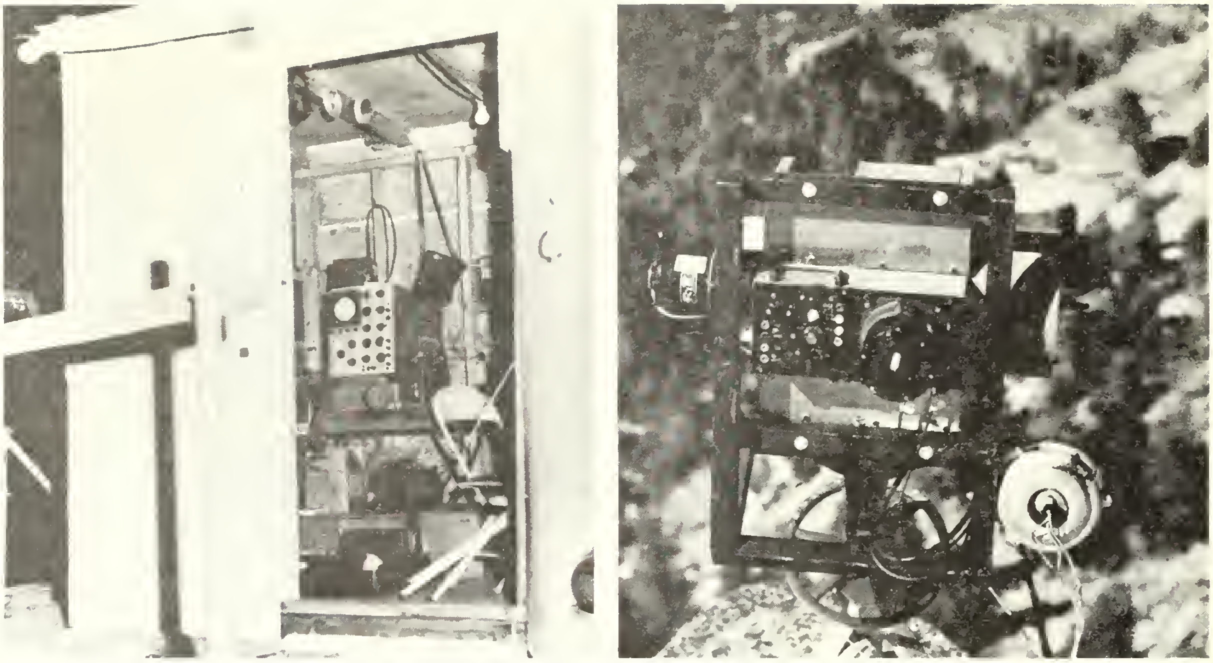


Figure 24. — Scanner installation at mountaintop location.

the horizontal profiles of all tree crowns were mapped, and studies were made of target signals received through 2,500 different optical paths from this test plot (Wilson and Noste 1966, p. 24). The profiles did not provide an accurate estimate of the amount of crown material actually intercepting the scanner-to-target line of sight. It was apparent that we needed some measurement of the vertical distribution of crown material to account for attenuation along various slant paths through the timber crowns.

In later tests on the 50°, 54°, and 60° test plots, an intercept profile cruise was made by mapping all crown material intercepting the scanner-to-target line of sight. That is, we mapped all material intercepting the plane determined by the test line and scanner location. These data provided the basic information for statistical correlation between target signals and the obscuring crown material.

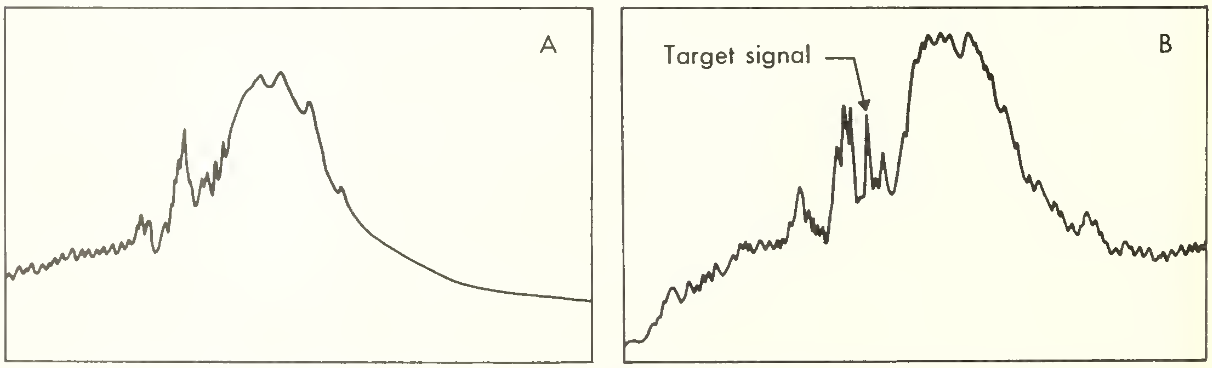


Figure 25. — Typical oscilloscope signal trace showing target signatures for mountaintop tests: A, signal trace of background adjacent to target area without target; and B, signal background with target.

Figure 26. — Burning target on 60° test line.

Operational Patrol Flights

Seven patrol flights were made during July and August of 1966. Sixty targets were detected on these seven missions — 29 campfires, 10 dwellings, 4 slash fires, 12 fire targets, and 5 false alarms. Eight fires were missed. Detailed data for the 1966 fire patrol season are given in tables 30 and 31, in Appendix IV.

A prototype pulse-height discriminator for automatic target alarm was evaluated during this patrol test season. Its performance was very encouraging. It was "alarming" on all hot targets; however, it also appeared to be "alarming" on lakes and other terrain details. The IR imagery was recorded on magnetic tape, which permitted further evaluation and development of the discriminator during the winter of 1966-67.

We concluded from the 1966 patrol tests that consideration should be given to the following:

1. The overall size of the patrol area should be enlarged to increase the likelihood of wildfire observance.

2. Forested areas should be assigned hazard priorities and graded into fire detection classes, using criteria developed in the feasibility studies.

3. Lightning storm activity and current weather information should be acquired for the patrol areas.

4. A plan for collecting fire reports from fire control personnel should be developed.

5. A pulse height/pulse width target discrimination module (TDM) should be added to the system.

6. The aircraft's navigation should be replaced.

An extensive zone 400 miles within a radius of Missoula, Montana, was established in which missions were to be flown in 1967 (fig. 27). This area was divided into eight zones, with preplanned refueling and overnight stops.

Meetings were held with personnel from the 41 National Forests located within this zone to explain the purpose of the study and to ensure timely acquisition of ground reports on wildfires. Information on lightning storms for such a large area had been extremely difficult to obtain. This problem was eased somewhat by use of the weather radar unit at Missoula and the Salt Lake City network. The Missoula radar unit provided hourly maps of individual storm cells within a 200-mile radius of Missoula; these

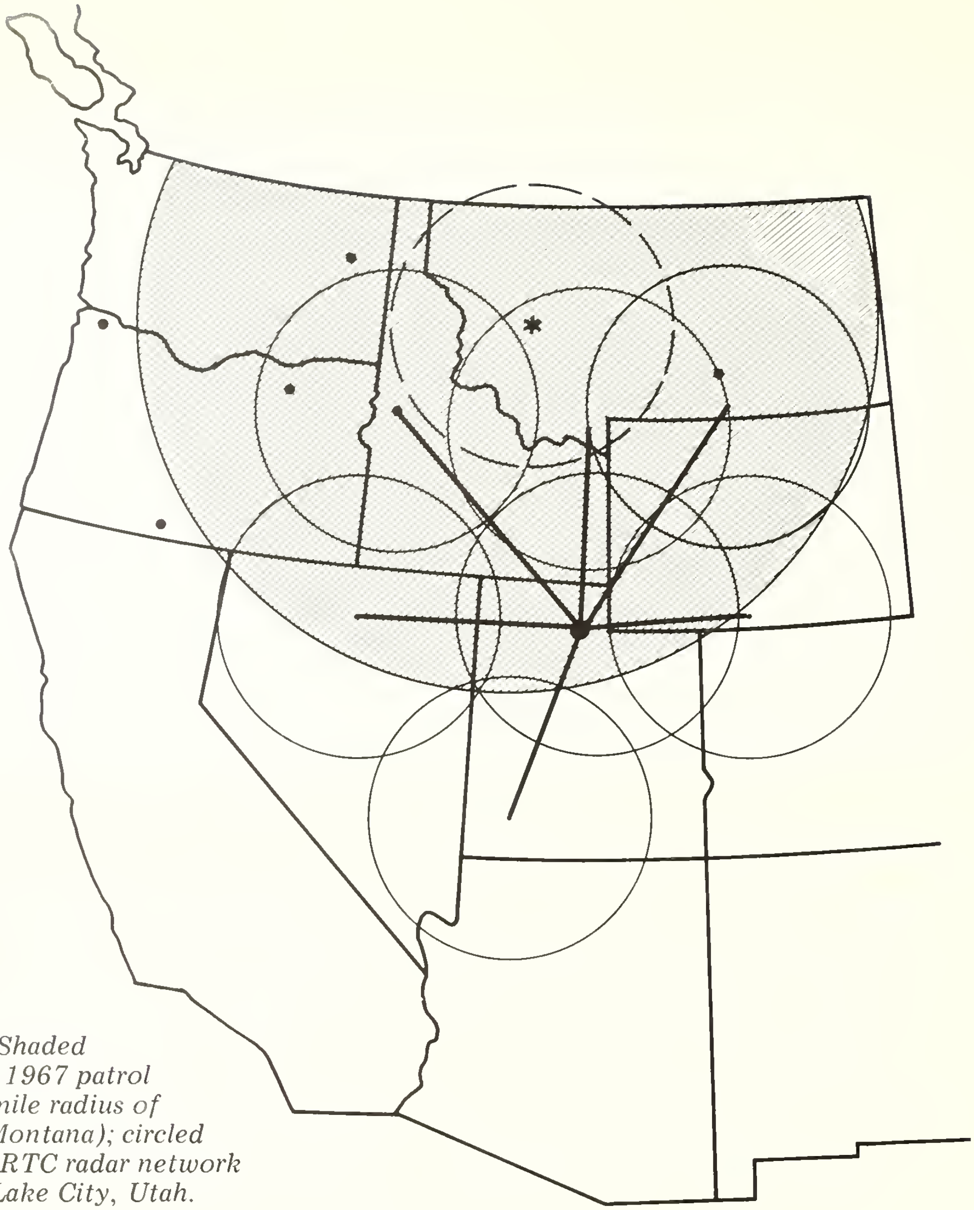


Figure 27. —Shaded area shows 1967 patrol area (400-mile radius of Missoula, Montana); circled areas are ARTC radar network from Salt Lake City, Utah.

maps were the backbone of our weather intelligence. The Salt Lake City center provided teletype reports every 2 hours of storm activity from six radar units in southern Idaho, Utah, and northwestern Wyoming. Telephone reports of lightning storms were obtained directly from National Forest personnel in the Cascade Mountain area of Washington and Oregon.

The probability was high that storms would occur simultaneously in a number of areas within the patrol zone, or would cover an area larger than could be flown on a single mission. Each National Forest was assigned a priority index in order that missions could be planned to observe a maximum number of fire targets. This priority factor (PF) was calculated from the past 10 years' fire-weather histories and expressed as a relative number of fires per storm day per million acres. The PF ranged from 0.29 for the Beaverhead National Forest to a high of 5.76 for the Malheur National Forest (table 32, Appendix II).

Inasmuch as the forest canopy plays a significant role in IR fire detection, we adjusted the PF's for species composition so that the PF value would more closely predict the number of fires that would be detected by IR. This had the effect of favoring patrols in the open timber types. The areas of timber in detection classes 1, 2, and 3 (see p. 33) were measured from USDA Forest Service maps; a weighted average of detection probability was calculated for each of the 41 National Forests, assuming: 100 percent detection for class 1 timber; 75 percent detection for class 2 timber; and 50 percent detection for class 3 timber. We assumed fires would be equally distributed in all timber types.

The elapsed time between lightning occurrence and the time an area could be flown was determined by the rate of dissipation of clouds after a storm. We also attempted to adjust the PF to account for fires that would be detected and, in some cases, manned and controlled before they could be flown with the IR scanner. From the fire histories of each National Forest, a tabulation was made of the percent of undetected fires versus elapsed time between origin and detection. This readjustment also accounted for time lapses between different storms in different areas. Thus, the urgency of patrolling an area that had had a high PF and a storm on the previous day could be compared to an area that had a lower PF and a storm since the previous day.

In the Northern Rocky Mountain region, lightning storm activity generally occurs in the afternoon and early evening; the storm dissipates by late evening. Thus, daily storm activity, which was plotted on a planning map, was updated until 1900 hours (fig. 28). Possible mission areas were blocked out on the map and an adjusted PF assigned to each of these areas. The area with the largest probable number of target detections was selected for patrol.

A patrol mission briefing was held for the aircrew, during which flight plans were finalized based on flying conditions and lightning storm activity. On occasion, a high priority area had to be passed over because of late cloud dissipation.

Latitude and longitude of the starting and ending points of the first patrol leg were read from the planning map; values were used to compute the course and distance of the first leg of the patrol. This first leg was transferred to a sectional aeronautical chart. The remaining legs were plotted parallel to the first (fig. 29). The average altitude over terrain determined the spacing interval, which varied from 5 to 7 nautical miles. A prominent land feature was selected on each leg of the patrol grid to be used as a checkpoint. Information was provided to the navigator in the format shown in figure 40, Appendix IV. The checkpoints also were plotted on a USDA Forest Service Series A map to provide detail to the flight observer when checking the imagery.

Missions were scheduled for sometime after 2200 hours, depending on time required to fly to the beginning point of the first leg of the mission. The course and distance of the first leg were set in the Doppler computer. As the plane proceeded down the first leg, the computer showed the miles-to-go to the end of the run and the miles right or left of the desired track. This navigation system worked well during the 1967 tests.

No attempt was made to locate targets in flight. The imagery was available to the PI's by 0600 hours. Targets were located on USDA Forest Service Series A maps and recorded on data forms (fig. 41, Appendix IV). In difficult areas, Forest Service timber-type maps also were used because they have vegetation cover information.

The PI classified targets into four categories:

1. **Fire target.** — (a) If in an isolated location, any well-defined target on the film; or (b) if near roads, streams, or possible human activity, any target of greater intensity than normally expected from a campfire.

2. **Possible fire.** — (a) These are targets that may have the same characteristics as a fire target, but are possible campfires because of their location; or (b) targets that tripped the TDM, but did not appear on the film because of their location and intensity.

3. **Campfire.** — These are targets in known campgrounds or situated in an area that makes it highly probable that they are campfires (e.g., by a major road or a heavily used stream or river).

4. **Other.** — All other hot targets (e.g., hot springs, houses, mills, etc.)

Targets in the first three categories were reported to the National Forests as soon as interpretation was completed.

The reports to the National Forests included target category, location by legal description, and recognizable landmarks. A followup call was made later in the day to determine if any targets had been confirmed and if any fires had

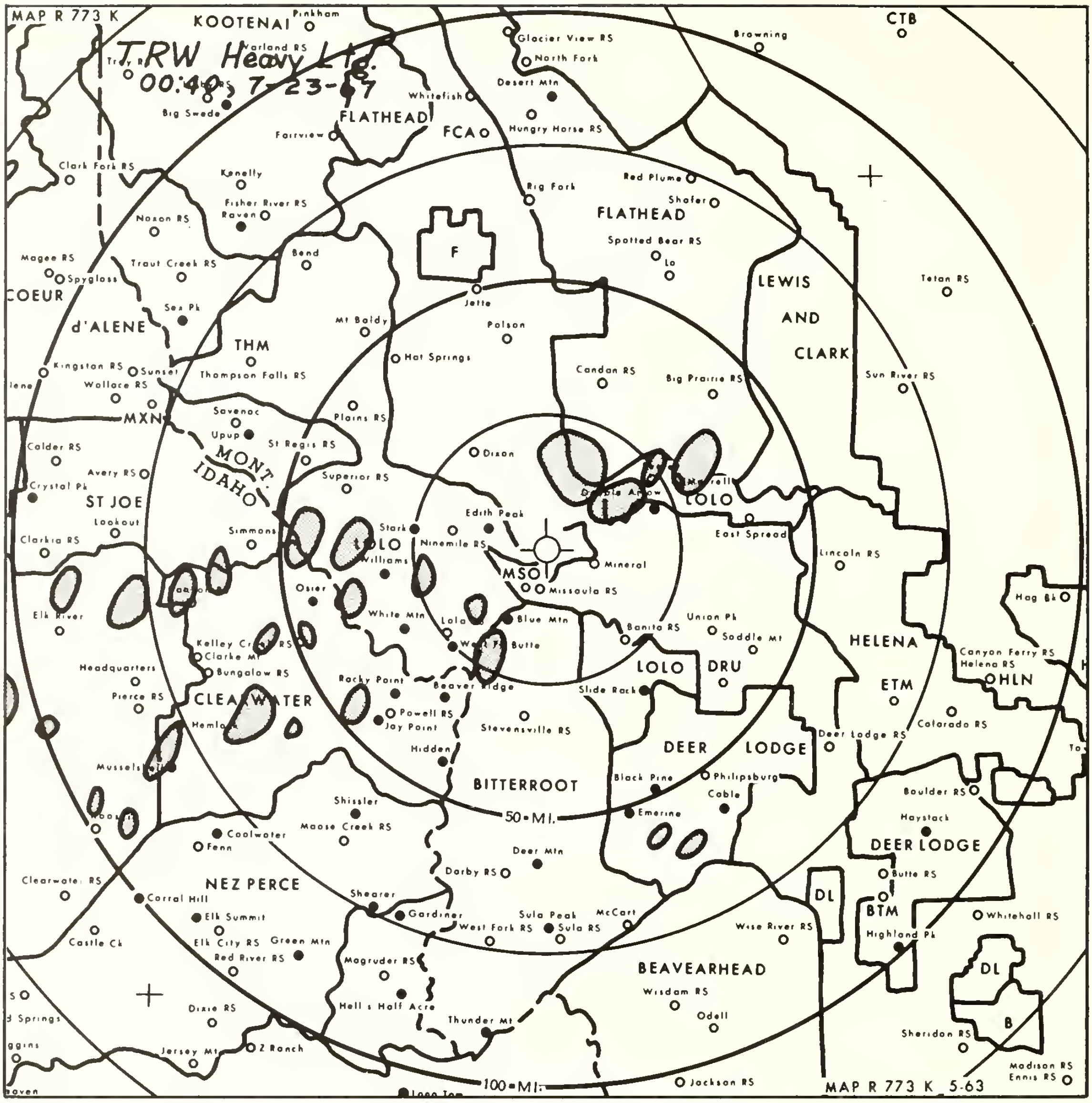


Figure 28. — Shaded areas show where lightning storms occurred on July 23, 1967, in the patrol area. This was derived using thunderstorm activity maps issued hourly by the Missoula radar unit for that day.

been missed by the scanner. The areas around fires that were accessible to our ground crew were examined to determine the type and density of crown obscuration, fire size, burning characteristics, location and fuel, and amount and type of smoke available for visual detection.

During 1967, lightning activity was limited in the western portion of the 400-mile patrol zone; thus, the number of missions flown in this area was less than anticipated. Patrol flights were made on 21 of the 35 possible operational days (table 1). Eight of the days (23 percent), on which flights were not made, had little or no lightning activity; 5 days (14 percent) had lightning but late cloud dissipation prevented scheduling a patrol mission. One mission had to be scrubbed because of restrictions on pilot hours. However, late dissipation of cloud cover caused some problems, primarily in the early part of the season. A daytime mission capability could alleviate this problem to some extent. It ap-

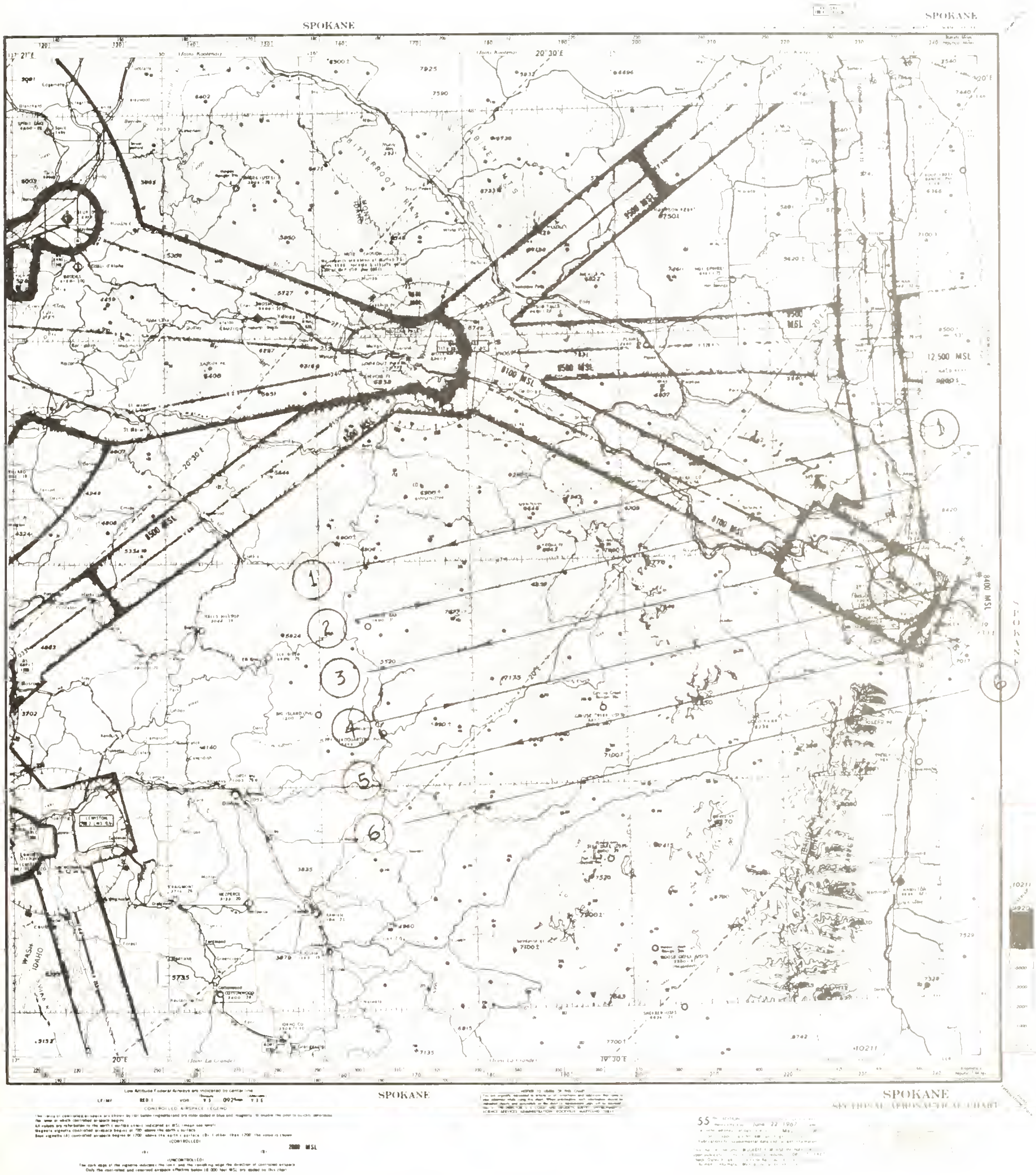


Figure 29. — Flight plan of Patrol #12, July 23, 1967. This patrol grid, of six flight legs, covers the high priority areas of lightning activity that are shown in figure 28. The imagery from this patrol is displayed on the supplemental foldout inside the back cover. Fifty-three hot targets were counted on this patrol (see table 33, Appendix IV).

pears that a normal convective storm will not cause problems. However, cloud cover associated with frontal systems may linger and prevent some missions.

The average dissipation time for thunderstorms within the patrol zone during 1967 was 1900 hours for the northwest forests, 2015 hours for the northeast forests, 2145 hours for the southwest forests, and 2315 hours for the southeast forests. Cloud cover resulted in 2-percent loss of total IR coverage. In most cases, this loss was due to patches of clouds scattered over the patrol area; however, on one flight, 25 percent of the mission was aborted because of solid cloud cover at one end of the mission area.

U. S. Weather Bureau reports were usually correct in predicting cloud dissipation. We did not miss any fires on the IR imagery because of cloud cover.

The effectiveness of the PF's that were used to plan patrol missions is difficult to evaluate. It was impossible to determine the number of fires that were started in areas that were not patrolled; consequently, we had no reference to compare to the number of fires in the partrol area. It appears that the basic premise for the PF is correct; there were no obvious errors in area selection. The information obtained from the U. S. Weather Bureau radar networks was essential for the planning of IR detection flights. Radar provides good weather information for large areas; this eliminates the need for contacting each National Forest in a proposed patrol area.

Table 1. — Difference between planned patrol coverage and area actually flown

Flight	Area planned to be flown	Area actually flown	Difference	Reason
	Square miles	Square miles	Square miles	
1	5,080	3,050	2,030	Navigational problems
2	3,910	3,910		
3	4,040	4,040		
4	2,680	2,680		
5	5,760	4,380	1,380	Low on fuel
6	5,080	3,810	1,270	Cloud cover
7	4,630	4,630		
8	2,690	2,690		
9	5,020	4,570	450	Cloud cover
10	5,740	2,870	2,870	High voltage failure
11	2,600	2,600		
12	4,320	4,320		
13	4,020	4,020		
14	3,540	2,820	720	High voltage failure
15	1,620	650	970	Aircraft engine failure
16	6,200	6,200		
17	5,510	5,510		
18	5,020	3,210	1,810	High voltage failure
19	5,140	5,140		
20	4,710	4,710		
21	2,640	2,640		
Total	89,950	78,450	11,500	
Average	4,283	3,736	548	

DISCUSSION OF RESULTS

Percent Detection From Airborne Tests

Yes-no detection probability is the percent of the existing fires that are observed and counted from the imagery. We must reemphasize that these data include, as detected fires, all targets that were observed at known locations. Detection probabilities are presented as a function of aspect angle out to 60° for fire radii of 3, 9, and 15 feet (Appendix III). Measurements of detection probability of 6- and 12-foot fire radii are included only when great differences are observed among the 3-, 9-, and 15-foot measurements. Furthermore, such measurements are incomplete beyond the aspect angle at which percent detection falls below one-half of its value at 0°.

We have discussed restraints imposed on data acquisition. The data, however, are sufficient to cover all marginal cases. For example, if a fire 3 feet in radius is detectable at 50- or 60-degree aspect angles in a particular timber type, one may infer that fires 6, 9, 12, and 15 feet in radius also are detectable at all aspect angles. Similarly, if fires 15 feet in radius are marginally detectable at the nadir, we infer that fire targets smaller than 15 feet in radius also would be difficult to detect at aspect angles greater than 0°.

The 13 timber types represented a wide range in species tolerance, composition, and crown configuration. We might expect canopy densities to be very different in other stands of the same type because of variations in species composition, age, stocking, and site quality. We can make predictions of detection probability, based on **percent detection** measurements, only for timber stands that are comparably stocked to our test sites. There is no basis in our data for predicting the effects of variation of timber density on detection probability within a given timber type. However, the attenuation of target signal strengths by timber crowns can be correlated with differences of stand characteristics between targets within a test area (see page 37).

The 13 timber types were divided into three categories of detection difficulty to evaluate our criterion of shade tolerance for site selection (table 17, Appendix II; fig. 30). Detection category 1 includes the generally more intolerant species, which are characterized by 95 percent detection at small vertical angles and at least 50 percent detection probability to 60°. The species in detection category 2 have a lower overall detection probability than those in category 1. Detection probability begins to drop off at smaller aspect angles than it does in category 1. The more tolerant species in category 3 exhibit poorer detection at smaller angles; detection probability rolls off with aspect angle more quickly than it does on species in either of the other two categories.

F. S. Baker (1949) states that his tolerance table is based on a general concensus of American foresters, and cautions that tolerance is not a scientifically (rigorous) defined variable. He further points out that tolerance changes with tree age and environment.

Our test sites were selected from medium to heavily stocked, mature stands. We must reemphasize that there is no rigorous basis for extrapolating our percent detection results into the broad range of stand densities within a particular timber type that one may encounter in practice.

Unaccounted variables — for example, terrain and slope — will lower the detection prob-

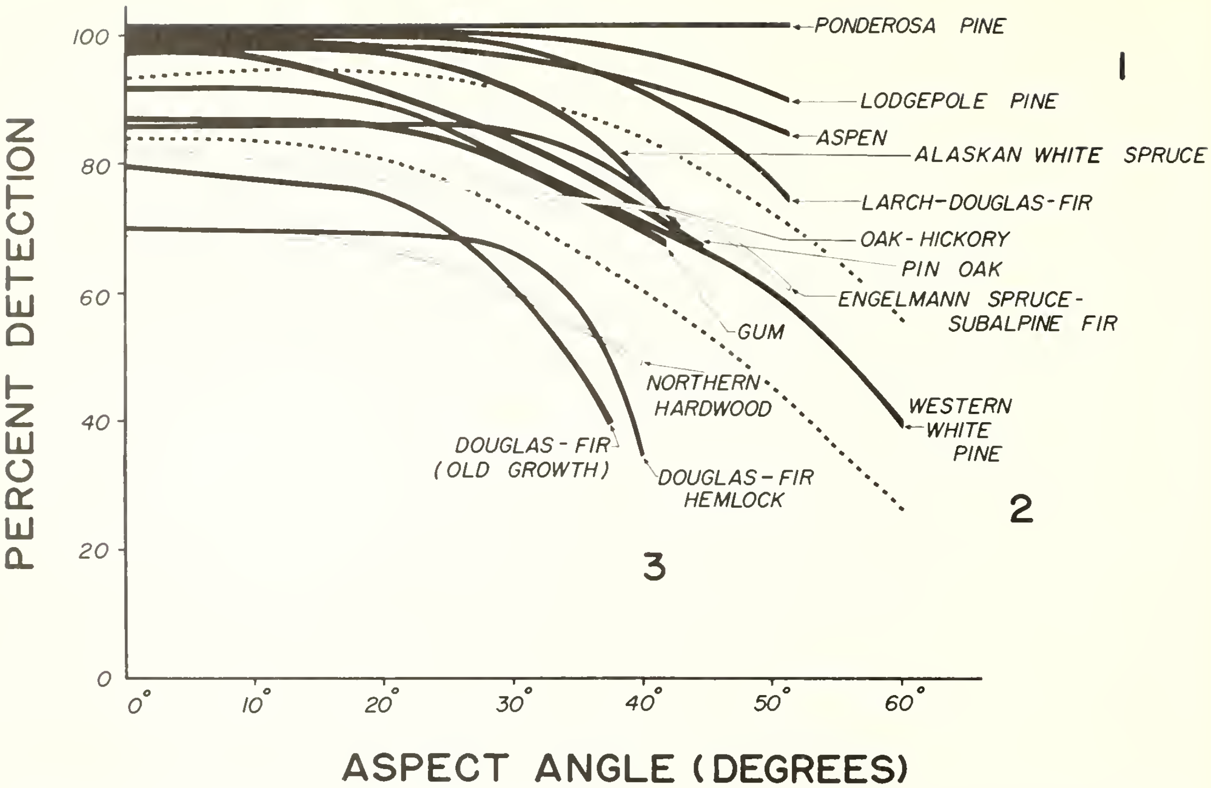


Figure 30. — Detection probability versus vertical scan angles in three major classes of timber types (9-foot fire radius).

ability curves that are shown in figure 30. PI bias (known locations of test targets) also makes these curves higher than we would expect on operational patrol. However, the heavily stocked, mature timber stands on our test sites made target detection more difficult than we would expect on patrol over typically stocked timber stands.

The mountaintop detection probabilities are shown in table 2 and in figure 31. To be detectable, a target signal must be larger than some threshold signal. This threshold signal is determined by the background signal around the target. This is analogous to the criteria used in the flight test for the five 1-square-foot targets. It permits simultaneous plotting of flight test and mountaintop test data (fig. 32).

In the Interim Report (Wilson and Noste 1966), we reported a function $(\text{Cos } \theta)^{1.40}$ as being best fit curve to the detection probability data. Our subsequent tests were more comprehensive and detection probability drops off much sharper beyond 50° than the cosine function predicted and approaches zero between 60° and 65°.

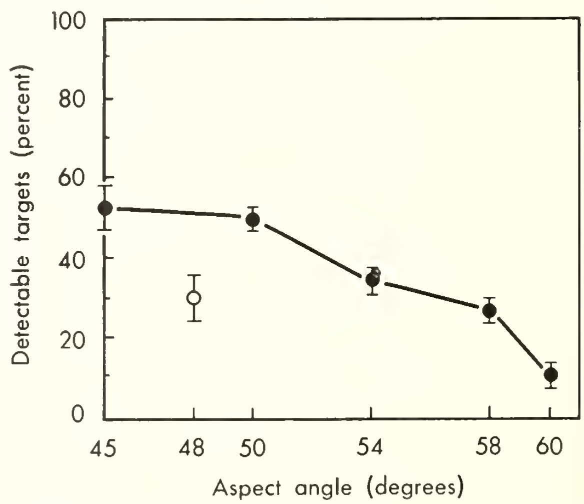


Figure 31. — Percent detection versus aspect angle for the mountaintop tests (larch — Douglas-fir timber type).

Table 2. -- Detection results of the mountaintop tests

Aspect angle	Total number targets	Number observed	Percent detection	Average signal strength (relative)
45°	323	168	52.0	20.9
48°[1]	266	81	31.0	12.8
50°	486	245	50.4	25.9
54°	548	186	33.9	10.3
58°	391	105	26.9	4.8
60°	485	51	10.5	1.8

[1] *The 48° test line was in a marginal location at an azimuth nearly parallel to the cliff and was partially screened by shrubs and rocks projecting from the cliff. Also, the 48° data were taken under marginal, inclement weather conditions.*

Target Signal Strength and Timber Obscuration

The optical density of target signatures on IR imagery provides sufficient information to make estimates of attenuating effects of timber crowns and boles. Attenuation of the target signal by a denser crown canopy results in a weaker target signature on the IR imagery. Target signatures were read subjectively by three independent PI's. The first step in our analysis was a simple statistical test to demonstrate that the estimates of signal strength are a justifiable measure of the detection system capability.

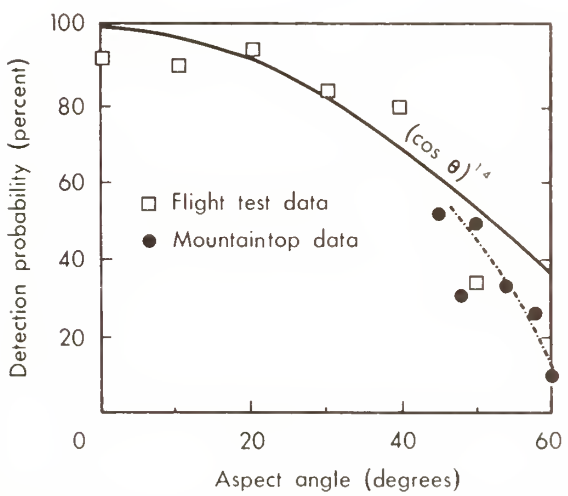


Figure 32. —Larch—Douglas-fir flight test data to 40°, extended past 60° by the mountaintop data.

This statistical test is demonstrated by plotting the average signal strength against the number of positive targets (yes detections) observed in all aspen imagery (fig. 33). Each point represents the average target signal strength that produced the given percent detection for all flight passes. A strong correlation exists between target strength and detection probability. Similar correlations exist for all 13 timber types.

Signal strengths remain constant or rise from 0° to 20° and then fall off towards 60° (fig. 34). We used an arbitrary 0 to 5 scale to estimate the fire target signatures. In so doing it is general practice to assign a signal strength of 1 to target intensities equal to or less than the maximum background density. It is these weak marginal targets (density approximately 1) that represent questionable targets counted in the percent detection results shown in figure 30. Under operational conditions, it is unlikely these targets would have been detected had their exact location not been known when the imagery was read by the PI.

Figure 35 attests to the large number of marginal tests that we counted. Indeed, successful detection in the aspen and pin oak timber types at aspect angles greater than 30° can be attrib-

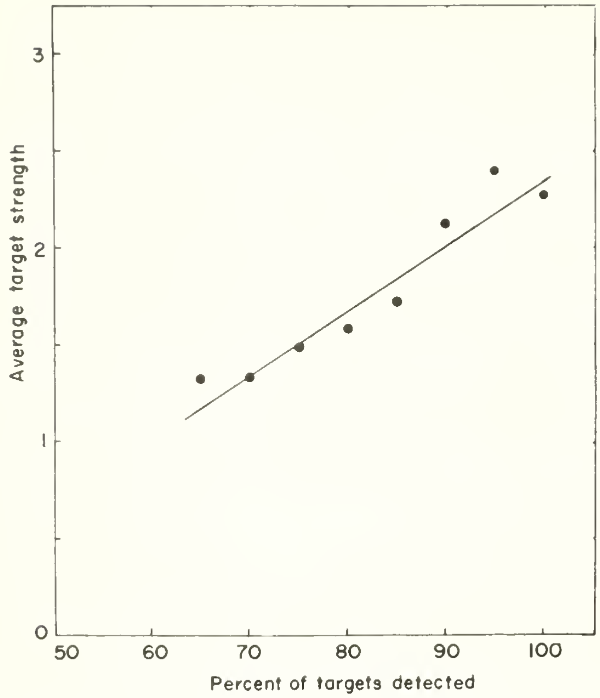


Figure 33. — Correlation of detection probability and signal strength for all aspen data.

uted directly to our ability to find a very large number of these marginal targets. Fortunately, we have a promising solution to this marginal target problem — a two-color temperature discrimination with scan-to-scan correlation (Appendix V).

If the frequency distribution of signal strength, N_S, is known (in particular, its dependence on the timber cruise parameters), then we can write a formulation for detection probability, P:

$$P = \frac{1}{N_O} \int_{S_T}^{\infty} \left(\frac{dN_S}{dS}\right) dS \qquad \text{Eq. 7}$$

where S is the signal strength and S_T is the detection signal threshold.

This distribution of signal strengths appears to depend on the spatial distribution ("patchiness") of the crown material. For example, the bimodel signal distribution of weak and strong signals in the old-growth Douglas-fir test stand is indicative of concentrated patches of crown material interspersed with patches of open spaces. On the other hand, the aspen was a homogeneous stand. Unfortunately, there is no standard forestry cruise parameter to measure this patchy effect, and we did not make provisions in our experimental design to make such measurements.

The model of timber obscurations (Appendix III) is based on the average crown density of the timber stand and thus it does not account for the variance from homogeneity in crown

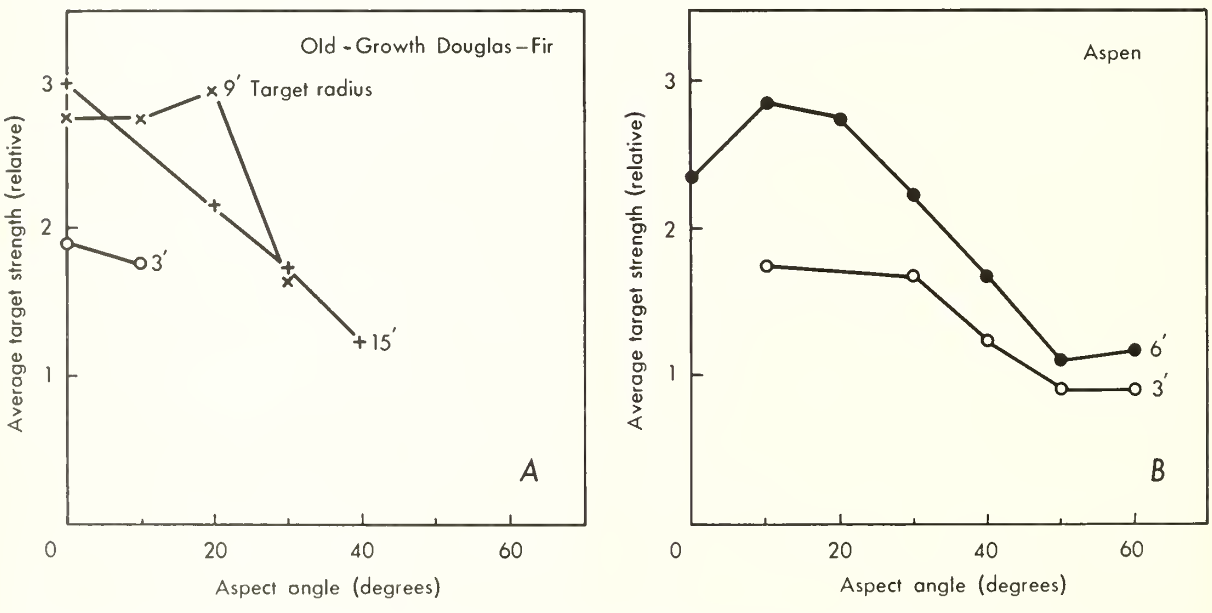


Figure 34. — Typical curves of the relative target signal strength distribution as a function of aspect angle for A, old-growth Douglas-fir and B, aspen timber types (post-1965 tests).

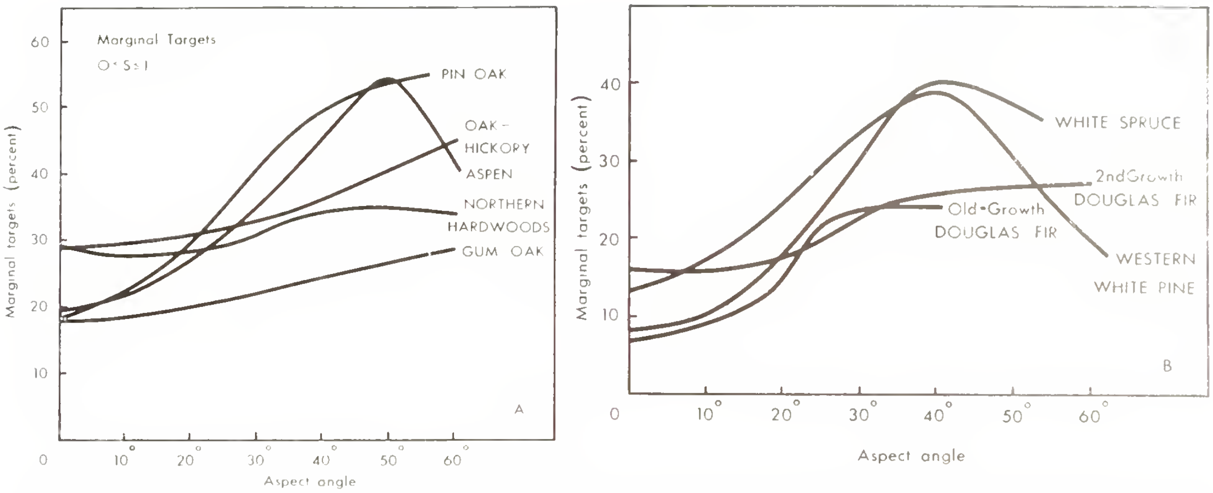


Figure 35. — Distribution of marginal targets with aspect angles ($O < S < 1$): A, Deciduous; and B, coniferous timber types.

material. The model reliably predicts the average signal strength but does not give a signal strength distribution from which we can predict a detection probability using equation (7). These signal distributions in tables 20-29 in Appendix III are also inadequate because each is measured from a single test area characterized only by an average stand density.

We established an empirical functional relation that was equivalent to equation (7) for our data. That is, detection probability, P_5 (five 1-square-foot targets), is empirically correlated with average signal strength, S:

$$P_5 = A + BS + CS^2 \qquad \text{Eq. 8}$$

The functional coefficients A, B, C and a "Coefficient of Determination," R^2 (table 3) were evaluated.[4]

[4] *The ratio of the regression sum of squares to the total sum of squares (i.e., the fraction of the total sum of squares accounted for by the regression) is sometimes called the coefficient of determination and denoted by R^2.*

Table 3. — Coefficients for target obscuration model

Timber stands	A	B	C	J	R^2
Northern hardwoods	0.233	2.503	-2.323	0.139	0.71
Oak-Hickory	.270	2.645	-2.624	.080	.67
Aspen	.452	1.946	-1.928	.113	.65
Gum-Oak	.194	2.237	-1.596	.098	.73
Pin oak	.540	1.420	-1.166	.128	.47
Western white pine	.463	1.207	-0.606	.171	.47
White spruce	.339	2.412	-2.090	.235	.79
Lodgepole pine	.463	1.710	-1.323	.194	.51
2nd-growth Douglas-fir	.136	2.737	-2.614	.106	.56
Old-growth Douglas-fir	.393	0.732	0.163	.080	.50

Coefficients A, B, and C describe the empirical fit of our data, equation (8), and should not be extrapolated beyond our observed signal strengths. The fit is not good for weak or strong average signal strengths, S. Graphs of the detection predictions, P_5, for the conifer and deciduous test areas are shown as A and B, respectively, of figure 36. These "predictions" may be compared to the measured detection probabilities in figure 30.

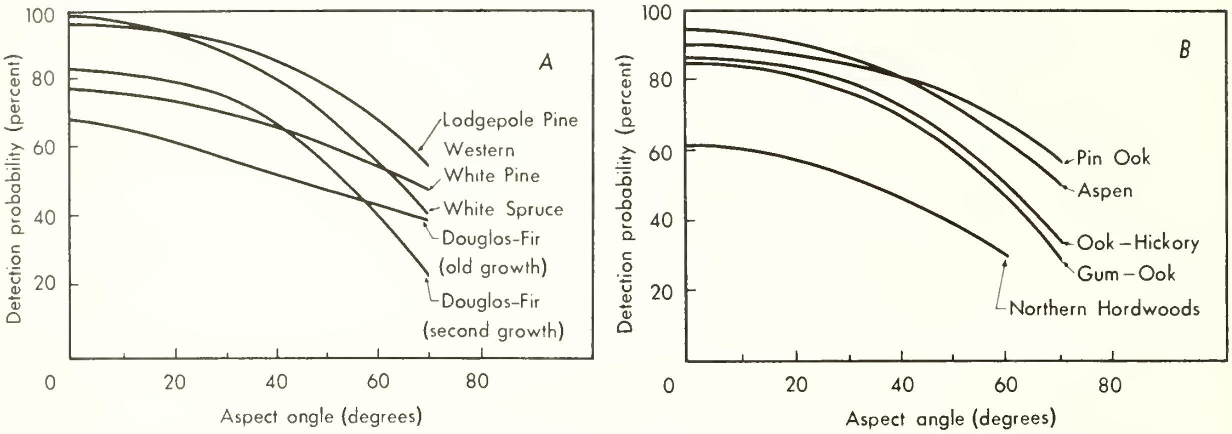


Figure 36. — Predicted detection probability (percent), P_5, versus aspect angle in A, coniferous and B, deciduous timber types.

Operational Tests

A total of 21 night detection missions was flown within the 400-mile-radius patrol zone during the 1967 fire season. Coverage per mission ranged from 650 square miles to 6,200 square miles.

There were 1,434 TDM trips on the imagery, of which 601 were interpreted as hot targets and the remaining 833 were initially interpreted as false alarms.

Hot Targets

Of the 601 hot targets, 310 were reported to the National Forests (table 34, Appendix IV) — 213 were confirmed by the ground crews and 55 could not be confirmed. Two targets reported as campfires turned out to be wildfires, 71 turned out to be other hot targets.

We flew over 134 wildfires that were possible targets of which 87 were detected (65 percent). Sixteen of the 47 fires missed registered a target on the imagery but did not trip the TDM system. These 16 fires were found on the imagery after reports were obtained from the National Forests.

False Alarms

Of the remaining 833 false alarms, 43 were roads, 56 snow, 43 ridges, 448 lakes and rivers, and 243 random noise.

In addition, 55 targets that had been reported as fires to the National Forests but could not be confirmed were later classified as errors — 34 were classed as false alarms and the remaining 21 had good target signatures on the imagery. These 21 targets were located in remote alpine areas and apparently burned out before they could be found by the ground crews.

Target Intensity

The distribution of target signal strengths for detected fires smaller than one-half acre is shown in figure 37. Signal strength is measured on a scale of 0 to 5, where 5 is a saturated target and 2 is a normal strength required by a PI to identify a random target above the background. Using this scale, 52 percent of all hot targets and 69 percent of the 39 natural wildfires might have been missed by the PI (signal less than 1) if he didn't have the aid of the TDM.

These 39 fires are considered to be a sample of incipient fires that must be found by any detection system. Fires under suppression attack provide unknown amounts of radiation for detection; therefore, in the following analysis, only unmanned fires are considered. Our detection success in this group is 23 of 39 (59 percent).

1. **Detected by TDM.** — There were 23 unmanned wildfires detected by the TDM, of which 9 were detected previously using conventional methods (14 had not been detected). Six of the previously detected fires were detected by visual method within 2 hours after ignition; however, no fire control problems would have resulted on these six fires if detection had been delayed until the area was patrolled with the IR scanner. The other two fires burned 13 and 18 hours before detection. They were not flown earlier because they ignited during the period the aircraft was under repair for engine failure. One of these fires burned 5 acres, which was caused primarily by a delay in initial attack rather than failure of early detection.

Of the 14 fires not detected by visual methods, four were subsequently found by visual methods using target locations determined from IR scanner; six were found and suppressed by ground crews, and the remaining four were never found. None of these 14 fires became serious control problems.

2. **Undetected by TDM.** — There were five fires undetected by the TDM. These fires were judged to be marginal targets for IR detection. (On such targets a spot is seen on the IR imagery at the location given for the fire, but the TDM does not mark the imagery, which is caused by incorrect setting of the TDM.) Such marginal targets normally should be detected. One of these five fires had been detected previously by conventional methods.

3. **Fires missed by airborne IR detection system.** — There were 12 fires missed by the IR system. Four of these were detected previously

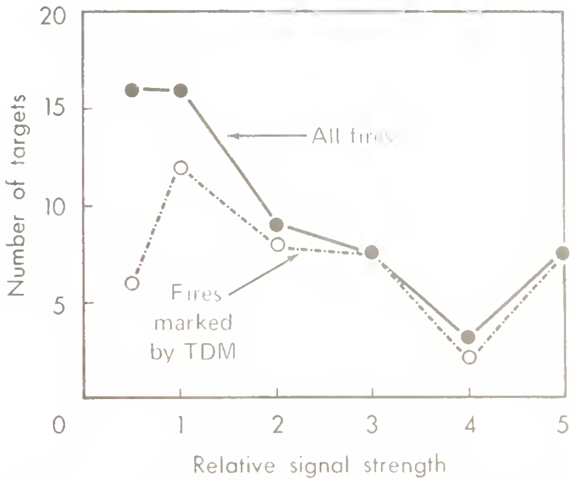


Figure 37. — Distribution of target signal strengths for detected fires smaller than one-half acre.

by conventional means and suppressed in less than 1 hour, which indicated that the fires were small. In these four fires, the time between IR mission and initial attack was at least 8 hours. They were ground fires that could have been detectable during a second patrol on a succeeding night if they had not been suppressed. Unfortunately, during the delay between patrol flights, fires of this size could develop into major fires that could cause considerable damage.

The remaining eight fires missed by the IR system had not been detected visually when the aircraft flew over them; they were found from 6 hours to 11 days later. Seven of these fires could have been scanned a second time before they were found (i.e., 24 hours between ignition and detection).

The unmanned fires were burning under various types of timber canopies and were scanned at various aspect angles. Of the 39 unmanned fires, 20 were burning in detection class 1 timber and 19 were in detection class 2 timber. This breakdown among classes is approximately what we had predicted because there are few detection class 3 timber stands in the patrol zone.

Fire locations read from the IR imagery were evenly distributed with regard to aspect angle — 13 were located at aspect angles of 20 or smaller, 15 were located between 20° and

40°, and 11 between 40° and 60°. This is close to what one would expect if detection probability versus angle was the only effect. However, it is quite surprising because equal angle increments do not subtend equal ground distances.

The 39 fires constitute a small sample for detailed analysis. However, we might conclude that:

1. Most of the detected fires were observed at aspect angles less than 40° and most of the misses occurred at aspect angles over 40°.

2. More targets were detected in detection class 1 timber than in detection class 2 timber; conversely, more targets were missed in detection class 2 timber.

3. Four out of the five TDM misses that had observable IR target signatures were in the detection class 2 timber. The distribution of these misses with aspect angle does not appear significant.

Many fires are started by lightning in the interior of snags and rotten trees. The size of a snag fire remains relatively small until a firebrand falls to the ground or the exterior of the tree begins to burn. We had assumed that fires confined to snags at the time of observation would be more difficult to detect than ground fires. However, 6 of 10 snag fires (60 percent) were detected; whereas, 16 of 24 (66 percent) of the ground fires were detected.

Target Location

We attempted to locate all targets to the nearest one-fourth mile, or 40-acre block, using Forest Service Series A maps which are scaled one-half inch to the mile (table 4). Targets located from the IR imagery were compared to the fire locations listed on the standard Forest Service fire report forms (5100-29).

The accuracy of location is dependent largely on image quality and terrain detail. Homogeneous timber stands and flat terrain provide little detail on IR imagery, thus, accurate location of targets is difficult. Some correlation is evident between scan angle and location accuracy; however, number of targets obtained at aspect angles over 40° is too small for reliable estimates of error.

The system must be adjusted to obtain maximum terrain contrast on the imagery. For most areas, the lack of terrain detail on available Forest Service maps poses a major problem. Aerial photographs provide better terrain detail than do these maps; however, they are not annotated so that the PI can identify targets according to legal descriptions.

Twenty-six fires within the area patrolled had not been exposed to visual detection. Eleven of these (42 percent) were detected and reported to the National Forests (table 36, Appendix IV). Three (12 percent) were detected by IR but had been detected by visual methods before the IR reports were sent to the National Forests. Four (16 percent) were recorded on the imagery but the TDM did not mark them. Eight (30 percent) were missed by the IR detection system.

The targets missed and the false alarms were due partially to our limited experience in adjusting the TDM trip level. However, the principal cause was a basic flaw in the TDM design; specifically, electronic filter differentiated the video signal thus nullifying the effect of pulse-width discrimination. This seriously affected the operator's ability to establish a satisfactory trip level.

In-flight photointerpretation is a realistic goal and would permit dispatching of fire control forces within 1 hour of detection.

Table 4.—Location accuracy for detected fires

	Scan angle			
Location error	0°-20°	20°-40°	40°-60°	Average
	Percent			
Less than 1/8 mile	24	22	6	18
1/8 mile	43	35	25	35
1/4 mile	19	13	32	20
1/2 mile	10	30	6	17
3/4 mile	4	0	19	7
1 mile	0	0	12	3

LITERATURE CITED

Baker, Frederick S.
1949. A revised tolerance table. J. Forest. 47: 179-181.

Biberman, Lucien M.
1967. Apples, oranges, and unlumens. Appl. Opt. 6(6): 1127-1128, illus.

Born, Max, and Wolf, Emil.
1964-65. Principles of optics, Ed. 3. 808 p., illus. New York: Pergamon Press.

Genoud, Richard H.
1959. Infrared search-system range performance. Inst. Radio Eng. Proc. 47(9): 1581-1586, illus.

Grosenbaugh, L. R.
1952. Plotless timber estimates — new, fast, easy. J. Forest. 50: 32-37, illus.

Harlow, William M., and Harrar, Ellwood S.
1950. Textbook of dendrology, Ed. 3. 555 p. New York, Toronto (etc.): McGraw-Hill Book Co., Inc.

Hirsch, Stanley N.
1962. Infrared as a fire control tool. Western Forest Fire Res. Counc. Proc. 1962: 5-10, illus.

____
1962. Possible application of electronic devices to forest fire detection. U. S. Forest Serv. Intermountain Forest and Range Exp. Sta. Res. Note 91, 8 p.

____
1963. Applications of remote sensing to forest fire detection and suppression. Second Symp. Remote Sensing Environ. Proc. 1962: 295-308, illus.

Hirsch, Stanley N.
1964. Forest fire detection systems. Western Forest Fire Res. Counc. Proc. 1964: 3-5, illus.

____
1965. Airborne infrared mapping of forest fires. Fire Technol. 1(4): 288-294, illus.

____
1965. Infrared line scanners — a tool for remote sensing of forested areas. Soc. Amer. Forest. Proc. 1965: 1969-1972, illus.

____
1965. Preliminary experimental results with infrared line scanners for forest fire surveillance. Third Symp. Remote Sensing Environ. Proc. 1964: 623-648, illus.

____
1968. Detecting small fires with airborne infrared line scanners (U). U. S. Atomic Energy Comm. Meeting on Search, Detection, and Recovery of Nuclear Heat Sources Proc. (U) 1968: 124-134, illus. (Classified)

____
1968. Forest fire control (in part). P. 187-188, in: 1968 McGraw-Hill Yearbook of Science and Technology. New York, St. Louis [etc.]: McGraw-Hill Book Co., Inc.

____
1968. Project Fire Scan — summary of 5 years' progress in airborne infrared fire detection. Fifth Symp. Remote Sensing Environ. Proc. 1968: 447-457, illus.

Hirsch, Stanley N., Bjornsen, Robert L., Madden, Forrest H., and Wilson, Ralph A.
1968. Project Fire Scan fire mapping final report, April 1962 to December 1966. U. S. Forest Serv. Res. Pap. INT-49. 49 p., illus.

Holmgren, Arthur H., and Reveal, James L.
1966. Checklist of vascular plants of the Intermountain Region. USDA Forest Serv. Res. Pap. INT-32, 160 p.

Holter, Marvin R., Nudelman, Sol, Suits, Gwynn H., Wolfe, William L., and Zissis, George J.
1962. Fundamentals of infrared technology. 442 p., illus. New York, London: The Macmillan Co.

Hudson, Richard D., Jr.
1969. Infrared system engineering. 642 p., illus. New York, London [etc]: John Wiley and Sons.

Institute of Science and Technology.
1962. Proceedings of the First Symposium on Remote Sensing of Environment. 124 p., illus. Ann Arbor, Mich.: Univ. Mich.

____
1963. Proceedings of the Second Symposium on Remote Sensing of Environment. 459 p., illus. Ann Arbor, Mich.: Univ. Mich.

____
1965. Proceedings of the Third Symposium on Remote Sensing of Environment. 821 p., illus. Ann Arbor, Mich.: Univ. Mich.

____
1966. Proceedings of the Fourth Symposium on Remote Sensing of Environment. 871 p., illus. Ann Arbor, Mich.: Univ. Mich.

____
1968. Proceedings of the Fifth Symposium on Remote Sensing of Environment. 946 p., illus. Ann Arbor, Mich.: Univ. Mich.

Jamieson, John A., McFee, Raymond H., Plass, Gilbert N., Grube, Robert H., and Richards, Robert G.
1963. Infrared physics and engineering. 673 p., illus. New York, Toronto [etc.]: McGraw-Hill Book Co., Inc.

Jones, R. Clark, Goodwin, Deryck, and Pullan, George.
1960. Standard procedure for testing infrared detectors and for describing their performance. 45 p., illus. Washington, D. C.: Office of Director of Defense Research and Engineering.

Karr, Philip R.
1957. Mathematical study of background "noise." 24 p., illus. Def. Doc. Center AD 608021.

Little, Elbert L.
1953. Check list of native and naturalized trees of the United States (including Alaska). USDA Forest Serv. Agr. Handbook 41, 472 p.

Losensky, B. John.
1968. A preliminary report on the infrared lightning fire patrol study. USDA Forest Serv. Fire Contr. Notes 29(2): 4-6, illus.

____
1969. An operational test of an infrared fire detection system. USDA Forest Serv. Fire Contr. Notes 30(2): 8-11, illus.

Robinson, David Z.
1959. Methods of background description and their utility. Inst. Radio Eng. Proc. 47(9):1554-1561, illus.

Society of American Foresters
1954. Forest cover types of North America (exclusive of Mexico). 67 p. Washington, D. C.: Soc. Amer. Forest. (Reprinted in 1967, 6th Edition.)

———
1956. Forestry handbook. (Reginald D. Forbes, ed.). 1143 p., illus. New York: Ronald Press.

Wilson, Ralph A.
1966. The remote surveillance of forest fires. Appl. Opt. 5(6): 899-904, illus.

Wilson, Ralph A.
1968. Fire detection feasibility tests and system development. Fifth Symp. Remote Sensing Environ. Proc. 1968: 165-177, illus.

———, and Noste, Nonan V.
1966. Project Fire Scan fire detection interim report, April 1962 to December 1964. U. S. Forest Serv. Res. Pap. INT-25, 55 p., illus.

Wolfe, William L., ed.
1965. Handbook of military infrared technology. 906 p., illus. Washington, D. C.: U. S. Government Printing Office.

APPENDIX I

Scientific Names of Forest Species

Following is a list of species, by common and scientific name (Harlow and Harrar 1950; Holmgren and Reveal 1966; Little 1953), mentioned in this report:

Common Name	Scientific Name
Alder	*Alnus B.* Ehrh.
Alpine fir	*Abies lasiocarpa* (Hook.) Nutt.
American elm	*Ulmus americana* L.
Ash	*Fraxinus* L.
Aspen	*Populus tremuloides* Michx.
	Populus grandidentata Michx.
Balsam fir	*Abies balsamea* (L.) Mill.
Balsam poplar	*Populus balsamifera* L.
Basswood	*Tilia americana* L.
Beaked hazel	*Corylus cornuta* Marsh.
Black oak	*Quercus velutina* Lam.
Cane	*Arundinaria tecta*
Cherry	*Prunus serotina* Ehrh.
Cherrybark oak	*Quercus falcata* var. *pagodaefolia* Ell.
Dogwood	*Cornus* L.
Douglas-fir	*Pseudotsuga menziesii* (Mirb.) Franco
Eastern hemlock	*Tsuga canadensis* (L.) Carr.
Elm	*Ulmus* L.
Engelmann spruce	*Picea engelmannii* Parry
Grand fir	*Abies grandis* (Dougl.) Lindl.
Hackberry	*Celtis occidentalis* L.
Hawthorn	*Crataegus* L.
Hickory	*Carya* spp.
Honeylocust	*Gleditsia triacanthos* L.
Lodgepole pine	*Pinus contorta* Dougl.
Mountain maple	*Acer spicatum* Lam.
Persimmon	*Diospyros virginiana* L.
Pin oak	*Quercus palustris* Muenchh.
Poison ivy	*Rhus radicans* L.
Ponderosa pine	*Pinus ponderosa* Laws.
Red alder	*Alnus rubra* Bong.
Red maple	*Acer rubrum* L.
Red oak	*Quercus rubra* L.
Sassafras	*Sassafras albidum* (Nutt.) Nees.
Serviceberry	*Amelanchier* Med.
Silver maple	*Acer saccharinum* L.
Soy (American) hornbeam	*Carpinus caroliniana* Walt.

Sugarberry	*Celtis laevigata* Willd.
Sugar maple	*Acer saccharum* Marsh.
Swampwhite oak	*Quercus bicolor* Willd.
Sweetgum	*Liquidambar styracitlua* L.
Sweet pecan	*Carya illinoensis* (Wangenh.) K. Koch
Vine maple	*Acer circinatum* Pursh
Water oak	*Quercus nigra* L.
Western hemlock	*Tsuga heterophylla* (Raf.) Sarg.
Western larch	*Larix occidentalis* Nutt.
Western redcedar	*Thuja plicata* Donn.
Western white pine	*Pinus monticola* Dougl.
White birch	*Betula papyrifera* Marsh.
White oak	*Quercus alba* L.
White spruce	*Picea glauca* (Moench) Voss.
Willow	*Salix* L.
Willow oak	*Quercus phellos* L.
Yellow birch	*Betula alleghaniensis* Britton

APPENDIX II

Description of Test Areas

The 13 test areas are a representative sample of the major forested areas of North America. They were chosen to cover a wide range of canopy densities on the basis of shade tolerance.

The following descriptions provide some insight into the character of these test areas (also see table 17).

Ponderosa Pine Test Area

The area is located on a bench south of the Big Blackfoot River, in the Lubrecht Experimental Forest, which is managed by the University of Montana.

The ponderosa pine type is very intolerant to shade. The timber primarily consists of a medium density stand of residual ponderosa pine interspersed with stagnated pole stands. Average height of dominant and codominant trees of the young, thrifty, and mature timber is 58 feet. In the areas of reproduction, the average height is 12 feet, consisting of about 80 percent total crown. Density of the ponderosa pine increases toward the south side of the test area (10 percent average slope with a north aspect) where it becomes intermingled with Douglas-fir. The ponderosa pine decreases to scattered clumps in a predominantly Douglas-fir stand. Basal area at target locations ranges from 0 to 190 square feet per acre; the less dense plots were on the north side of the area. The timber density can be estimated from table 5.

Lodgepole Pine Test Area

The area is located on the east side of Gold Creek approximately 6¼ miles north of State Highway 200, on the Missoula Ranger District, Lolo National Forest.

The area is situated on a bench with low ridges and minor draws. A marsh borders the northeast side of the area. No slopes exceed 20 percent.

The timber is a very dense stand of stagnated lodgepole pine; this type is very intolerant to shade. Some young ponderosa pine sawtimber grows on the northeastern portion of the area. Larch — Douglas-fir timber borders the south and east edges. Density of the lodgepole pine is fairly uniform throughout. Basal area at the target locations ranges from 0 (in small openings within the stand) to 227 square feet per acre. The timber density can be estimated from table 6.

Western White Pine Test Area

The area is located along Moores Creek in the Priest River Drainage about 5 miles northwest of the Falls Ranger Station in the Kaniksu National Forest. Terrain is variable with flat valley bottoms and abrupt steep ridges. Slopes increase to 30 percent in the southwest portion of the test area.

The timber consists of mature western redcedar and western white pine with an understory of western hemlock and cedar. The average height of dominant and codominant mature timber is 120 feet. The average diameter of the dominant species is 17 inches but the average for the stand overall is 12 inches. This site is classed as tolerant of shade because of the dominance of cedar and hemlock in the test area. The timber density can be estimated from table 7.

White Spruce Test Area

The stand is located on State land about 37 air miles southeast of Fairbanks, Alaska, on an island formed by two channels of the Tanana River.

The topography is flat — typical of the Tanana River Valley. Islands and bars are continually being built up and eroded away by the river. As these islands increase in size, brush invades and helps to stabilize them, which in turn is followed by invasions of white or black spruce. These islands will be present until erosion occurs following a shift in the river. Fire also plays a part in the ecological pattern of the land. These factors result in fairly young, even aged stands.

The test area is predominantly white spruce with a few balsam poplar. The stand is quite dense; however, the crown cover averages only 47 percent. Average height of dominants is 79 feet. The understory is generally sparse; a few willow and alder shrubs are scattered through the stand and along the shore. The ground cover is composed almost entirely of a deep, heavy cover of mosses and lichens. During the test period in late June, the frostline was about 3 feet below the ground. White spruce is a shade tolerant species.

Reproduction and understory of this stand have an average height of 7 feet and an average diameter of 3 inches. The density of the understory species in stems per acre follows: white spruce (381), balsam poplar (1.7), willow (3.4), alder (8.6).

The timber density can be estimated from table 8.

Engelmann Spruce Test Area

The area is located on a plateau about 2 miles southeast of Skookum Butte Lookout on the Powell Ranger District, Clearwater National Forest, in Idaho. Terrain is slightly rolling, and no slopes exceed 10 percent.

The timber is a heavy density stand of overmature Engelmann spruce with scattered grand fir and alpine fir in association. The average height of dominant and codominant trees is 98 feet. Basal areas around the test targets range from 120 to 360 square feet per acre, averaging 225 square feet per acre. The Engelmann spruce cover type is tolerant to shade. The timber density can be estimated from table 9.

Oak-Hickory Test Area

The test area is located in the Stinchfield Wood Management Unit, which is maintained by the University of Michigan, approximately 15 miles northwest of Ann Arbor. The area is characterized by a morainic topography, which is rolling with deep depressions. The soils are generally of the Bellefontaine sandy loam type and their quality has been reduced by severe grazing and fire treatments carried on before 1925. In addition to the fire treatments, selective cutting carried on prior to 1925 contributed to a marked reduction in the quality of the stand.

Until 1952, management activities were limited to protective measures to control fire and prohibit grazing. In 1952, a hardwood management unit was established and cutting treatments have been made periodically to remove inferior trees and thus the quality of the stand has been improved. As a result of the prohibition against grazing, a hardwood understory has now become established.

The present overstory is composed largely of black oak. White oak, cherry, and a minimal amount of hickory and miscellaneous species make up the remainder of the stand. We judged the site to be in the intermediate shade tolerance class. The reproduction and understory average 7 feet in height and 3 inches diameter.

The average density of the understory species in stems per acre follows: cherry (262), ash (111), hickory (95), sugar maple (90), sassafras (57), serviceberry (42), silver maple (28), white oak (23), basswood (14), red oak (9), elm (9), and black oak (7).

The timber density can be estimated from table 10.

Larch—Douglas-fir Test Area

The area is approximately 1¼ miles east of State Highway 31, and 1½ miles north of Pierce Lake on the Condon Ranger District, Flathead National Forest, in Montana. Terrain is moderately rolling slopes.

Timber on the area is medium density old-growth Douglas-fir and larch, which is classed as intolerant to shade. Reproduction is sparse and predominantly Douglas-fir, an average of 40 feet high and almost 100-percent crown closure. Density of the timber is uniform over the entire area, varying only in species composition. Basal area ranges from 20 square feet to 260 square feet; average overall basal area was 149 square feet per acre. The timber density can be estimated from table 11.

Aspen Test Area

The stand is located about 10 air miles southwest of Kenton, Michigan, on the Kenton Ranger District, Ottawa National Forest, in Ontonagon County. The topography is flat to gently rolling, interspersed by boggy areas. The soil type is a Gogebic fine sandy loam. Repeated burning has depleted the soil quality.

The original stand was composed of a mixture of white pine and northern hardwoods with white pine predominating. The white pine was logged about 1898 — and the hardwoods about 1907. Until 1928, the area was burned every year to "green up the woods" so it could be used as pasture.

The present stand is composed predominantly of aspen and red maple with some scattered white birch and balsam fir. The dominant trees average 69 feet in height. It appears that the site has not recovered sufficiently to support much more than aspen and at least one more cycle of aspen may be expected. We classified this site as very intolerant of shade.

The reproduction and understory have an average height of 7 feet and an average diameter of 3 inches. The average density of the understory species in stems per acre follows: red maple (127), aspen (64), cherry (35), balsam fir (28), silver maple (24), sugar maple (21), serviceberry (7), white spruce (5), and white birch (5).

The timber density can be estimated from the table 12.

Second-Growth Douglas-fir Test Area

The test area is located on State land in the Toutle River Drainage, approximately 35 miles east of Castle Rock, Washington. The test site is located on the river bottom land and has no major land relief.

The stand was originally composed of Douglas-fir with some western hemlock. Cutting occurred at a very early date (around 1900). It is apparent from the old stumps and the present stand that fire did not follow the logging. The present stand is composed of a mixture of Douglas-fir and hemlock with minor amounts of western redcedar. The understory is composed of hemlock, vine maple, and red alder, varying in density from light to medium stocking. With the continued exclusion of fire, the stand will eventually revert to western hemlock and western redcedar. It is a shade tolerant site. The timber density can be estimated from table 13.

Old-Growth Douglas-fir Test Area

The test area is located 2 miles south of Willow Flats on the Glide Ranger District of the Umpqua National Forest in Oregon, on a high, rolling plateau, bordered on the east and west by clearcuts. It is bisected by a ridge approximately 30 feet high. Test plots were placed along the top and bottom of this ridge on relatively flat ground.

The timber is composed of well stocked old-growth Douglas-fir with some scattered western hemlock. The understory is composed of hemlock poles and some scattered vine maple and rhododendron, varying in density from light to medium stocking. The stand is approximately 450 years of age, and averages 187 feet in height. The shade tolerance is intermediate.

Data derived from the timber cruise on this area were limited. The gross volume figures in board feet per acre are as follows: Douglas-fir, 150,000; hemlock, 32,000. The basal area is 392 square feet per acre.

Sweetgum-Water Oak Test Area

The stand is located in Madison Parish about 12 air miles southwest of Tallulah, Louisiana, on land owned by the Chicago Mills and Lumber Company. The topography is flat. Relics of drainage ditches constructed during the period it was farmed are still discernible.

The stand is typical of a river bottom hardwood type. Prior to the Civil War the area was cultivated primarily for cotton. After the war, the land was left idle and reverted to timber.

The stand is even aged; however, current cutting practices and the maturation of the stand are changing it to an uneven aged stand. The soils are quite deep and heavy; as a result, large areas of similar stands are being cleared and planted to soybeans. The stand is well stocked (68 percent sweetgum and water oak), averaging 118 feet high and 70 percent crown closure. The remainder is composed of a wide mixture of sweet pecan, willow oak, honey locust, red maple, elm, red oak, and hackberry. It is classed as intolerant to shade. Intermediate and improvement cuts have been made in the stand; as a result, the residual volume is generally of high quality.

The understory is light to medium and parts of the stand have a heavy cover of cane. Lianas are common throughout the stand; however, few dense tangles are found. The reproduction and understory of this stand have an average height of 7 feet and an average diameter of 3 inches. The average density of understory species in stems per acre follows: dogwood (121), hackberry (81), water oak (71), elm (34), ash (26), sweetgum (24), and soy hornbeam (16).

The timber density can be estimated from table 14.

Pin Oak-Sweetgum Test Area

The stand is located about 19 air miles west of Carbondale, Illinois, on the Murphysboro Ranger District, Shawnee National Forest, in Jackson County. The topography is flat; about half of the area was under water to a depth of up to 4 inches during the test period.

The stand is situated between the Mississippi and the Big Muddy Dikes on the Mississippi flood plain. Periodic inundation occurs on most of the stand during high water periods, which normally occur in the spring of the year. As a result, tree growth is restricted to water tolerant trees (such as pin oak) on a large portion of the stand.

The stand is well stocked, primarily with pin oak, cherrybark oak, and swampwhite oak (83 percent). The remainder includes varying amounts of red maple, sweetgum, hickory, and elm. The average height of the dominant species is 101 feet; their average crown closure is 76 percent. The understory is relatively light, made up primarily of elm and red maple. The ground cover is dense in some areas, composed primarily of poison ivy; it is bare where inundation occurs. Except for the cherrybark oak on the drier sites, the timber is short and of poor form. Logging has been limited since the formation of the present stand, which is of intermediate shade tolerance.

Reproduction and understory have an average height of 7 feet and an average diameter of 3 inches. The density of the understory species in stems per acre follows: elm (71), red maple (66), hickory (17), ash (17), sweetgum (10), pin oak (7), and swampwhite oak (7).

The timber density can be estimated from table 15.

Northern Hardwoods Test Area

The test area is located 4 miles south of Kenton, Michigan, on the Kenton Ranger District, Ottawa National Forest, in Ontonagon County. The topography is flat; a few dry streams intersect the area. The soil types are of the Gogebic-Munising association, which have a relatively deep, fine sandy loam surface soil.

The original stand on the test area was composed of a mixture of conifers and hardwoods. The conifers were logged during the period 1890-1910. Logging of the hardwoods started about 1910 and continued through 1925. The area was covered with seedlings about 8 feet high and a few old culls when it was acquired by the Forest Service in 1931.

In 1961, the stand was cut and thinned to improve its quality. The present stand is in excellent condition, composed primarily of sugar maple with minor amounts of birch, cherry, hemlock, red oak, and silver maple, all in excellent condition. The test stand is classified as very tolerant to shade. The reproduction and understory have an average height of 7 feet and an average diameter of 3 inches.

The average density of the understory species in stems per acre follows: sugar maple (364), silver and red maple (58), and miscellaneous (12).

The timber density can be estimated from table 16.

Table 5. — Data derived from timber cruise of ponderosa pine test area

Timber measurements	Ponderosa pine	Larch-Douglas-fir	Average or total
Trees/acre	67	0.1	67.1
Volume (bd. ft./acre)[1]	5,316	13	5,330
Average basal area/tree (sq.ft.)	1.14	1.06	1.12
Average diameter (inches), weighted	14.5	11	14.5
Average tree height (ft.), weighted	58	[illegible]	[illegible]
Average lower crown limit, both species in mixed stand (ft.)	—	—	18
Average crown thickness (ft.), both species	—	—	40
Cumulative stem density, all plots (inches)	6,540	82	6,622
Apparent crown cover density (percent) from aerial photos over test fire areas	—	—	60

[1] *Scribner log rule was used for all merchantable volumes. Cruise includes all merchantable trees 8 inches diameter and larger (by 2-inch classes).*

Table 6. — Data derived from timber cruise of lodgepole pine test area

Timber measurements	Lodgepole pine	Ponderosa pine	Average or total
Trees/acre	156	5.2	161.2
Volume (bd. ft./acre)[1]	8.730	320	9,050
Average basal area/tree (sq. ft.)	.57	1.02	.795
Average diameter (inches), weighted	10	14	10.1
Average tree height (ft.), weighted	62	53	61.7
Average lower crown limit, both species in mixed stand (ft.)	—	—	28
Average crown thickness (ft.), both species	—	—	44
Cumulative stem density, diameter. Trees in each diameter class (inches)	—	—	2,662
Crown cover density (percent) as estimated by aerial photos over test fire area	—	—	80

[1] *Scribner log rule was used for all merchantable volumes. Cruise includes all merchantable trees 8 inches diameter and larger (by 2-inch classes).*

Table 7. — Data derived from timber cruise of western white pine test area

Timber measurements	Western white pine	Western hemlock	Western redcedar	Grand fir	Average
Trees/acre	126.8	75.0	156.5	61.1	104.9
Volume (bd. ft./acre)[1]	12,611	4,361	13,287	3,333	8,398
Volume (cu. ft./acre)	2,281.25	1,004.73	2,791.50	704.00	1,695.37

[1] *Scribner log rule was used for all merchantable volumes. Cruise includes all merchantable trees 8 inches diameter and larger (by 2-inch classes).*

Table 8. —Data derived from timber cruise (size class: 3+ inches) of white spruce test area

Timber measurements	White spruce	Balsam poplar	Average or total
Volume (cu. ft./acre)	4,542	31	4,573
Average diameter (inches)	5.8	9.5	5.8
Basal area (sq. ft./acre)	185.5	1.5	187.0
Average height (ft.)	53.4	58.7	53.4
Trees/acre	892	3	895
Percentage of species in area	99.6	0.4	

Table 9. — Data derived from timber cruise of Engelmann spruce test area

Timber measurements	Larch—Douglas-fir	Grand fir	Alpine fir	Engelmann spruce	Average or total
Trees/acre	0.7	6.3	20.7	133.0	160
Volume (bd. ft./acre)[1]	63	1,621	3,841	35,864	41,208
Average basal area/tree (sq. ft.)	1.48	1.74	1.47	1.71	1.6
Average diameter (inches), weighted	16.5	18	16.5	18	17.5
Average height (ft.), weighted	48	83	82	88	86
Average lower crown limit (ft.), all species in mixed stand	—	—	—	—	23
Average crown thickness (ft.), all species	—	—	—	—	62
Cumulative stem density (inches), all plots	—	—	—	—	10,344
Crown cover density (percent) from aerial photos over test areas	—	—	—	—	100

[1] *Scribner log rule was used for all merchantable volumes. Cruise includes all merchantable trees 8 inches diameter and larger (by 2-inch classes).*

Table 10. — Data derived from timber cruise of oak-hickory test area

Timber measurements	Size class	Black oak	White oak	Cherry	Hickory	Miscel-laneous	Average or total
	Inches						
Volume (cu. ft./acre)	3+	816.4	399.9	69.3	66.5	92.8	1,444.9
Volume (bd. ft./acre)[1]	9+	3,156	1,110	—	—	128[2]	4,694
Density (stems/acre)	3+	51.5	43.0	42.8	60.6	88.6	286.5
Basal area (sq. ft./acre)	3+	38.5	18.5	4.5	7.0	6.5	75.0
Average diameter (inches)	3+	12	8	4	4	4	6

[1] *Scribner log rule was used for all merchantable volumes. Cruise includes all merchantable trees 8 inches diameter and larger (by 2-inch classes).*

[2] *Includes cherry and hickory.*

Table 11. — Data derived from timber cruise of larch—Douglas-fir test area

Timber measurements	Douglas-fir	Lodgepole pine	Engelmann spruce-alpine fir	Larch	Average or total
Trees/acre	71.1	14.9	11.0	23.8	120.8
Volume (bd. ft./acre)[1]	8,168	1,316	1,800	5,639	16,923
Average basal area/tree (sq. ft.)	1.20	.69	1.25	1.73	1.21
Average diameter (inches), weighted	15	11	15	17	14.9
Average height (ft.), weighted	75	77	80	97	82
Average lower crown limit, all species in mixed stand (ft.)	—	—	—	—	35
Average crown thickness (ft.), all species	—	—	—	—	47
Cumulative stem density, all plots (inches)	2,656	238	450	1,536	2,224
Apparent crown cover density (percent) from aerial photos over test areas	—	—	—	—	80

[1] *Scribner log rule was used for all merchantable volumes. Cruise includes all merchantable trees 8 inches diameter and larger (by 2-inch classes).*

Table 12. — Data derived from timber cruise (size class: 3+ inches) of aspen test area

Timber measurements	Aspen	Red maple	White birch	Balsam fir	White spruce	Average or total
Volume (cu. ft./acre)	3,092.7	395.2	184.7	63.5	20.6	3,756.7
Basal area (sq. ft./acre)	154	47	10	7	2	220
Trees/acre	529	166	34	18	2	749
Average diameter (inches)	8.2	6.5	7.9	6.8	9.5	7.9
Cords/acre	39.1	5.0	2.3	.8	.3	47.6

Table 13. — Data derived from timber cruise of second-growth Douglas-fir test area

Timber measurements	Size class	Douglas-fir	Hemlock	Western redcedar	Hardwood	Average or total
	Inches					
Volume (bd. ft./acre)[1]	12+	40,097	25,200	1,031	900	67,230
Volume (cu. ft./acre)	3+	6,559.10	4,402.92	245.88	114.17	11,327.55
Average diameter (inches)	3+	24.7	14.9	11.1	6.3	17.1
Average height (ft.)	3+	172	113	61	40	123
Trees/acre	3+	30	56.2	9.6	6.4	102.2

[1] *Scribner log rule was used for all merchantable volumes. Cruise includes all merchantable trees 8 inches diameter and larger (by 2-inch classes).*

Table 14. — Data derived from timber cruise of sweetgum-water oak test area

Timber measurements	Size class	Sweet-gum	Water oak	Sweet pecan	Willow oak	Miscellaneous[1]	Average or total
	Inches						
Volume (bd. ft./acre)[2]	3+	4,907	3,584	576	579	466	10,112
Volume (cu. ft./acre)	3+	1,626	977	174	168	236	3,181
Average diameter (inches)	3+	10.9	11.1	16.0	7.2	6.4	9.7
Average diameter (inches)	10+	12.9	15.1	16.0	17.6	13.3	13.7
Average height (ft.)	10+	78.5	79.0	106.0	51.0	44.0	69.0
Basal area (sq. ft./acre)	3+	47.5	24.5	4.0	4.5	9.5	90.0
Trees/acre	10+	43.3	16	2.7	1.7	3.9	68.0
Trees/acre	3+	65.3	28.1	2.7	10.7	30.7	137.5
Species percentage in area	All	48	20	2	8	22	

[1] *Includes honey locust, sugar berry, red oak, red maple, and elm.*

[2] *Scribner log rule was used for all merchantable volumes. Cruise includes all merchantable trees 8 inches diameter and larger (by 2-inch classes).*

Table 15. — Data derived from the pin oak-sweetgum test area

Timber measurements	Size class	Pin oak	Cherry-bark oak	Swamp-white oak	Red maple	Sweet-gum	Hickory	Elm	Average or total
			Inches						
Volume (bd. ft./acre)[1]	3+	3,729	1,456	—	—	1,143	—	—	6,328
Volume (cu. ft./acre)	3+	1,509	561	169	152	127	70	60	2,648
Average diameter (inches)	3+	10.1	10.7	7.4	10.8	8.0	8.1	9.1	9.7
Basal area (sq. ft./acre)	3+	51	19	6.5	5.0	4.0	2.5	2	90.0
Trees/acre	10+	46.4	14.1	—	—	13.9	—	—	74.4
Trees/acre	3+	80.1	26.6	18.7	7.5	9.3	5.0	3.8	151.0
Species percentage in area	All	53	17.6	12.4	5.0	6.2	3.3	2.5	

[1] *Scribner log rule was used for all merchantable volumes. Cruise includes all merchantable trees 8 inches diameter and larger (by 2-inch classes)*

Table 16. — Data derived from timber cruise of Northern Hardwoods test area

Timber measurements	Size Class	Sugar maple	Red oak	Hemlock[1]	Yellow birch	Red and silver maple	Cherry	Miscel-laneous	Average or total
	Inches								
Volume (cu.ft. /acre)	3+	1,522.7	188.3	296.4	56.2	95.4	51.1	32.3	2,242.4
Volume (bd. ft./acre)[2]	9+	4,835	—	1,015	—	—	—	294[3]	6,144
Density (stems/acre)	3+	167.9	41.7	16.3	6.3	39.8	6.9	10.8	289.7
Basal area (sq. ft./acre)	3+	58.84	8.31	12.45	2.15	4.94	2.00	1.68	90.38
Average diameter (inches)	3+	6.6	5.7	10.8	6.7	4.4	6.9	1.9	6.59
Average height (ft.)	3+	50.2	52.7	41.6	51.8	44.5	55.0	41.4	48.6

[1] *Includes all conifers.*

[2] *Scribner log rule was used for all merchantable volumes. Cruise includes all merchantable trees 8 inches diameter and larger (by 2 inch classes)*

[3] *Includes all hardwoods except sugar maple.*

Table 17. — Pertinent physical factors of test areas used in study

Timber cover type[1]	No. of test plots	Elevation m.s.l.	Flight path direction[2]	Legal description
		Feet		
Interior ponderosa pine (I)[3]	8	3,650	East & west	NE 1/4 sec. 35, T. 14 N., R. 15 W., Principal meridian of Montana (PMM) (Montana)
Lodgepole pine (I)	8	4,200	North & south	S 1/2 SW 1/4 sec. 6, N 1/2 NW 1/4 sec. 7, T. 14 N., R. 16 W., PMM (Montana)
Engelmann spruce-Alpine fir (IV)	8	5,800	North & south	SW 1/4 sec. 7, T. 38 N., R. 22 W., Bench mark (BM) (Idaho)
Larch—Douglas-fir (II)	8	4,500	North & south	NE 1/4 or SW 1/4 sec. 10, T. 19 N., R. 16 W., PMM (Montana)
Western white pine (IV)	20	2,450	North & south	SW 1/4 sec. 21 and NW 1/4 sec. 28, T. 58 N., R. 5 W., BM (Idaho)
Oak-Hickory (III)	20	1,000	North & south	N 1/4 of NE 1/4 sec. 14 and SE 1/4 of SE 1/4 sec. 11, T. 1 S., R. 4 E., Washteneaw Co. (Michigan)
Northern hardwoods (V)	20	1,500	North & south	N 1/2 sec. 35, T. 47 N., R. 37 W., Michigan Meridian, Ontonagon Co., (Michigan)
Aspen (I)	20	1,500	North & south	SE 1/4 of sec. 5, T. 46 N., R. 38 W., Michigan Meridian, Ontonagon Co. (Michigan)
Second-growth Douglas-fir (IV)	20	1,400	East & west	NE 1/4 sec. 2, T. 9 N., R. 3 E., Willamette Meridian (Washington)
Old-growth Douglas-fir (III)	15	4,000	North & south	SE 1/4 of sec. 3, T. 27 S., R. 1 W., Willamette Meridian (Oregon)
Sweetgum-Water oak (II)	20	50	East & west	SE 1/4 sec. 15, T. 15 N., R. 11 E., Washington Meridian, Madison Parish (Louisiana)
Pin oak-Sweetgum (III)	20	500	North & south	Sec. 19, T. 10 S., R. 3 W., 3rd Principal Meridian, Jackson Co. (Illinois)
White spruce (IV)	20	700	North & south	Sec. 17 and 18, T. 6 S., R. 4 E., Fairbanks Meridian (Alaska)

[1] *Society of American Foresters. Forest cover types of North America (exclusive of Mexico). 67 p. Washington, D. C.: Soc. Amer. Forest. (Reprinted in 1967, 6th Edition).*

[2] *Flight directions are precisely 0°, 90°, 180°, and 270°, true azimuth.*

Table 18. — Log of detection probability test flights

Test area	Flight Date	Flight No.	Test area	Flight Date	Flight No.
Interior	6/17/63	4	Oak-Hickory	7/17/65	64
ponderosa pine	6/18/63	5	(52)[1]	7/18/65	75
(237)[1]	6/26/63	6		7/19/65	76
	6/27/63	7		7/20/65	77
	7/1/63	8			
			Northern	7/28/65	80
Lodgepole pine	7/9/63	11	hardwoods	7/29/65	81
(218)	7/12/63	12	(25)		
	7/16/63	14			
	7/19/63	15	Aspen	8/2/65	82
	6/25/64	20	(16)		
	7/9/64	23			
	8/4/64	29	Second-growth	9/20/65	95
	8/6/64	31	Douglas-fir		
	6/22/65	67	(230)		
	7/9/65	71			
	7/10/65	72	Old-growth	9/25/65	97
	6/28/67	195	Douglas-fir		
			(229)		
Engelmann	7/25/63	18			
spruce	7/26/63	19	Sweetgum-	5/20/66	130
(206)	7/29/63	20	water oak	5/21/66	131
	7/31/63	22	(92)	5/24/66	132
	8/1/63	23			
	8/21/63	33	Pin oak-Sweetgum	5/31/66	135
			(65)		
Larch—Douglas-fir	8/27/63	34			
(212)	8/28/63	35	White spruce	6/18/66	143
	8/29/63	36	(Interior Alaska)	6/20/66	144
	9/3/63	37	(201)	6/22/66	145
	9/6/63	38			
	9/18/63	41			
Western	7/22/64	2			
white pine	7/23/64	3			
(215)	8/30/65	91			
	8/31/65	92			
	9/1/65	93			

[1] *Numbers in parentheses are type designations assigned by the Society of American Foresters, "Forest cover types of North America (exclusive of Mexico)," 67 p. Washington, D. C.: Soc. Amer. Forest. (Reprinted in 1967, 6th Edition).*

Table 19. — Detection probability classes for forest cover types of North America

CLASS 1

SAF[1] type no.	Timber type	SAF type no.	Timber type
	WESTERN UNITED STATES		
202	White spruce-Birch	234	Oak-Madrone
203	Poplar-Birch	235	Cottonwood-Willow
204	Black spruce	236	Bur oak
205	Mtn. hemlock-Subalpine fir	*237	Interior ponderosa pine
208	Whitebark pine	238	Western juniper
209	Bristlecone pine	239	Pinyon-Juniper
*212	Larch—Douglas-fir	240	Arizona cypress
214	Ponderosa pine—Larch- Douglas-fir	241	Interior live oak
217	Aspen	242	Mesquite
*218	Lodgepole pine	245	Pacific ponderosa pine
219	Limber pine	246	California black oak
220	Rocky Mtn. juniper	247	Jeffrey pine
221	Red alder	248	Knobcone pine
222	Black cottonwood-Willow	249	Canyon live oak
233	Oregon white oak	250	Digger pine-Oak
	EASTERN UNITED STATES		
1	Jack pine	51	White pine-Chestnut oak
2	Black spruce-White spruce	57	Yellow-poplar
3	Jack pine-Paper birch	61	River birch-Sycamore
6	Jack pine-Black spruce	66	Ashe juniper
8	Jack pine-Aspen	67	Mohrs oak
9	White spruce-Balsam fir-Aspen	68	Mesquite
10	Black spruce-Aspen	69	Sand pine
11	Aspen-Paper birch	70	Longleaf pine
13	Black spruce-Tamarack	71	Longleaf pine-Scrub oak
15	Red pine	72	Southern scrub oak
* 16	Aspen	73	Southern redcedar
17	Pin cherry	74	Sand live oak-Cabbage palmetto
18	Paper birch	75	Shortleaf pine
19	Gray birch-Red maple	77	Shortleaf pine-Virginia pine
21	White pine	78	Virginia pine-Southern red oak
36	White spruce-Balsam fir-Paper birch	79	Virginia pine
38	Tamarack	80	Loblolly pine-Shortleaf pine
42	Bur oak	81	Loblolly pine
43	Bear oak	83	Longleaf pine-Slash pine
45	Pitch pine	84	Slash pine
46	Eastern redcedar	86	Cabbage palmetto-Slash pine
47	Eastern redcedar-Pine	95	Black willow
49	Eastern redcedar-Pine-Hardwood	98	Pond pine
50	Black locust		

(con. next page)

Table 19. — (con.)

CLASS 2

SAF type no.	Timber type	SAF type no.	Timber type
	WESTERN UNITED STATES		
*201	White spruce	216	Blue spruce
*206	Engelmann spruce-Subalpine fir	226	Pacific silver fir-Hemlock
210	Interior Douglas-fir	227	Western redcedar-Western hemlock
211	White fir	228	Western redcedar
213	Grand fir-Larch-Douglas-fir	243	Ponderosa pine-Sugar pine-Fir
*215	Western white pine	244	Pacific ponderosa pine-Douglas-fir
	EASTERN UNITED STATES		
4	White spruce-Balsam fir	54	Northern red oak-Basswood-White ash
5	Balsam fir	55	Northern red oak
7	Black spruce-Balsam fir	56	Northern red oak-Mockernut hickory-Sweetgum
14	Northern pin oak	58	Yellow-poplar-Hemlock
20	White pine-Northern red oak-White ash	59	Yellow-poplar-White oak-Northern red oak
22	White pine-Hemlock	76	Shortleaf pine-Oak
29	Black cherry	82	Loblolly pine-Hardwood
30	Red spruce-Yellow birch	85	Slash pine-Hardwood
32	Red spruce	87	Sweetgum-Yellow-poplar
33	Red spruce-Balsam fir	88	Laurel oak-Willow oak
34	Red spruce-Fraser fir	89	Live oak
35	Paper birch-Red spruce-Balsam fir	93	Sugarberry-American elm-Green ash
37	Northern white-cedar	94	Sycamore-Pecan-American elm
40	Post oak-Black oak	96	Overcup oak-Water hickory
41	Scarlet oak	97	Atlantic white-cedar
48	Eastern redcedar-Hardwood		
* 52	White oak-Red oak-Hickory		
53	White oak		

CLASS 3

	WESTERN UNITED STATES		
207	Red fir	*229	Pacific Douglas-fir
223	Sitka spruce	*230	Douglas-fir-W. hemlock
224	Western hemlock	231	Port-Orford-cedar-Douglas-fir
225	Sitka spruce-Western hemlock	232	Redwood
	EASTERN UNITED STATES		
23	Hemlock	39	Black ash-American elm-Red maple
24	Hemlock-Yellow birch	60	Beech-Sugar maple
* 25	Sugar maple-Beech-Yellow birch	* 65	Pin oak-Sweetgum
26	Sugar maple-Basswood	62	Silver maple-American elm
27	Sugar maple	90	Beech-Southern magnolia
28	Black cherry-Sugar maple	91	Swamp chestnut oak-Cherrybark oak
31	Red spruce-Sugar maple-Beech	* 92	Sweetgum-Nuttall oak-Willow oak

[1] *Society of American Foresters' type designation.*
**Flight tests conducted.*

APPENDIX III

Mathematical Model and Detection Probability Test Data

As noted on page 33, we concluded that detection probability cannot be predicted reliably from our data for other stand densities. However, we can show that the effect of stand density on signal attenuation is predictable.

In actuality, timber stands are quasirandom distributions of trees of various sizes and species. In order to develop a mathematical model to predict the obscuration of targets by timber canopy we will define an ideal timber stand as having randomly distributed trees of the same species. All of the trees will have the characteristics of the average tree; i.e., diameter, crown height, etc. In such a stand we recognize that there are two mechanisms that will obscure a fire target from an airborne IR line scanner: (1) the total attenuation of the target by very large obscuring material (single tree boles, combinations of tree boles, etc.); and (2) the partial attenuation due to smaller (finer) canopy material (small limbs and foliage).

In any natural timber stand an individual target may be completely unobscured, partially attenuated, or totally obscured. We cannot expect to predict the signal strength from a target for a given single observation. The following formulation is to predict a probable target signal — the signal one would expect to observe on an "average" observation. We consider that the timber stand is made up of a random stand of trees boles (large material) that support a homogeneous and spatially continuous canopy (fine material) as diagramed in figure 38.

The total expected transmission, T, for the timber stand is equal to the product, $T_C T_B$, of the expected transmissions through the canopy (T_C) and boles (T_B), respectively. The attenuation density of the obscuring media must be expressed in terms applicable to forest mensuration in order that the model be of practical use.

A tree bole closely approximates an inverted paraboloid of revolution whose vertical cross-sectional area is 2/3 dh, where d = tree diameter, h = tree height. When viewed from an aspect angle, Θ, the horizontal ground area, a, obscured by the tree, a = 2/3 dh tan Θ.

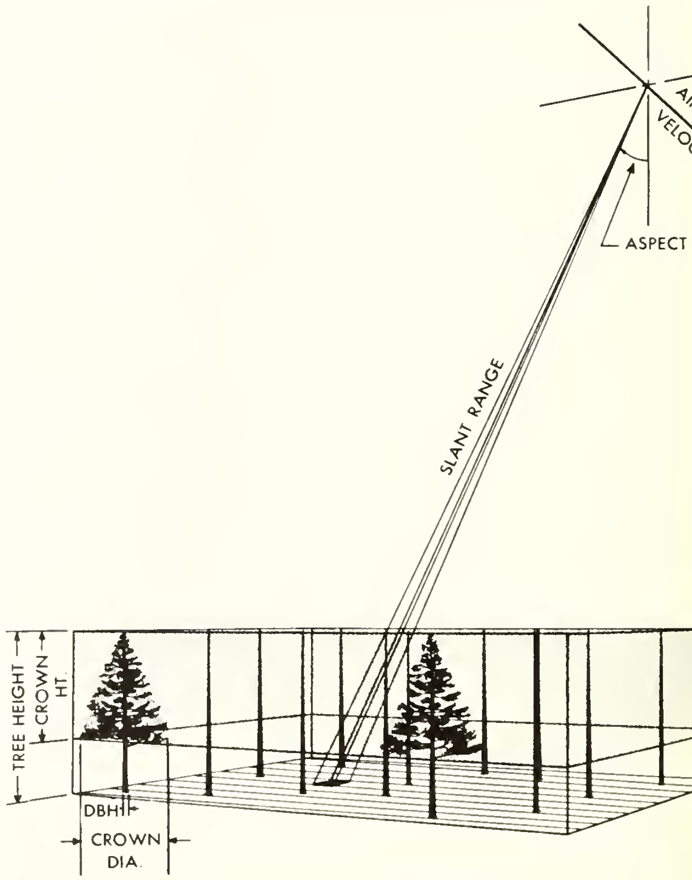


Figure 38. — Conceptual model showing obscuration effects of timber canopies.

The observable, or unobscured, part of a unit area in which there is one obscuring tree bole is $T_B = (1\text{-}a) = \left(1 - \frac{2/3\ dh \tan \Theta}{43{,}560}\right)$ Eq. 9

In this equation we have defined unit area (1 acre = 43,560 square feet) in forest mensuration terms. This means that d and h must be measured in feet to satisfy this equation.

The probable transmission through the tree boles for a stand of n (tree boles/acre) with individual characteristics, d_i, h_i, is equal to the probable unobscured ground area,

$$T_B = \prod_{i=1}^{n} \left(1 - \frac{2/3\ d_i h_i \tan \Theta}{43{,}560}\right).$$

If all trees are of average size as we have assumed, then

$$T_B = \left(1 - \frac{2/3\ dh \tan \Theta}{43{,}560}\right)^n$$

If an adjustment is made for the orientation of the shadows thrown by the bole (all oriented in the same direction), this equation is more properly of the form

$$(1 - d)^n (1 - h \tan \Theta)^n.$$

Similar adjustments could be made for the nonrandom spacing of trees, the vignetting of a target on the edge of a shadow, the exclusion of fire from the basal area, etc.

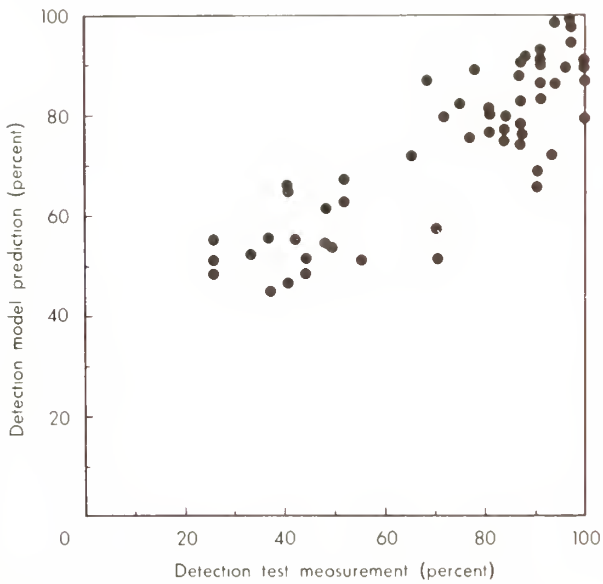


Figure 39. — Correlation of detection probabilities between model predictions and test measurements.

This formulation provides the mechanism for handling several size classes of trees in the same stand (e.g., different species in an understory-overstory association). One might have n_1 trees/acre of size class d_1, h_1; n_2 trees/acre of d_2, h_2; and n_3 trees/acre of d_3, h_3. Obviously, the expected tree bole transmission for such an association would be

$$T_B = \left(1 - \frac{2/3\ d_1 h_1 \tan \Theta}{43{,}560}\right)^{n_1}$$

$$\times \left(1 - \frac{2/3\ d_2 h_2 \tan \Theta}{43{,}560}\right)^{n_2}$$

$$\times \left(1 - \frac{2/3\ d_3 h_3 \tan \Theta}{43{,}560}\right)^{n_3}$$

In general, the finer material of the timber crowns only partially attenuates the target radiation (by absorption and scattering phenomena). A continuous and homogeneous attenuating material suggests an exponential transmission model. In such a material, the differential intensity, -dI, absorbed out of a small optical path, is proportional to the path length, dx, and the incident intensity, I. Thus,

$$dI = -\sigma I dx$$

or $T_C = I/I_o = e^{-\sigma x}$

where the constant of proportionality, σ, is the attenuation coefficient of the material (i.e., σ is similar to a loosely defined optical density). It remains for us to determine this "optical density" and path length through the timber crowns.

Consider a unit volume, V = aH, where a = 1 acre and H = one average crown height. And, consider the volume of one average tree crown, $v_c = 2/3(\frac{\pi}{4} D^2 H)$ for deciduous trees (ovaloids of revolution).

Given n trees per acre, the ratio nv_c/V is the fraction of unit volume that is filled with obscuring crown material. The slant path, r, through the unit volume is H sec Θ (aspect angle is measured from the vertical). Thus, the expected (or probable) path length, X, intercepted by crowns is

$$X = \left(\frac{nv_c}{V}\right) r = \frac{nG\frac{\pi}{4} D^2 H}{a \cdot H} H \sec \Theta$$

or

$$X = G \frac{n \frac{\pi}{4} D^2}{43,560} H \sec \Theta$$

where G is geometrical factor (1/3 for conifers, 2/3 for deciduous).

The factor, $\frac{n \frac{\pi}{4} D^2}{43,560}$, is equal to crown closure, cc, (in percent). The individual crowns are not opaque but have an optical density, J; thus, the average or expected transmission through the crowns is

$$T_C = \exp(-JG\,(cc)\,H \sec \Theta).$$

The optical density, J, is independent of timber stand density (J will vary from one timber type to another but will not vary with the number of trees or their size).

To complete the exposition of the concept, one may conceive of the attenuation coefficient, σ, and path length, x, [$\sigma = JG(cc)$ and $x = H \sec \Theta$], as representing the transmission through a continuous and homogeneous attenuating media. Note here also that the product $\sigma x = \sigma_1 x_1 + \sigma_2 x_2 = [J_1 G_1 (cc)_1 H_1 + J_2 G_2 (cc)_2 H_2] \sec \Theta$ provides for several possible crown classes.

The expected transmission, T, of target radiation through the timber is

$$T = e^{-JG\,(cc)H \sec\Theta} \left(1 - \frac{2/3\ dh \tan \Theta}{43,\ 560}\right)^n. \qquad \text{Eq. 10}$$

Estimates of T were made by measuring the signal strength of the target signature. These estimates were made from the voltage output of the scanning system for the mountaintop tests, and from the film density on the airborne IR imagery.

The primary reason for constructing the obscuration model was to predict the dependence of detection probability on measurable timber cruise parameters.

The timber cruise parameters from the white spruce test plots were used in equation (10) to generate transmission predictions for each target at each aspect angle. These calculated canopy transmissions were used in equation (8), page 37, to generate a set of detection probability predictions. In figure 39, these probability predictions are plotted in comparison with the actual measurements of percent detection from the test flights.

Detection probability measurements, P_5, are made from observations of an array of five 1-square-foot targets (see page 37). The coefficients A, B, and C in the correlation equation (8) are valid only for signal strengths that are comparable to the five 1-square-foot target configurations. However, we can estimate the probability of detecting any number of 1-square-foot targets.

Assume (1) that the obscuring media are randomly oriented relative to the five individual 1-square-foot targets, and (2) that the probability of detecting a single target is P_1, then the following logical sequence gives the probability of detecting m targets. The probability of *not detecting one target* is $(1\text{-}P_1)$. The probability of *not detecting at least one of m targets* is $(1\text{-}P_1)^m$. The probability, P_m, of *detecting at least one of m targets* is $P_m = 1 - (1\text{-}P_1)^m$.

The assumption of randomness is not rigorously true in actual timber stand distributions. Any formulation based on this assumption will only predict a lower limit for detection probability when the size of openings between trees, size of the tree crowns, and size of the target arrays are similar. That is, with actual spatial distribution it is *more likely* that one of the m targets is observable; thus, in practice, actual detection probabilities should be higher.

Measurements of signal strength (or timber obscuration) and measurements of percent detection must be considered as two separate and independent sets of data for statistical analysis. A rigorous formulation of detection probability as a function of target signal strength is impossible because (1) the spatial distribution of timber crown material was not known in the airborne tests; (2) the meteorological and environmental conditions were not constant; and (3) calibration controls for the several mountaintop and airborne systems were inadequate.

In principle, such a formulation should be possible. A questionable example is our comparison of airborne and mountaintop data in figure 32. In this example, the comparison is based on target signal-to-background signal ratios, but the control measurements of the backgrounds are inadequate.

Table 20.—Signal strength frequency distribution by aspect angle for old-growth Douglas-fir test area[1]

Relative signal strength	Aspect angle (degrees)						
	0	10	20	30	40	50	60
0	25.33	31.85	9.33	28.33	13.33	0	0
.33	2.22	1.48	2.67	10.00	0	0	0
.67	2.22	1.48	8.00	2.50	6.67	0	0
1.00	4.44	5.19	9.33	11.67	16.67	0	0
1.33	4.00	2.22	1.00	5.83	0	0	0
1.67	2.22	.74	6.67	3.33	3.33	0	0
2.00	5.78	9.63	4.00	2.50	10.00	0	0
2.33	7.56	2.22	6.67	3.33	3.33	0	0
2.67	3.11	3.70	2.67	2.50	0	0	0
3.00	2.67	5.19	10.67	1.67	0	0	0
3.33	7.56	1.44	1.00	6.67	3.33	0	0
3.67	4.89	1.44	10.67	6.67	6.67	0	0
4.00	7.11	3.70	1.33	3.33	0	0	0
4.33	3.11	2.96	4.00	1.17	3.33	0	0
4.67	6.67	9.63	10.67	4.17	0	0	0
5.00	11.11	11.11	5.33	3.33	3.33	0	0

[1] *Society of American Foresters forest cover type designation No. 229*

Table 21.—Signal strength frequency distribution by aspect angle for second-growth Douglas-fir test area[1]

Relative signal strength	Aspect angle (degrees)						
	0	10	20	30	40	50	60
0	22.73	23.00	27.50	28.08	32.31	36.67	0
.33	6.36	3.00	4.50	7.31	7.31	6.67	0
.67	4.55	3.00	4.00	6.54	6.15	13.33	0
1.00	5.91	9.00	9.00	11.54	14.23	6.67	0
1.33	3.18	5.00	4.50	6.54	4.62	3.33	0
1.67	5.45	7.00	5.50	6.54	6.15	6.67	0
2.00	5.45	5.00	7.00	6.54	3.46	0	0
2.33	6.36	4.00	4.00	2.69	5.00	5.00	0
2.67	5.91	12.00	8.50	4.23	4.62	8.33	0
3.00	2.73	0	6.50	3.08	3.46	1.67	0
3.33	3.64	4.00	3.50	3.85	2.69	3.33	0
3.67	4.09	3.00	3.00	2.69	2.69	6.67	0
4.00	7.27	7.00	5.00	1.92	1.92	1.67	0
4.33	6.82	1.00	.50	1.92	.77	0	0
4.67	2.73	6.00	2.50	3.08	1.92	0	0
5.00	6.82	8.00	4.50	3.46	2.69	0	0

[1] *Society of American Foresters forest cover type designation No. 230.*

Table 22. — Signal strength frequency distribution by aspect angle for white spruce test area[1]

Relative signal strength	Aspect angle (degrees)						
	0	10	20	30	40	50	60
0	1.79	1.67	5.82	9.69	21.04	45.00	0
.33	.36	1.11	2.73	5.00	9.38	12.73	0
.67	1.43	1.67	3.18	4.69	9.79	9.55	0
1.00	6.79	6.67	12.27	20.00	22.50	15.00	0
1.33	5.00	7.22	6.36	8.13	7.50	4.09	0
1.67	6.07	5.00	8.18	5.94	5.42	3.18	0
2.00	4.64	5.56	10.91	10.31	6.25	3.64	0
2.33	6.43	9.44	7.27	10.31	4.38	1.82	0
2.67	9.29	6.67	5.91	5.00	4.79	2.27	0
3.00	6.43	3.89	6.36	4.69	2.08	.91	0
3.33	7.86	11.67	8.64	4.69	2.92	.45	0
3.67	7.86	9.44	5.00	4.06	2.50	.45	0
4.00	8.93	11.67	5.91	2.50	1.04	.45	0
4.33	7.14	3.33	3.64	3.75	.42	0	0
4.67	4.29	10.00	4.55	.31	0	0	0
5.00	15.71	5.00	2.27	.94	0	0	0

[1] *Society of American Foresters forest cover type designation No. 201.*

Table 23. — Signal strength frequency distribution by aspect angle for western white pine test area[1]

Relative signal strength	Aspect angle (degrees)						
	0	10	20	30	40	50	60
0	11.88	13.00	12.00	20.83	27.50	33.75	50.00
.33	3.13	0	4.00	3.33	3.00	1.25	0
.67	2.50	4.00	0	2.50	6.50	6.25	10.00
1.00	15.63	17.00	22.00	23.33	28.00	26.25	0
1.33	1.88	4.00	5.00	4.17	7.00	8.75	5.00
1.67	5.00	4.00	4.00	6.67	2.50	0	10.00
2.00	8.75	6.00	13.00	9.17	5.50	6.25	5.00
2.33	1.88	4.00	6.00	2.50	4.50	5.00	5.00
2.67	4.38	3.00	7.00	5.00	5.50	2.50	10.00
3.00	11.88	8.00	3.00	5.00	2.00	2.50	5.00
3.33	5.63	5.00	5.00	2.50	1.00	1.25	0
3.67	5.00	5.00	7.00	5.00	2.00	6.25	0
4.00	9.38	7.00	4.00	3.33	.50	0	0
4.33	2.50	2.00	2.00	1.67	1.50	0	0
4.67	5.00	7.00	2.00	2.50	2.50	0	0
5.00	5.63	11.00	4.00	2.50	.50	0	0

[1] *Society of American Foresters forest cover type designation No. 215.*

Table 24. — Signal strength frequency distribution by aspect angle for lodgepole pine test area[1]

Relative signal strength	Aspect angle (degrees)						
	0	10	20	30	40	50	60
0	4.17	15.63	12.50	12.07	16.07	14.06	21.88
.33	2.08	6.25	6.73	5.60	6.55	7.81	17.19
.67	2.08	0	.96	6.90	6.55	9.38	17.19
1.00	7.64	0	5.77	14.22	8.33	4.69	15.63
1.33	7.64	0	.96	4.31	10.71	1.56	4.69
1.67	9.03	9.38	2.88	11.64	8.33	3.13	9.38
2.00	13.89	15.63	3.85	11.21	3.57	6.25	9.38
2.33	15.28	6.25	6.73	9.91	5.95	9.38	3.13
2.67	7.64	0	11.54	6.47	7.74	12.50	0
3.00	7.64	6.25	5.77	5.60	4.76	3.13	0
3.33	4.17	3.13	10.58	3.02	3.57	14.06	1.56
3.67	6.25	3.13	19.23	3.02	1.79	6.25	0
4.00	4.17	6.25	2.88	2.16	4.17	6.25	0
4.33	2.78	3.13	5.77	2.16	7.14	1.56	0
4.67	1.39	15.63	3.85	.43	1.79	0	0
5.00	4.17	9.38	0	1.29	2.98	0	0

[1] *Society of American Foresters forest cover type designation No. 218.*

Table 25. — Signal strength frequency distribution by aspect angle for aspen test area[1]

Relative signal strength	Aspect angle (degrees)						
	0	10	20	30	40	50	60
0	11.67	6.67	2.50	12.50	11.50	17.50	25.00
.33	1.67	3.33	0	5.00	4.50	4.17	10.63
.67	0	5.00	2.50	5.00	7.00	11.67	5.63
1.00	15.00	16.67	25.00	18.75	33.50	38.33	25.63
1.33	3.33	8.33	2.50	3.75	4.00	7.50	6.88
1.67	6.67	0	0	3.75	5.50	1.67	6.25
2.00	11.67	5.00	2.50	7.50	7.00	4.17	3.13
2.33	6.67	8.33	5.00	7.50	7.00	5.00	3.13
2.67	6.67	6.67	15.00	7.50	4.00	2.50	3.75
3.00	6.67	1.67	2.50	6.25	4.50	2.50	3.13
3.33	8.33	5.00	2.50	7.50	2.50	.83	1.88
3.67	1.67	8.33	12.50	2.50	2.50	1.67	2.50
4.00	5.00	5.00	7.50	3.75	1.50	0	1.88
4.33	3.33	3.33	2.50	3.75	1.50	.83	.63
4.67	0	5.00	10.00	3.75	2.50	.83	0
5.00	11.67	11.67	7.50	1.25	1.00	.83	0

[1] *Society of American Foresters forest cover type designation No. 16.*

Table 26. — Signal strength frequency distribution by aspect angle for Northern Hardwoods test area[1]

Relative signal strength	Aspect angle (degrees)						
	0	10	20	30	40	50	60
0	19.38	21.00	23.89	25.00	33.50	36.67	50.71
.33	5.63	5.00	6.11	7.78	7.00	7.08	7.14
.67	6.25	6.50	5.56	7.22	6.50	3.75	2.86
1.00	21.25	17.50	13.33	26.67	22.50	24.58	18.57
1.33	1.88	3.50	6.11	3.89	4.00	5.00	2.14
1.67	4.38	2.50	5.56	4.44	4.50	1.25	1.43
2.00	11.25	9.00	8.89	6.67	5.50	7.08	7.86
2.33	.63	4.00	3.33	3.33	4.50	3.75	1.43
2.67	3.13	1.00	3.33	.56	3.00	2.08	1.43
3.00	3.75	3.50	6.11	2.78	1.00	2.50	3.57
3.33	2.50	6.00	5.56	2.78	3.50	3.75	1.43
3.67	6.88	10.50	2.78	1.67	.50	1.25	0
4.00	5.63	4.50	2.78	3.33	2.00	.83	.71
4.33	1.25	.50	1.11	1.67	1.50	.42	.71
4.67	1.88	4.50	2.22	1.67	0	0	0
5.00	4.38	.50	3.33	.56	.50	0	0

[1] *Society of American Foresters forest cover type designation No. 25.*

Table 27. — Signal strength frequency distribution by aspect angle for pin oak-sweetgum test area[1]

Relative signal strength	Aspect angle (degrees)						
	0	10	20	30	40	50	60
0	3.33	9.44	8.33	11.67	18.13	0	0
.33	.83	1.11	2.50	6.67	6.25	0	0
.67	1.67	2.22	5.83	10.00	9.38	0	0
1.00	22.50	15.56	20.83	24.17	33.75	0	0
1.33	2.50	7.22	10.83	9.17	5.00	0	0
1.67	4.17	7.78	9.17	6.67	3.75	0	0
2.00	6.67	7.22	4.17	2.50	6.25	0	0
2.33	6.67	11.11	2.50	9.17	3.13	0	0
2.67	8.33	5.56	5.00	3.33	1.25	0	0
3.00	5.83	6.11	7.50	4.17	6.25	0	0
3.33	10.83	7.78	5.83	6.67	3.75	0	0
3.67	5.83	3.33	5.00	1.67	2.50	0	0
4.00	6.67	2.78	5.00	.83	.63	0	0
4.33	1.67	4.44	1.67	2.50	0	0	0
4.67	2.50	2.22	2.50	0	0	0	0
5.00	10.00	6.11	3.33	.83	0	0	0

[1] *Society of American Foresters forest cover type designation No. 65.*

Table 28. — Signal strength frequency distribution by aspect angle for gum-oak test area[1]

Relative signal strength	Aspect angle (degrees)						
	0	10	20	30	40	50	60
0	6.00	14.38	13.33	15.00	23.21	31.00	0
.33	3.00	2.50	2.50	2.50	5.00	6.00	0
.67	3.50	2.50	4.17	5.00	3.57	4.00	0
1.00	15.00	7.50	17.50	19.17	11.43	17.00	0
1.33	2.50	3.75	1.67	4.17	3.57	8.00	0
1.67	5.50	3.13	2.50	9.17	6.43	4.00	0
2.00	7.00	4.38	4.17	5.00	8.57	3.00	0
2.33	4.50	5.63	3.33	8.33	5.36	1.00	0
2.67	13.50	11.25	8.33	6.67	7.14	4.00	0
3.00	6.00	8.75	5.83	5.83	4.64	5.00	0
3.33	2.00	3.75	5.00	3.33	4.64	5.00	0
3.67	5.00	6.88	6.67	1.67	2.50	3.00	0
4.00	4.00	6.25	4.17	4.17	3.57	2.00	0
4.33	1.00	6.25	3.33	2.50	1.79	2.00	0
4.67	8.50	3.75	7.50	2.50	4.64	4.00	0
5.00	13.00	9.38	10.00	5.00	3.93	1.00	0

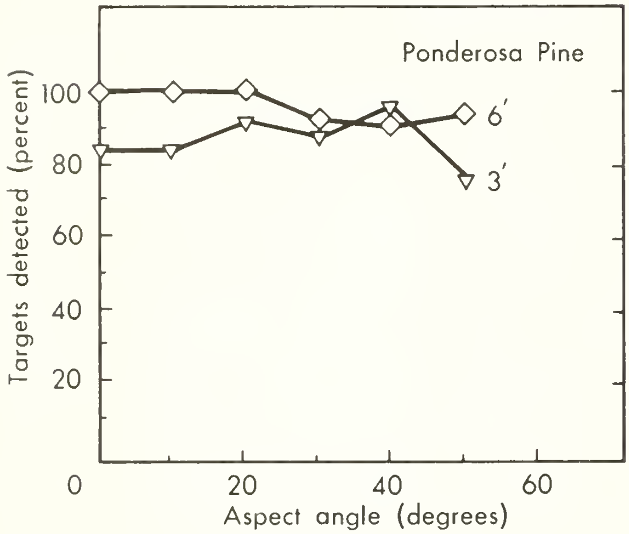
[1] *Society of American Foresters forest cover type designation No. 92.*

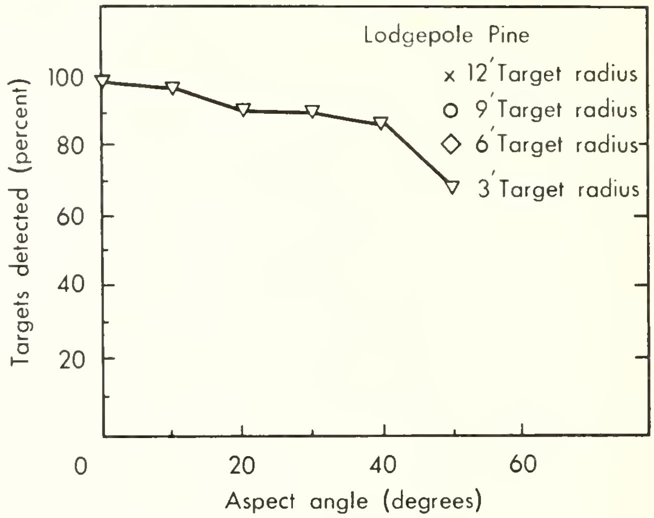
Table 29. — Signal strength frequency distribution by aspect angle for oak-hickory test area[1]

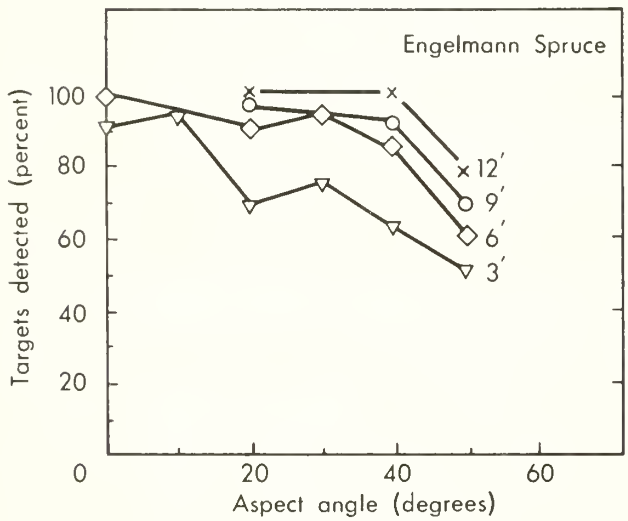
Relative signal strength	Aspect angle (degrees)						
	0	10	20	30	40	50	60
0	10.32	7.14	9.44	15.00	18.33	35.00	38.00
.33	5.32	5.00	6.11	3.46	7.50	5.00	9.00
.67	3.71	3.57	3.89	7.69	6.11	7.67	10.00
1.00	21.29	22.14	16.67	21.54	25.28	24.67	25.00
1.33	5.16	2.86	3.89	3.08	5.83	4.67	4.00
1.67	4.35	3.57	1.67	3.85	4.44	4.67	4.00
2.00	8.39	8.57	7.78	9.62	5.00	4.00	2.00
2.33	6.77	5.00	6.11	8.46	4.72	4.33	4.00
2.67	5.48	1.43	4.44	3.85	5.83	3.33	2.00
3.00	6.45	7.86	8.89	5.38	3.89	1.67	1.00
3.33	4.35	2.86	5.56	2.31	1.11	1.00	0
3.67	2.90	5.00	1.67	3.08	1.39	1.33	1.00
4.00	5.32	7.14	3.89	2.69	4.44	1.67	0
4.33	1.77	3.57	2.22	3.85	1.11	.67	0
4.67	1.45	2.14	2.78	1.54	1.94	.33	0
5.00	6.94	12.14	15.00	4.62	3.06	0	0

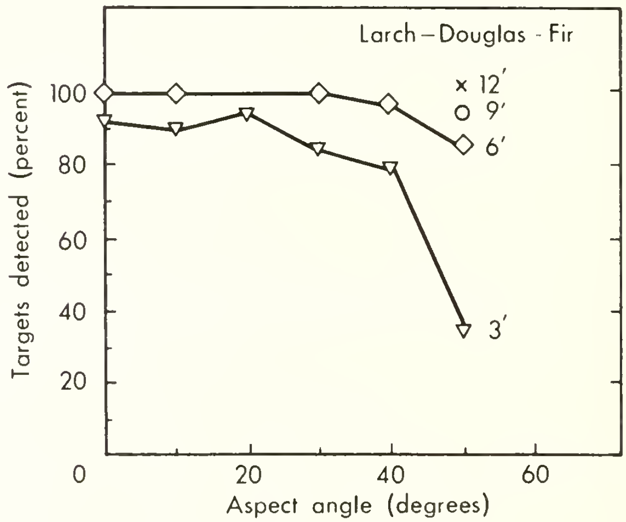
[1] *Society of American Foresters forest cover type designation No. 52.*

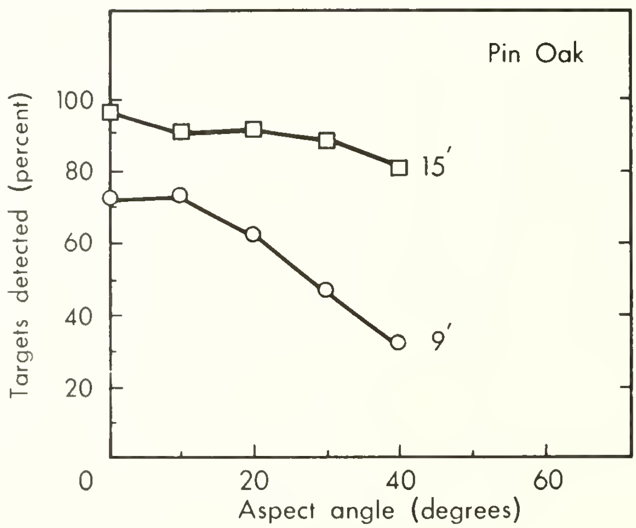
DETECTION PROBABILITY CURVES FOR 13 TEST AREAS

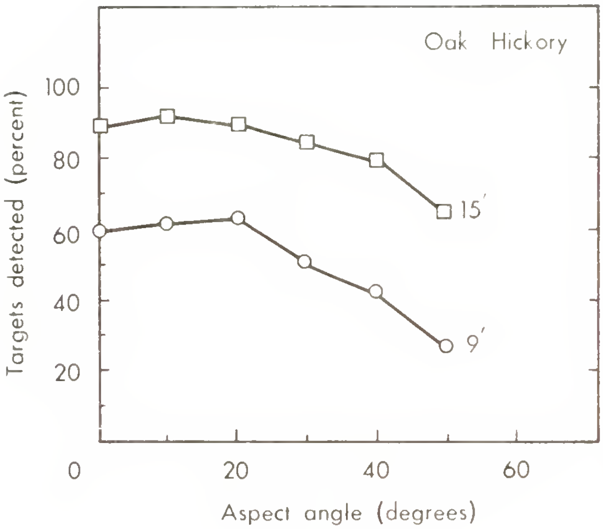


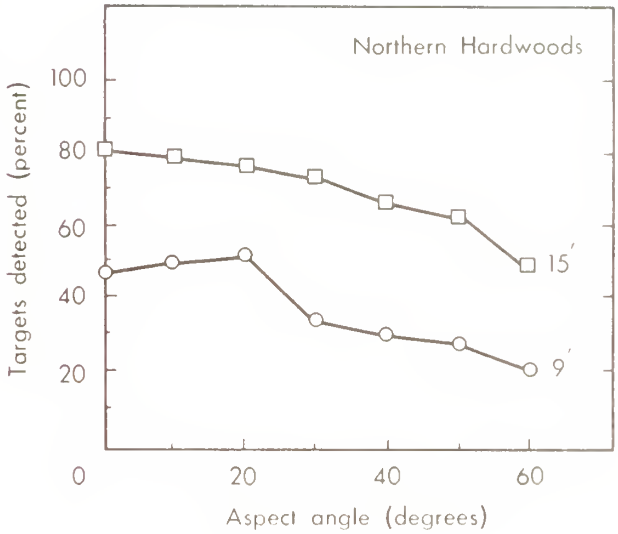


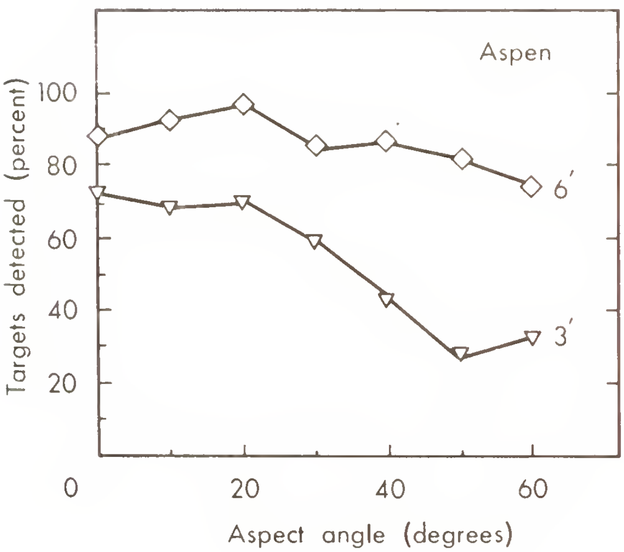


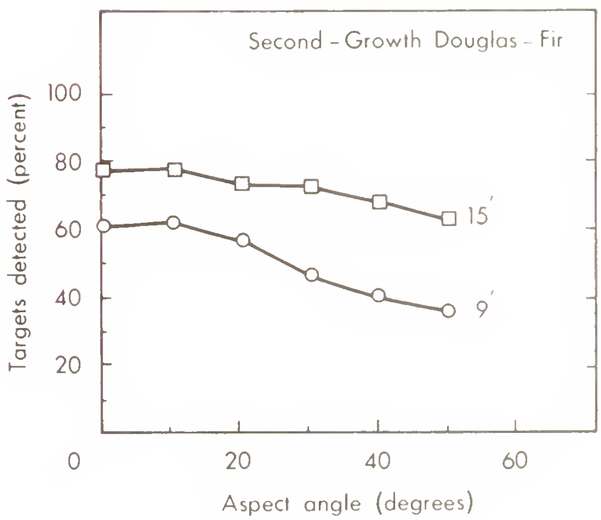


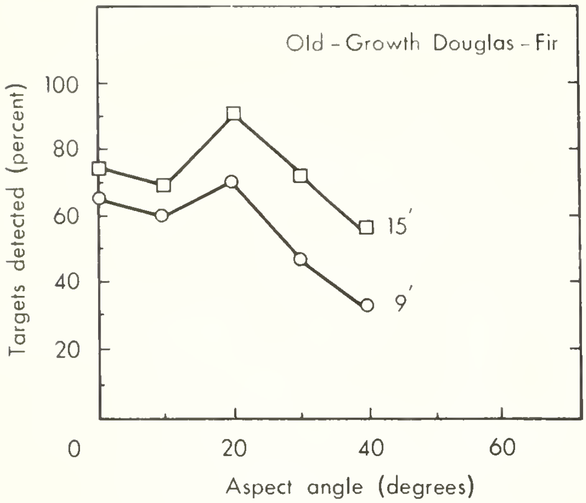


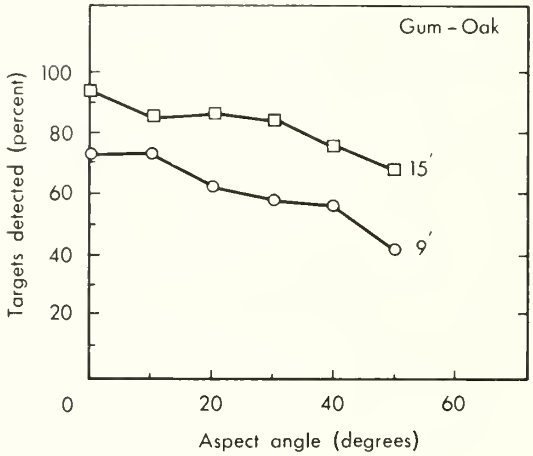

Oak Hickory
Targets detected (percent)
Aspect angle (degrees)
15′
9′
0
20
40
60
80
100

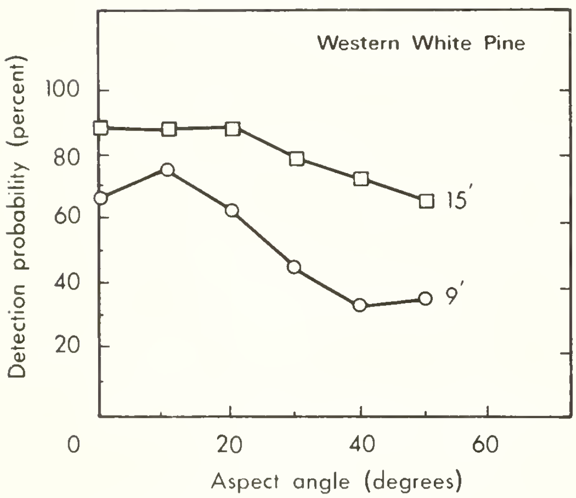

Northern Hardwoods
Targets detected (percent)
Aspect angle (degrees)
15′
9′
0
20
40
60
80
100

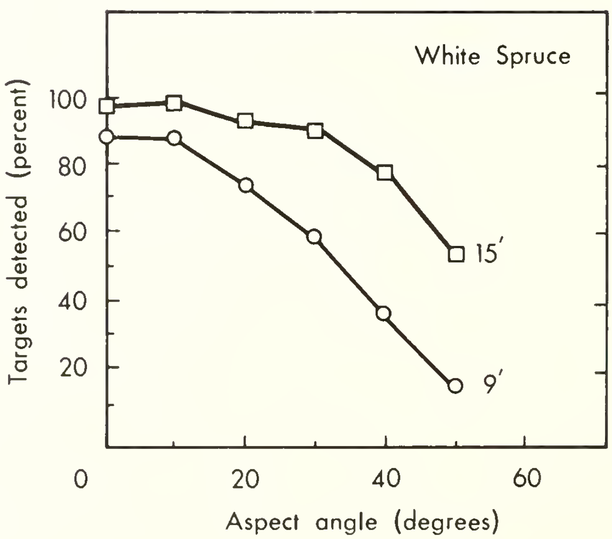

Aspen
Targets detected (percent)
Aspect angle (degrees)
6′
3′
0
20
40
60
80
100


Second - Growth Douglas - Fir
Targets detected (percent)
Aspect angle (degrees)
15′
9′
0
20
40
60
80
100


Old - Growth Douglas - Fir
Targets detected (percent)
100
80
60
40
20
0
20
40
60
Aspect angle (degrees)
15′
9′


Gum - Oak
Targets detected (percent)
100
80
60
40
20
0
20
40
60
Aspect angle (degrees)
15′
9′


Western White Pine
Detection probability (percent)
100
80
60
40
20
0
20
40
60
Aspect angle (degrees)
15′
9′


White Spruce
Targets detected (percent)
100
80
60
40
20
0
20
40
60
Aspect angle (degrees)
15′
9′

APPENDIX IV

Data From Operational Patrol Tests

Table 30. — Fire targets detected using airborne infrared equipment during the 1966 fire patrols

Fire no.	Date	Scan angle	Fire size	Time interval between IR scan and visual detection[1]	Fire manned[2]	Detection class[3]	Difference in location between IR and visual report	Remarks
				Hrs.:Mins.				
1	7/14	47°	Snag	−35:30	Yes	1	Same	In old burn, hot fire. Duff burning also.
2	7/15	40°	1 acre	−40:42	Yes	1	SE SE (NE SE)	Old-growth timber, hot fire.
9	7/26	10°	3 × 3 feet	+13:30	No	1	Same	In heavy brush field, very little fire.
10	8/5	30°	Spot	+ 4:00	No	1	Same	
13	8/5	42°	Unknown	—	No	1	—	Detected only on IR, never visually; nothing found on ground search.
14	8/5	38°	5 acres	−10:54	Yes	1	Same	Missed on morning patrol, burning hot when detected on evening patrol.
16	8/5	25°	Spot	+12:51	No	1	Same	
17	8/6	35°	200 acres	Unknown	Yes	1	Same	
18	8/6	50°	Spot	−13:00	Yes	1	Same	
19	8/15	23°	Snag	− 2:22	Yes	1	SW NE 27 (SE 28)	Lone snag on open ridge.
20	8/15	48°	1/4 acre	− 7:00	Yes	2	SW NW (NW NW)	In heavy timber and brush, fire out or cooled before flight.
21	8/15	30°	Spot	—	Yes	1	Same	Hotspot remaining in large fire on Cedar Creek.

[1] *Negative means that detection was first made visually.*
[2] *Whether or not fire was already being suppressed when first detected using airborne infrared equipment.*
[3] *See table 19 on pages 62, 63.*
[4] *Location in parentheses taken from official Forest Service fire suppression reports.*

Table 31. — Fires not detected using airborne infrared equipment during the 1966 fire patrols

Fire no.	Date	Scan angle	Fire size	Time interval between IR scan and visual detection[1]	Fire manned[2]	Detection class[3]	Remarks
				Hrs.:Mins.			
3	7/15	25°	Unknown	−6:20	Yes	1	Pulse-height circuit not operating on patrol. Heavy brush, possible target on film, no overstory, may have been out at time of patrol.
4	7/14	10°	Treetop	+ 4½ days	No	1	Pulse-height circuit not operating on patrol. In top of live tree, possible target on film.
5	7/15	35°	Tree	+13½ days	No	1	In live tree, no pulse-height circuit, nothing on film.
6	7/16	30°	Tree	−8:00	Yes	2	Pulse-height circuit not operating on patrol. No target on film. Fire may have been out at time of patrol.
7	7/16	20°	Tree crotch	−5:20	Yes	1	Same as above.
8	7/16	25°	Spot in duff	−5:21	Yes	1	Same as above.
14	8/5	35	Unknown	+ 7:30	No	1	
22	8/15	15°	Tree crotch	+ 2½ days	No	2	Smoldering in tree fork. Did not trip pulse-height alarm.

[1] *Negative means that detection was first made visually.*
[2] *Whether or not fire was already being suppressed when first detected using airborne infrared equipment*
[3] *See table 19 on pages 62, 63.*

Table 32. — Priority of National Forests for flight patrols

Order of priority	National Forest	Fire frequency per million acres	Average No. forest fires per storm	Priority factor[1]
		REGION 1		
1	Clearwater	53.4	4.11	3.74
2	St. Joe	64.9	4.33	3.74
3	Bitterroot	53.8	2.56	2.40
4	Nezperce	57.8	2.27	2.13
5	Coeur d' Alene	44.8	2.17	1.83
6	Kootenai	35.9	1.69	1.66
7	Kaniksu	36.4	1.67	1.54
8	Colville	31.2	1.56	1.50
9	Lolo	38.8	1.44	1.36
10	Helena	32.0	.94	.87
11	Flathead	19.5	.92	.86
12	Custer	29.6	.85	.83
13	Deerlodge	12.7	.43	.42
14	Lewis & Clark	12.9	.41[2]	.40
15	Gallatin	9.9	.31[2]	.30
16	Beaverhead	8.6	.29	.28
		REGION 2		
1	Bighorn	6.8	.49[2]	.48
2	Shoshone	5.1	.36[2]	.34
		REGION 4		
1	Boise	52.9	2.59	2.32
2	Cache	17.3	2.47	2.30
3	Payette	36.4	2.53	2.27
4	Salmon	32.2	1.53	1.36
5	Caribou	10.4	.94	.88
6	Bridger	8.2	.77	.73
7	Sawtooth	13.2	.63[2]	.59
8	Challis	13.8	.63[2]	.58
9	Targhee	9.5	.58	.54
10	Teton	6.5	.38	.36
		REGION 6		
1	Malheur	106.0	5.76	5.64
2	Ochoco	78.1	5.10	4.87
3	Deschutes	46.1	4.61	4.43
4	Fremont	50.2	4.18[2]	4.15
5	Gifford Pinchot	16.7	5.57	3.83
6	Umatilla	69.3	3.96[2]	3.59
7	Wenatchee	49.8	3.61	3.33
8	Mt. Hood	20.8	4.16[2]	2.97
9	Wallowa-Whitman	49.5	2.92	2.72
10	Snoqualmie	16.0	2.67[2]	2.60
11	Okanogan	25.6	2.41[2]	2.11
12	Winema	39.4	2.08	2.02
13	Mt. Baker	11.1	1.48	1.04

[1] *Development of priority factor is explained on page 28.*
[2] *Based on estimated storm occurrence.*

Flight No. 16

Zone A

Date 8-21-67

Elevation 5,000

Strip Interval 7

PROJECT FIRE SCAN FIRE DETECTION PATROL

NAVIGATOR'S FORM

Forests Covered CLEARWATER, NEZPERCE, BITTERROOT, LOLO

VOR MISSOULA VOR to start of run Course 252.6° Distance 57 3/4

Strip 1. Course 170.3 Distance 84 1/4 Slate Start 4 End 4 of run

Checkpoint LOCHSA RIVER Miles to go 35 1/2

Strip 2 Course 350.3 Distance 84 1/4 Slate Start ___ End ___ of run

Checkpoint LOCHSA RIVER Miles to go 43 3/4

Strip 3 Course 170.3 Distance 84 1/4 Slate Start ___ End ___ of run

Checkpoint LOCHSA RIVER Miles to go 49 1/2

Strip 4 Course 350.3 Distance 84 1/4 Slate Start ___ End ___ of run

Checkpoint LOCHSA RIVER Miles to go 28 1/2

Strip 5 Course 170.3 Distance 84 1/4 Slate Start ___ End ___ of run

Checkpoint LOCHSA RIVER Miles to go 60 3/4

Strip 6 Course 350.3 Distance 84 1/4 Slate Start ___ End ___ of run

Checkpoint LOCHSA RIVER Miles to go 21

Strip 7 Course 170.3 Distance 84 1/4 Slate Start ___ End ___ of run

Checkpoint WHITE SAND CREEK Miles to go 64 1/4

Strip 8 Course 350.3 Distance 84 1/4 Slate Start ___ End ___ of run

Checkpoint BIG SAND LAKE Miles to go 70 1/4

REMARKS

Figure 40. — Typical completed form with course, distance, and checkpoints detailed for each patrol leg.

Target No. 5

Flight No. 1

Date 7-5-67

PROJECT FIRE SCAN FIRE DETECTION PATROL

TARGET DATA SHEET

2 Mile Marker

District Challis Forest Challis State Idaho

Sec NWNE 23 T 16N R 18E

CN BEAR CREEK SIDE OF DIVIDE

AT EDGE OF TIMBER

2040 (7-6-67) Scan Angle 36° Heading 62° TRUE

X

X House Other

Image quality GOOD Detected X Undetected ___ by IR

0700 Date 7 6 67 reported to Forest

Date reported by Forest NOT DETECTED

NO Lookout Other

1900 CST Date 7-4-67

REMARKS

Figure 41. — Typical completed form used to document reported fires.

Table 33. — Number of targets detected on 1967 patrol flights by kind

Flight patrol no.	Wildfires		Slash fires	Oil waste	Campfires	Hot springs	Towns	Houses	Trains	Mills	Fires not found[1]	False alarms	Missed by photo-interpreter	Fires never verified	Total
	Initial detection	Second reports													
1	2				8			1	1	1				1	14
2					17	1		5		3	1	2			29
3					20	1	2	6		2		1		2	34
4				4	7	1	1	3					3		19
5	9		3		17	3	2	1		1	3	4	2	2	47
6	1	5			3	2	1	2							14
7	9	1			17	1	4	6		2	6	2			48
8			1		16		1	6							24
9	2		1		17	4	4	1		2	1	14	3		49
10			1		18	1	2	1		1		3			27
11					3	1	3	8	4	2			5		26
12	3		3		17	1	7	11	3	3	1	3		1	53
13	2		3	1	14	2	3	2		3		1	4	1	36
14			4		6	1		1				1			13
15					5			5		1					11
16	44				5	2	2				5	1			59
17	2	8			1		4	5		3	1				24
18	9				1	1	1	1		1					14
19	4				12		2	5		1	1	2			27
20	2				3	3	1			4	2				15
21					11	2	2	3							18
Total targets	89	14	16	5	218	27	42	73	8	30	21	34	17	7	601

[1] *See table 35 on page 84.*

Table 34. — Confirmation of target identification of campfires and wildfires reported to the National Forests

Identification	Number	Percent
TARGETS REPORTED AS WILDFIRES		
Wildfires confirmed by Forest	84	56.3
Second reports on a previously detected fire	14	
Campfires	21	12.1
Slash burning	14	8.0
Miscellaneous hot targets	11	6.3
Unconfirmed reports	30	17.2
Total	174	
TARGETS REPORTED AS POSSIBLE WILDFIRES		
Wildfires confirmed by Forest	3	7.7
Campfires	7	17.9
Miscellaneous hot targets	4	10.3
Unconfirmed reports	25	64.1
Total	39	
TARGETS REPORTED AS POSSIBLE CAMPFIRES		
Confirmed as wildfires	2	
Reported as campfires or miscellaneous	95	
Total	97	

Table 35. — Targets detected on the 1967 fire patrols, but never found by suppression forces

Date	Fire no.	SAF timber cover type	Elevation	Remarks
			Feet	
7/6	21-2	Douglas-fir	8,000	Fire found near area on 7/19, but location given makes it impossible to be the target.
7/13	88-5	Alpine fir	7,000	High, rocky area.
7/13 7/14	95-5	Alpine fir and lodgepole pine	7,000	Detected on two flights. High alpine and goat rock area.
7/13 7/14	98-5	Alpine fir	7,000	Detected on two flights. High alpine and goat rock area.
7/14	117-7	Ponderosa pine	6,000	Lookout reported lightning strike and burst of flames—fire never found.
7/14	124-7	Alpine fir	8,000	High alpine and goat rock area.
7/14	134-7	Lodgepole pine	7,000+	
7/14	140-7	Alpine fir (?)	7,000+	High, rocky area.
	143-7	Alpine fir (?)	7,000	High, rocky area.
7/14	154-7	?	7,000	
7/17	183-9	Lodgepole pine	5,000+	Even stand of lodgepole pine.
7/23	272-12	Douglas-fir, larch, and lodgepole pine	6,000+	High, rocky country with pockets of good timber. Broken up by rockslides and cliffs.
8/21	362-16	?	5,000+	Appears to be heavy timber.
8/21	364-16	?	7,000	
8/21	386-16	NCF[1]	6,000	Appears to be high, rocky country.
8/21	401-16	Alpine fir (?)	7,000+	High, rocky country.
8/21	405-16	Alpine fir (?)	6,000+	High and rocky.
8/22	435-17	NCF	7,000	
8/28	487-19	Juniper (?)	4,000	Fire reported. Never found.
8/30	492-20	Ponderosa pine	5,000	
8/30	495-20	Douglas-fir	7,000	Lightning hit tree in average stand of Douglas-fir.

[1] *Noncommercial forest, no information on site.*

Table 36. — 1967 wildfires detected by IR before visual detection

Fire no.	IR detected		Time reported to forest		Visually detected		Found by suppression forces		Size
	Date	Time	Date	Time	Date	Time	Date	Time	
5-1	7/6	0400		0700	Not detected		7/8	0930	2,700 sq. ft.
69-5	7/13	0210		0830	Not detected		7/13	1110	< .25 acre
92-5	7/13	0505		0830	Morning		7/13	1940	< .25 acre
93-5	7/13	0505		0830	Morning		7/13	1435	< .25 acre
94-5	7/13	0505		0830	Morning		No action taken		Snag
176-9	7/18	2310	7/19	0730	7/19	1655	7/19	2015	< .25 acre
273-12	7/23	2220	7/24	0530	Not detected		7/24	1520	800 sq. ft.
459-18	8/28	0317		0730	9/1	1621	9/1	1730	2.3 acres
460-18	8/28	0330		0730	8/28	0830	8/28	0900	.03 acre
489-19	8/29	0347		0800	Not detected		8/29	1010	360 sq. ft.
498-20	8/31	0345		0700	8/31	0725	8/31	1145	.1 acre

Table 37. — IR detection performance by timber classes and aspect angle

Timber detection class[1]	Aspect angle						
	0°-10°	10°-20°	20°-30°	30°-40°	40°-50°	50°-60°	Total
				DETECTED FIRES			
1	1	6	2	3	0	1	13
2	2	2	2	2	1	0	9
3	0	0	0	0	0	0	0
Total	3	8	4	5	1	1	22
				UNDETECTED FIRES[2]			
1	0	1	0	0	0	0	1
2	0	1	0	0	2	1	4
3	0	0	0	0	0	0	0
Total	0	2	0	0	2	1	5
				COMPLETE MISSES (NO TARGET ON IMAGERY)			
1	0	0	2	1	2	1	6
2	0	0	2	1	2	1	6
3	0	0	0	0	0	0	0
Undetected Total	0	2	4	2	6	3	12

[1] *See definition of these classes on page 33.*
[2] *Target recorded on imagery but alarm on automatic target discriminator failed to trip.*

APPENDIX V

Equipment and Instrumentation

Under certain environmental conditions, we might expect that the minimum and maximum temperatures of the terrain background could be $T_{min}=290°K$ and $T_{max}=310°K$. Thus, the maximum temperature difference, $\Delta T_{max} = 20°K$.

The effective radiation difference can be calculated by equation (2) on page 15. $\Delta W(20°K)=1.8$ watts/(cm^2 steradian °K). The radiation difference available at the scanner aperture from the background would be $\Delta W_A(20°K) = 2.4 \times 10^{-10}$ watts/cm^2 assuming a spectral band pass of 3 to 6 microns, an atmospheric transmission of 50 percent, and a scanner resolution of 4×10^{-6} steradians.

A 700°K fire target has a radiant power, W(fire) (between 3 and 6μ with 50 percent attenuation), $W(f)=.095$ watts/cm^2 steradian. The radiation from the fire that is available at the scanner is $W_A(f)$, and $W_A(f)=\omega_f W(f)$ where ω_f is the solid angle subtended by the fire target from the scanner. The criterion for this fire to be detected is that its radiation output, $W_A(f)$, must exceed the background radiation signal $W_A(20°K)$; $\omega_f \; W(f) > \Delta \; W_A(20°K)$ or

$$\omega_f > \frac{\Delta W_A(20°K)}{W(f)}$$

$$=2.5 \times 10^{-9} \text{ steradians.}$$

Then, for a scanner resolution, $\omega_s = 4 \times 10^{-6}$ steradians, $\omega_f/\omega_s > 6 \times 10^{-4}$. Thus, we conclude that a 700° K fire is detectable from a 20° K terrain background if it exceeds 6/10,000 of the instantaneous field of view (IFOV) of the scanner.

The following equation, which is based on equations (2) and (7) (see pages 15 and 36), provides a more exact solution for detection criterion:

$$\frac{\text{Fire Area}}{\text{IFOV Area}} > \frac{\int \frac{dW(\lambda,T_{BG})}{dT} \Delta T_{max} \Upsilon(\lambda)R(\lambda)d\lambda}{\int W(\lambda,T_f) \; \Upsilon(\lambda)R(\lambda)d\lambda} \quad \text{Eq. 11}$$

IR Scanner, Receiver, Optics, Filters

Most of the optical-mechanical scanners that are commercially available are adequate for general thermal mapping. Our present scanner (Texas Instruments, Inc. FFS-1) is a modified version of the Texas Instrument RS-7 (table 38). It has an effective aperture of about 100 cm^2, a focal length of 16.5 cm, and a field stop of 0.0625 cm^2. The scanner (including the 3-to 6-micron filters) has a typical transmission of 70 percent (filters are changed from time to time). We can characterize its response function (see page 14) as an "optical gain," G_o, which is defined as the output-to-input ratio of radiant flux density. For our scanner,

$$G_o = \frac{100 \text{ cm}^2}{.0625 \text{ cm}^2} (.7) \approx 1.1 \times 10^3$$

This optical gain is a constant. It is not subject to "saturation" or "roll off," nor does it affect the noise threshold of our complete detection system. These are logical concepts; for example, it is conceivable that the input flux could be large enough to cause a decrease in transmission or a "roll off" in optical gain. In this sense, the filters are used to control the spectral band pass of the system (i.e., optical gain is a function of spectral wavelength).

Scanning systems of the RS-7 type sweep the resolution element across the object plane at twice the rotational speed of the scanning mirror. Our mirror rotates at 4,000 r.p.m. The lateral resolution, α, is 2 mrd. (determined by focal length and field stop). The active scan, or total field of view, is 120° (nominally 2 radians).

The 4,000 r.p.m. mirror provides a scan rate

$$\dot{\theta} = \frac{2\pi}{60} 4{,}000 \times 2 \approx 800 \text{ rad/sec.}$$

The dwell time, τ, of each resolution element is

$$\tau = \alpha/\dot{\theta} = \frac{2 \times 10^{-3}}{800 \text{ rad/sec}} = 2.5 \mu\text{sec.}$$

The scanning rate and the geometrical configuration of the resolution element completely specify the modulation function, $\delta(\mathbf{r}-\dot{\mathbf{r}}t)$, of the scanner. The rectangular resolution element is determined by the square field stop. The field stop produces a square wave modulation for a point source by means

Table 38. — History of development of equipment for IR forest fire detection system

Year	Aircraft	Equipment	Results
1962	Beechcraft AT-11	AN/AAS-5 scanner	First imagery obtained through smoke. Preliminary look at detection of small fires under forest canopy.
1963	Beechcraft AT-11	AN/AAS-5 (modified for Polaroid readout)	16 flights over wildfires, imagery dropped to fire bosses. Data collected on detection probability versus scan angle in four coniferous types.
1964	Aero Commander 500B	AN/AAS-5, Polaroid	49 flights over wildfires, gained experience in use of imagery for fire control.
	Convair T-29	AN/AAS-5, KD-14 rapid film processor	No data due to equipment problems.
1965	Aero Commander 500B	Reconofax XI scanner	Preliminary equipment evaluation, no operational data due to equipment problems.
	Convair T-29	RS-7 scanner, Litton CRT, KD-14, Tape recorder	Data collected on detection probability versus scan angle in three coniferous and three deciduous timber types.
1966	Aero Commander 500B	Reconofax XI, Dual Polaroid	System delivered to Div. Fire Control for operation.
	Convair T-29	RS-7, Litton CRT, KD-14, Tape recorder, APN 81 Doppler	Data collected on detection probability versus scan angle in one coniferous and two deciduous timber types. First fire patrols.
1967	Aero Commander 500B	Reconofax XI, Dual Polaroid	Operational, R&D terminated.
	Convair T-29	RS-7, Litton CRT, KD-14, Target discrimination module Bendix DRA-12 Doppler	21 fire detection patrols.
1968	Convair T-29	RS-7, Litton CRT, KD-14, TDM, DRA-12 Doppler	Equipment modified for 2-color system and to reduce size and weight for installation in smaller aircraft.
1969	Beechcraft King Air	RS-7, Litton CRT, KD-14, TDM, DRA-12 Doppler, 2-color temperature discriminator	Equipment tested. 25 operational fire detection patrols.

of the displacement vector, (r-ṙt). The width of the square wave (δ) is α in the object space and τ in the time domain. The resultant resolution on the IR imagery depends on the fidelity of subsequent processing of this square wave signal.

Detectors

Several types of detectors have adequate response in the 3- to 6-micron spectral region around the 1,000° K (fire) blackbody peak. Selected examples of photoconductive (PbS, PbSe, and InSb) detectors have produced good fire detection imagery. Since 1964 we have used photovoltaic (PV) InSb detectors exclusively for fire detection. We have had consistently good performance from the PV, InSb detector; thus, our electronic problems (coupling detectors to preamplifiers) were minimized by standardizing on one good type of detector.

Manufacturers publish typical response curves for their detectors (fig. 42). PV, InSb detectors develop a short circuit current, which is directly proportional to the number of effective photons, and also develop an open circuit voltage, which is proportional to the log of the number of effective photons. Like all photodiodes, PV, InSb detectors do not require the use of bias current for signal generation.

Standard procedures for system design generally recommend that detector detectivity, $D^*(\lambda)$, be used for analysis such as in equation (3) on page 15 and for detector procurement specifications. However, there is a very real danger in this procedure. D* (Jones, Goodwin, and Pullan 1960) is a normalized signal-to-noise, S/N, measurement from the detector for given incident power. A given detector material (e.g., InSb or Ge:Hg) has an inherent responsivity, R, (volts/watt) that is determined by the type of material and, more or less, by the *art* of detector manufacture.

Solid state technology has improved the D* of detectors primarily by lowering the internal detector noise approaching the background noise limit ("BLIP" detectors). Thus, a detector with large D* may not have as high *responsivity* as another detector with poor D*.

The quality of a scanning system is determined by the S/N ratio at the output terminals of the system. The cryogenic IR detector enjoys an inherently lower noise level than the electronic load that it is trying to drive; and therein lies the danger. We have *never* observed this detector noise at the output of an operational system. Good IR scanning systems are almost invariably noise limited in the first preamplifier stages of the electronic chain. Thus, if we desire a large S/N ratio at the system output, we must start with a large detector responsivity at the input and not necessarily the best D*.

If the average responsivity, R, of our detector is taken as 1×10^6 volts per watt between 3 to 6 microns for ambient temperature sources, we can estimate the signal from the detector as follows: Recall

$$\frac{\Delta W_A}{\Delta T} = 1.2 \times 10^{-11} \text{ watts/(cm}^2\,{}^\circ\text{K)}$$

then

$$\frac{\Delta S}{\Delta T} = \frac{\Delta W_A}{\Delta T} \cdot G_o \cdot A\,(\text{detector}) \cdot R\,(\text{detector})$$

$$= 7.5 \times 10^{-6} \text{ volts/}^\circ\text{K}.$$

The signal representing a 20° K contrast would be $\Delta S_{20^\circ K} = 150$ μvolts, and the signal from a 700° K fire that is big enough to *fill the field of view* will exceed $S_f > 250$ millivolts.

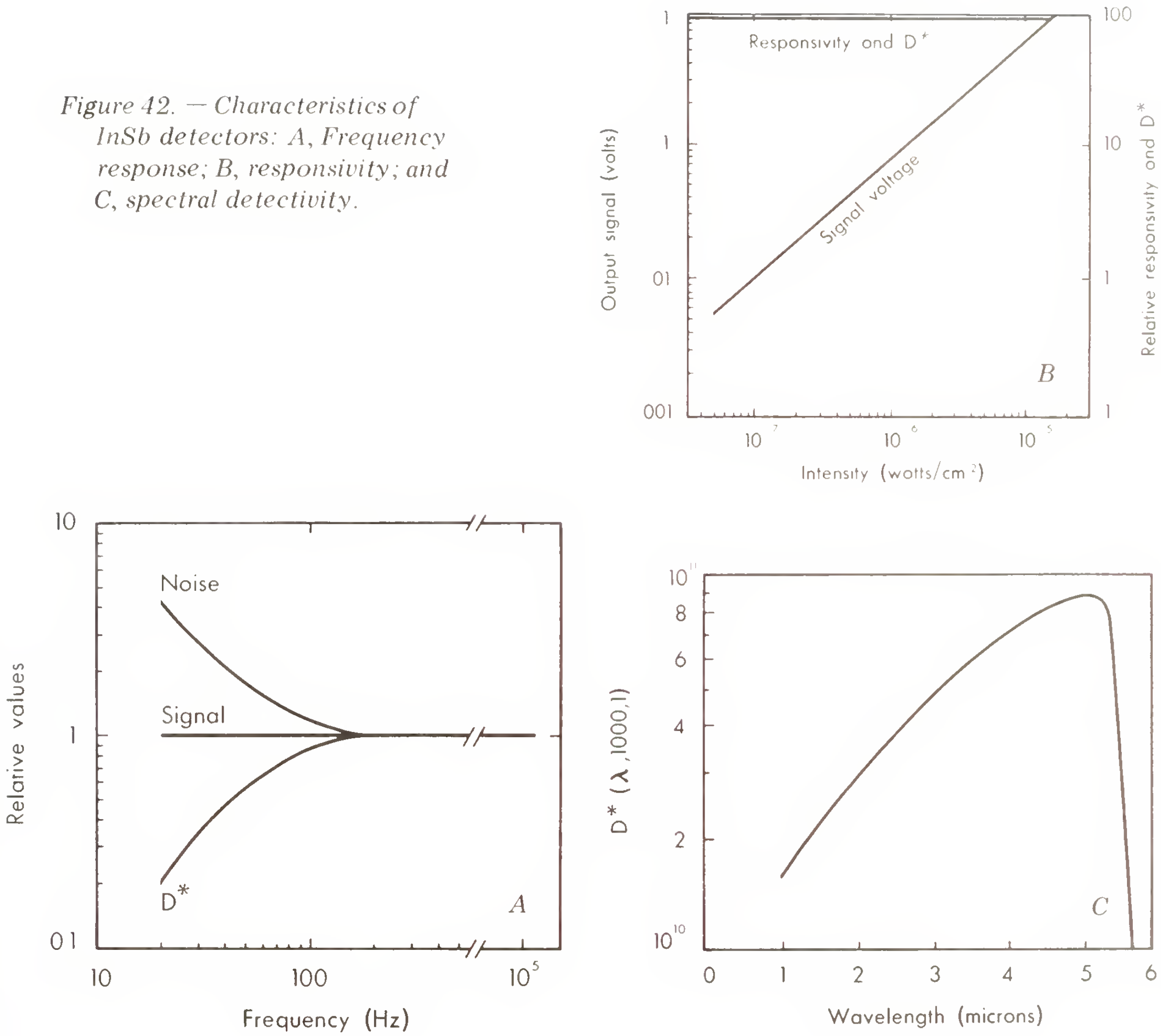
The time varying signal will have components whose amplitude will depend on their thermal contrast and whose duration will depend on their size. The sizes will range in extent from a full scan line (for a broad uniform source) equivalent to a time duration of about 2½ msec, down to a small point (smaller than the resolution element) that will produce a pulse whose width is 2.5 μsec. (i.e., the dwell time of the resolution element). The above response and modulation requirements are well within the capabilities of PV, InSb detectors.

Several detector-preamplifier coupling techniques are appropriate for IR line scan thermal mappers. Each technique has particular advantages:[5]

---

[5] *Texas Instruments. Infrared devices. 33 p., illus.*

Figure 42. — Characteristics of InSb detectors: A, Frequency response; B, responsivity; and C, spectral detectivity.



1. The detector may be operated directly into the preamplifier through a d.c. blocking condenser. This method is advantageous for small detectors, or in cases where spectral band-pass filter has reduced the input radiation and, as a result, also reduces the short circuit current of the detector to less than 1 μamp.

2. The detector may be operated in series with a variable bias supply and in parallel with a fixed load resistor whose resistance is much larger than that of the detector. Low noise, solid state circuitry must be used in the preamp. The preamp should be designed for a minimum noise figure for the parallel load. This technique complements high responsivity detectors.

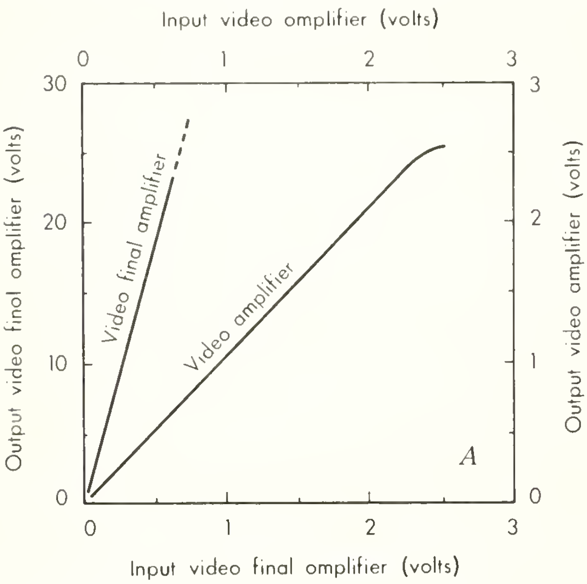
3. The detector may be operated into a preamp load resistance much lower than that of the detector. This technique reduces the RC time constant of the circuitry and utilizes the fast intrinsic response speed of InSb photodiodes.

4. The detector may be coupled directly into a current gain preamp that will automatically maintain the zero bias condition of the detector as the input irradiance changes.

Preamplifiers, Amplifiers, and Video Signals

The electric signals from the detector are time dependent. Following standard engineering practice, the modulation characteristics of electronic components are designed and evaluated in the time-frequency domain through the LaPlace transform $S(f) = \int S(t)e^{i2\pi ft}dt$.

The spatial resolution of the scanner is dependent on amplifier frequency bandwidths, etc. In this regard, IR line scanners require relatively wide bandwidths. The high frequency



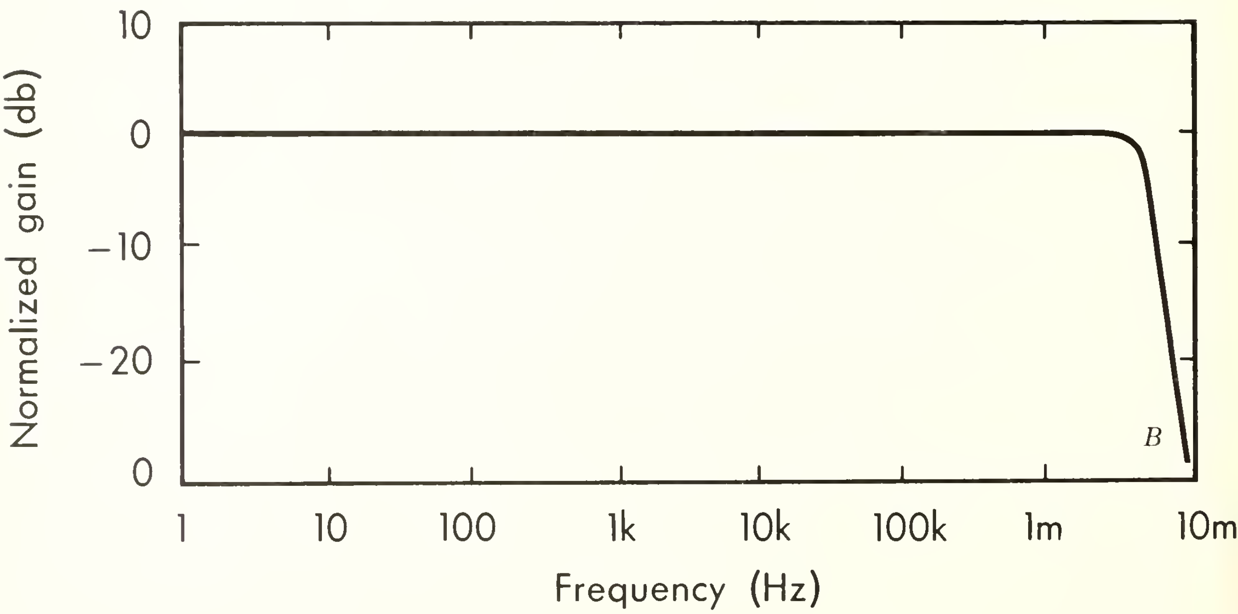


Figure 43. — Characteristics of the video amplifier: A, Gain; and B, frequency response.

limit is determined by the fidelity with which the square wave resolution element is to be reproduced. Recall it has a pulse width, $\tau \approx 2.5$ μsec. Each full cycle would be 5 μsec long and an upper frequency limit of 200 kc would be adequate, if one were to reproduce a cyclic input signal representing alternate hot and cool sources, each one resolution element wide.

Another high frequency limit, $f = n/\tau$, is indicated if the requirement is to respond with a signal, S, to a hot point target (smaller than the resolution element) signal, S_0, $S = S_0(1\text{-}1/e)$ within 1/n of the dwell time, τ. Or, one might require 1 mc upper frequency limit if the requirement is to reproduce the resolution element's square wave response to a hot point source with the fidelity required by the fifth harmonic of the fundamental frequency.

On the low frequency side of the modulation function, we must reproduce the profile of the 120° scan line, 200 Hz square wave without slope or distortion of any kind. A d.c. lower limit is desirable for this purpose; however, we have made satisfactory imagery with capacitive coupling and a 2.0 Hz low frequency cutoff (for exceptions, see Hirsch and others 1968, app. IV, p. 41).

The "response" function, or gain of an amplifier, is the ratio of output-to-input signals (S_{out}/S_{in}) and is generally unitless (volts/volt, etc.). In some cases (as in the current mode detector-amplifier circuit), the units may be volts of output per amperes of input. Gains of electronic components are a function of the amplitude of the signal being processed (fig. 43). The electronic components are saturated by large signals.

In a well-designed system, the practical limiting noise is most likely the thermal ($T\Delta fR$) noise from the load resistance in the early stages of amplification. This noise is most noticeable because it is amplified by all succeeding stages. When the limiting noise is measured at the system output and compared to an equivalent input temperature contrast, it determines the system NET.

The dependence of gain on signal amplitude and signal frequency may be used to advantage in many cases. For example, we faced the problem of maintaining enough sensitivity to observe small signals of background contrast and yet restricting large amplitude signals from hot targets to the dynamic range of the film. This was easily solved by proper selection of amplifier gain versus signal amplitude curve.

The time dependent output signal, $S(t')$, is determined by the inverse LaPlace transform, $S(t') = \int S(f)e^{-i2\pi ft'}df$, which takes into account all applicable amplitude and bandwidth limitations on $S(f)$. The gain of the electronic system is $G_e = S(t')/S(t)$. The performance characteristics of some of the amplifiers we have evaluated are shown in fig. 44.

Target Discrimination Module

Our early development of automatic target discriminators exploited the unique character of the hot target signals. These targets are much smaller than the instantaneous field of view (IFOV) and thus produce a pulse width, τ, the IFOV dwell time. The signal amplitude of the targets exceeds the maximum background contrast if the targets are hot enough and exceed some small fraction of the scanner resolution element (700°K and $6 \cdot 10^{-4}\,\omega_{scanner}$ in the case developed on page 88). Our first discrimination circuits were simple signal threshold discriminators whose performance was very poor because of the many false alarms generated by high amplitude random noise pulses from aircraft electronic and radio frequency sources. The technique of narrow band filtering was incorporated into a pulse height/pulse width discrimination circuit. The resistance/capacitance filter networks created many false alarms by differentiating the sharp thermal edges of lakes, roads, ridgetops, etc. Although these circuits produced excessive false alarm rates they were successful in detecting signals of hot fire targets.

In the summer of 1967 we added a target discrimination module (TDM) to our system. It takes advantage of the overscanning capability of the system (fig. 45). Signals from the video electronics are amplified and filtered to obtain signals that are scaled to threshold levels and pulse width limits of interest for detection. The signal is fed to a pulse selector that produces logic pulses coinciding with any signal element above a selected amplitude threshold and signal elements within selected minimum and maximum pulse widths. The logic pulses are delayed in a serial memory for one scan line and are compared at the comparator with logic pulses produced by the corresponding portion of the following scan line. If a pulse occurs in the same place on two successive scan lines, the comparator activates the output driver, which in turn triggers an external alarm and marks the target on the imagery.

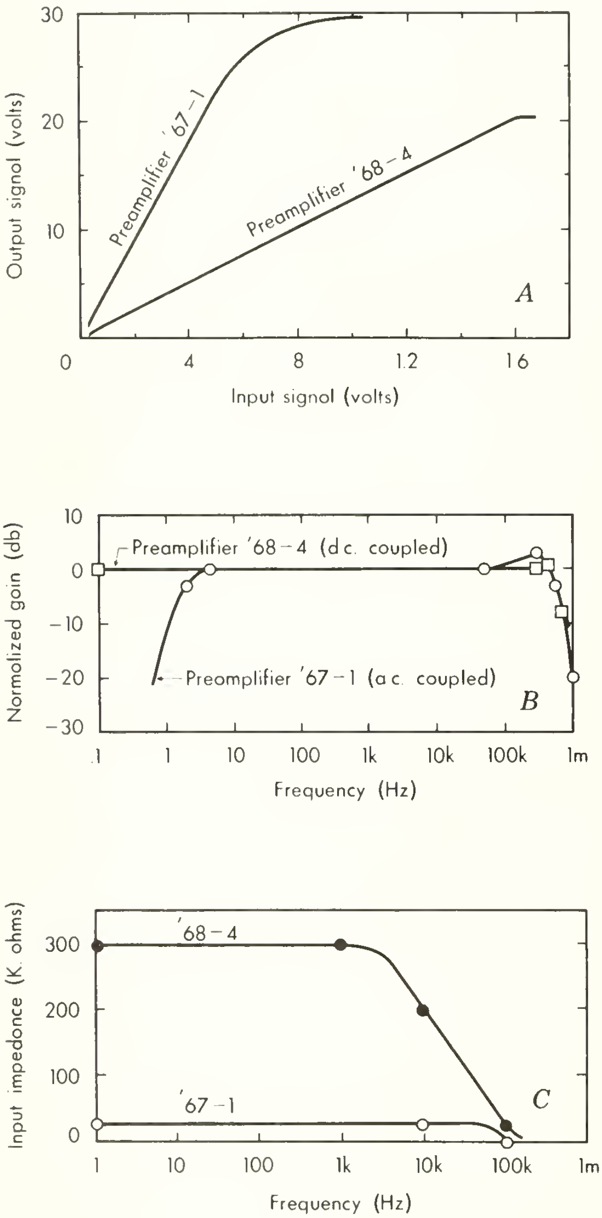


Figure 44. — Characteristics of detector preamplifiers: A, Gain; B, frequency response; and C, impedance.

Cathode Ray Tube, Camera, and Recording Film

The cathode ray tube (CRT) transforms an electronic signal to light intensity. The analogous time-space transform is made by electromagnetic deflection of the CRT spot, $\delta'(r-\dot{r}t)$, which is the inverse of the scanning mirror operation.

The CRT sweep, or beam deflection system, is responsible for keeping the video signal in register on the output IR imagery. The four major criteria for undistorted imagery are:

1. The CRT spot must be synchronized with the scanning mirror to very close toler-

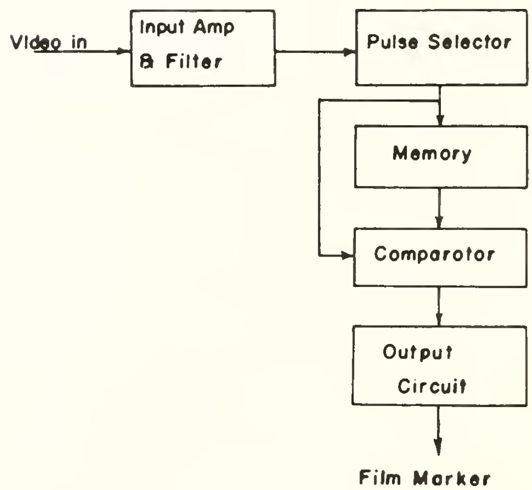


Figure 45. — Block diagram of target discrimination module.

ances. These tolerances are referred to the system input and specified typically as ±1/10 of the resolution element (or ±.2 mrd).

2. The sweep is also stabilized for aircraft roll. In our system the imagery is corrected for ±10° of aircraft roll by electronic stabilization from a vertical gyro reference.

3. The constant scanning speed, $\dot{\theta}$, produces a nonlinear displacement, $\dot{r} \propto \sec^2 \theta$ (where $\theta \propto \dot{\theta}t$) across the terrain. We rectilinearize our imagery (i.e., correct this lateral angular distortion) by electronically driving the CRT spot at a velocity, $\dot{r}' \propto \sec^2 \theta$, such that distance on the imagery is proportional to distances on the ground.

4. The film slew rate must be adjusted relative to the operational V/H of the aircraft. The basic requirement is that the ratio of the lateral and longitudinal components of the image printing vector, $\dot{r}'$, must equal the ratio of the respective components of the scanning vector, $\dot{r}$. Geometrically, it follows that the film slew rate equals $\frac{V}{H}\frac{d}{2}\cot\frac{\pi}{3}$, where d = width of the imagery.

The size and shape of the CRT spot, δ', (fig. 46) is different than that of the scanning (δ); it is circular and is nearly constant in size (d), as it is displaced over the face of the CRT. When we drive the CRT sweep, $\dot{r}' \propto \sec^2 \theta$, for rectifinearization, we produce a nonlinear dwell time, τ', for the CRT spot. Geometrically $\tau' = d/\dot{r} \propto \cos^2 \theta$.

The exposure of the film is proportional to the product of the light flux density transmitted to the film by the relay camera lens from the CRT spot and the dwell time of the spot, $E \propto I \cdot \tau'$.

To maintain constant exposure across the film, we must remove the $\cos^2 \theta$ dependence of exposure. This is done by electronically generating a $\sec^2 \theta$ intensity correction. The effect of the intensity correction and rectilinearized sweep is that the CRT spot is brighter and moves faster at the edges of the scan line while it is dimmer and moves slower in the center.

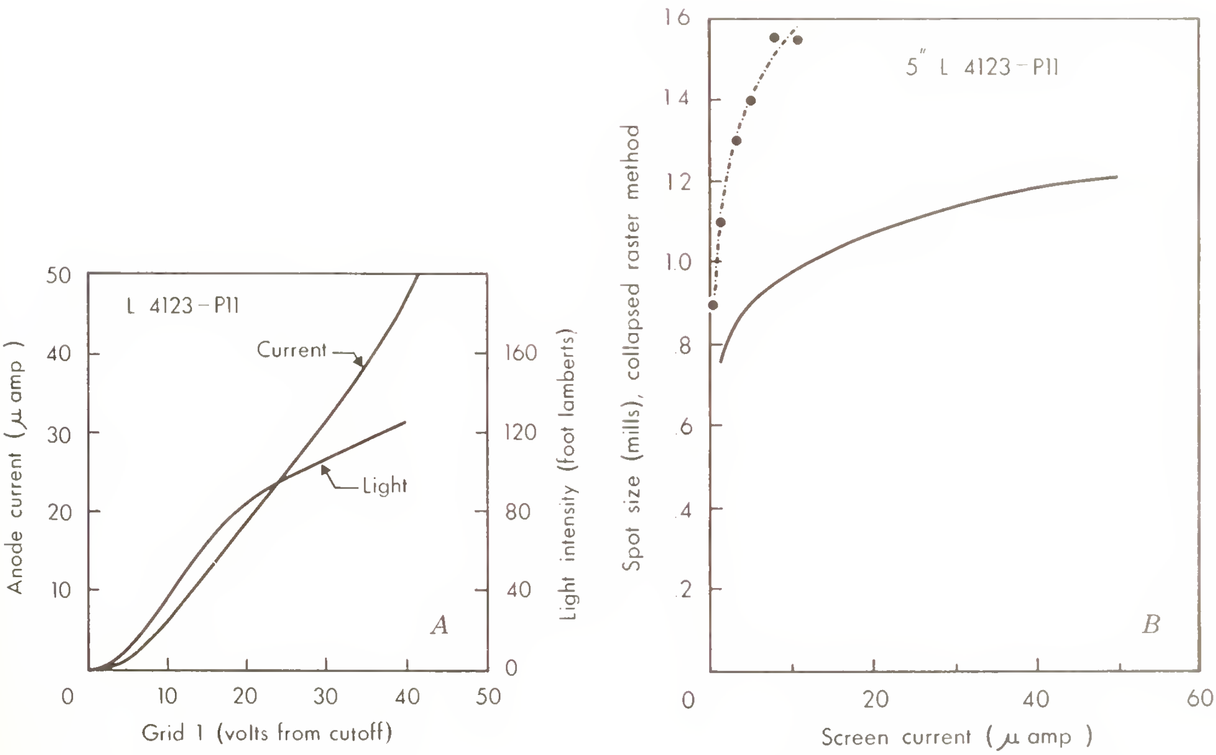
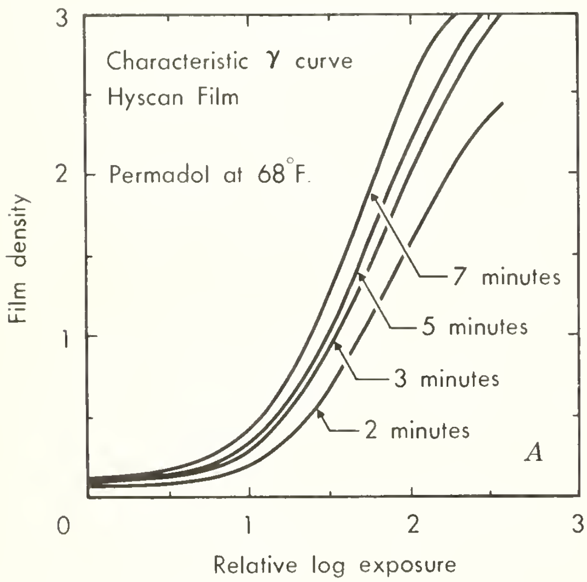
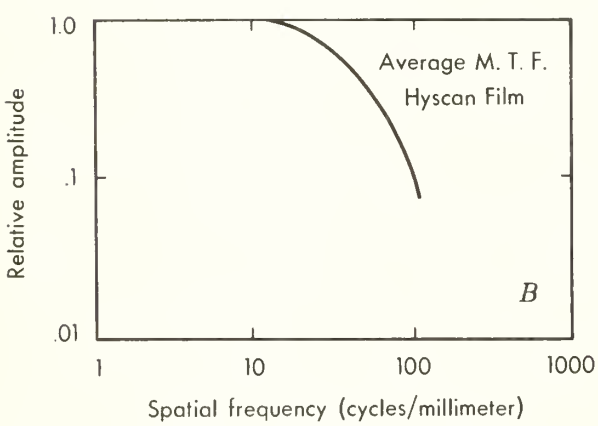


Figure 46. — Characteristic curves of the CRT: A, Response function; and B, resolution.

The camera relay lens is a 6-inch focus f/1.9 Cathode Ray Navitar (ELGEET Optical Co., Rochester, New York) with an adjustable iris to f/16. The resolving power of this lens greatly exceeds the resolution requirements of the system (i.e., its modulation transfer function (MTF) is constant — approximately 100 percent) over the range of spatial frequencies of interest. The magnification ratio (photo image/CRT image = 3.5 in./4.5 in.) is approximately 0.8. The lens response function and photographic exposure of the film depend on the adjustment of f/stop.

Our IR imagery is recorded on high resolution, high contrast films designed for high temperature, rapid access processing. General Aniline and Film Corporation's Hyscan film characteristic γ curve and transfer function are given in fig. 47. A rigorous calculation of exposure is almost impossible because of ambiguous definitions of light flux density (Biberman 1967). A rough judgment of the response of Hyscan film to P-11 phosphor on the CRT can be made from the spectral curves of figure 47, but it is difficult to relate this sensitivity to the ordinate of the CRT response function (foot candles) of figure 46. In addition, the film speed depends on the processing and exposure conditions. At the beginning of each flight operation, a series of test exposures under prevailing conditions is made to determine CRT brightness, lens f/stop, etc. The dynamic ranges and shapes of these curves (figs. 42 through 47) are useful in system design to properly engineer the total system response. In particular, the electronic amplifiers (where we have considerable design freedom and latitude) must be adjusted so that the desired background thermal sensitivity, dynamic range, and resolution are properly reproduced on the IR imagery.





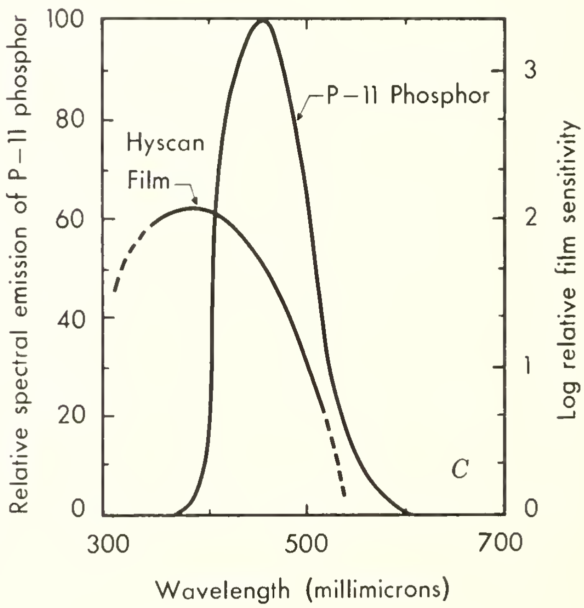


Figure 47. — Characteristics of Hyscan film: A, v curve (response function; B, resolution function (MTF); and C, spectral response of Hyscan film and P-11 phosphor.

Standard Performance Parameters

It is standard practice to calculate a well defined set of performance parameters (Wolfe 1965) for the purposes of evaluating and comparing airborne IR line scanners. The characteristic parameters of our system follow.

- 120° total field of view (TFOV)$\pm 10^\circ$ for aircraft roll correction.

- 2-mrd optical resolution determined by ¼-mm^2 detector area in the image plane of a 6.5-inch focus collector. The optical system is capable of much better resolution (<.5 mrd); however, we have compromised at 2-mrd optical resolution because of practical considerations of resolution, signal/noise ratios, scanning rates, etc.

- 200 line scans per second. For contiguous scanning, the ultimate capability of the system is 0.4 rad/sec (velocity/height ratio) if the longitudinal optical resolution is 2×10^{-3} radians. The V/H concept is a source of much confusion and ambiguity in the literature (e.g., we normally *operate* our system in the neighborhood of .02 rad/sec-15,000 to 20,000 feet over terrain at 250 to 300 m.p.h.). This produces an overscan such that each point of terrain is scanned or observed about 20 separate, unique, independent times.

- Approximately 2° C noise equivalent temperatures (NET) measured in the laboratory under conditions equivalent to the 0.4 rad/sec scan rate with ambient backgrounds. A statistical integration occurs on the output imagery when we operate at 0.02 rad/sec. We would observe $(S/N)_1 = 1$ for one scan observation if we were to observe a 2°C background temperature difference in the presence of an effective 2°C noise. If we overscan 20 times, $(S/N)_{20} = 1 \cdot \sqrt{20} = 4.5$. Thus, our observed NET is less than ½° C.

- A figure of merit, $n = R/(\Delta T \cdot \Delta \alpha)$, is determined by the system limited resolutions, ΔT = NET, and $\Delta\alpha$ = IFOV, and the field sampling rate R (i.e., the rate at which independent thermal measurements are made). When the performance parameters are properly interpreted, the figure of merit, n, of our system between 1964 and 1967 was approximately $n = 4 \times 10^5$ (sec °K mrd$)^{-1}$.

Because fast scanners and detectors are available, it is not necessary to degrade the other performance parameters of the system just to improve thermal resolution (e.g., one might be tempted to slow the scan speed to produce contiguous scanning at V/H = 0.02 rad/sec and give the detector time to make the ½°C temperature measurement by "one look" contiguous scanning, as recommended by design-tradeoff philosophy).

The improvement in effective NET by overscan has a fortunate effect on image quality when we significantly change altitude. As we go to higher altitudes, the resolution element projected on the ground increases in size. We would expect from equation (2) on page 15 that the observable thermal contrast, T_{BB}, between adjacent resolution elements would decrease because T_{BB} is averaged over larger terrain areas. By overscanning, this lower thermal contrast remains observable.

Another alternative that we have speculated about might be to utilize the full 0.4 rad/sec contiguous scan capability to improve our optical resolution by decreasing the size ($\times$ 1/20) of the resolution element and argue that individual measurements in 20 smaller, adjacent areas will provide just as good an average thermal measurement as before. However, consider the convolutions (equations (3) and (5) on pages 15 and 16, respectively) and the sets of orthogonal scanning functions, δ and δ' in the case of the 20 times overscan. If the scanning functions are in phase and register (i.e., $\dot{r}t \equiv \dot{r}'t'$ within tolerances required by the 1/20 resolution scan), then the overscan generates 20 *complete* sets of contiguous imagery — thermal distribution functions that have a unique value at each resolution element. The 20 sets are interlaced such that the maximum cross correlation that can exist between corresponding resolution elements of consecutive sets is about 0.95 (i.e., no two sets overlap more than 19/20). By the same reasoning, the minimum cross correlation is 0.5 (50-percent overlap between the first and eleventh scan lines).

If we superimpose these 20 sets of imagery in exact register (recall that they are not completely correlated spatially), we should observe an improved spatial resolution. In principle, special δ's can be designed that have zero correlation; thus, the ultimate resolution would be determined only by the displacement between scan lines. However, we have the following practical engineering limitations such as: (1) The synchronization and register are difficult to achieve; (2) the video electronic bandwidths that would be required are the same as those required of a 20-times resolution system; and (3) the transforms, δ and δ', are not exact inverses of one another (i.e., δ is generally determined by the area of the detector in the focal plane of the scanner and is a rectangular spatial function with unknown contour, while δ' is usually a circular CRT spot).

Brute force methods, such as more horsepower to turn a scan mirror faster, have a limit. With *good design technique*, system performance depends on the *tolerances* of such parameters as scan sync-register and signal processing fidelity at least as much — probably more — than it depends (1) on scan rate, (2) the V/H ratio at which the system is operated, or (3) the optical resolution. Furthermore, one must have some insight to properly handle these tradeoffs in order to design a better than average system.

Later Equipment Development

The equipment used through 1967 was optimized to detect small, hot targets in wildland terrain. We performed extensive field tests of its operational capability. However, the critical question still remained, "Is it an effective operational tool for finding small, hot targets?" The answer depended in part on the specific operational goals: How small are the targets? How reliable must they be detected? We concluded that the system of 1967 was at the margin of effectively detecting the small targets of interest to the Forest Service.

Our studies demonstrated that a large number of these small, marginal targets does exist. If the small target signals were buried in the background contrast, the target was not detectable. However, even for many small targets a temperature discrimination between target and background could be made by comparing the relative amplitudes of target and background signals in two spectral regions. Furthermore, the system was readily adapted to a two-color temperature discrimination technique.

Since 1967 we have added a second spectral channel to our system (fig. 48). This channel operates in the 8.5- to 11-micron region of the ambient background radiance peak. An Hg:Ge detector is placed in the focal plane of the scanner beside the InSb (3- to 4.1-micron) detector and brought into scan register by electronic-time delay. Thus, both channels look simultaneously at the same IFOV.[6]

The two spectral bands (3- to 4.1-micron and 8.5- to 11-micron) were very carefully chosen to eliminate the effects of changes in concentration of atmospheric moisture on the relative signal amplitudes in the two channels. The effective blackbody temperatures defined in equation (2) on page 15 emphasize the concept of the $T_{BB}(\lambda)$ average over the IFOV at the two widely different wavelengths.

The electronic signal in channel A is adjusted (by a factor K) relative to channel B such that $KS_{A max} = S_{B max}$, or:

$$K \int \frac{dW}{dT}(\lambda, t)\, \Delta T_{max}\, \Upsilon(\lambda)\, R_A(\lambda)\, d\lambda$$
$$= \int \frac{dW(\lambda T)}{dT}\, \Delta T_{max}\, \Upsilon(\lambda)\, R_B(\lambda)\, d\lambda$$

at the A and B inputs to a differential amplifier. $\Delta T_{max} = T_2 - T_1$ is determined by the warmest and coolest IFOV's of the background, respectively. The output signal of the differential amplifier, S_{KA-B}, from internal calibration sources, is nulled (zero contrast) for the temperatures, T_1 and T_2. The contrast, $\Delta T = T_2 - T$ is not zero for any other background temperature, $T \neq T_1$. Fig. 49 shows computed values of the relative signal, S_{KA-B}, as a function of background temperature for various values of K.

This bispectral difference signal enhances the target signal-to-background signal ratio. A comprehensive description of this system and a performance analysis are being prepared for publication.

[6]*By convention, the InSb (3- to 4.1-micron) channel is "A" channel and the Hg:Ge (8.5- to 11-micron) channel is "B" channel.*

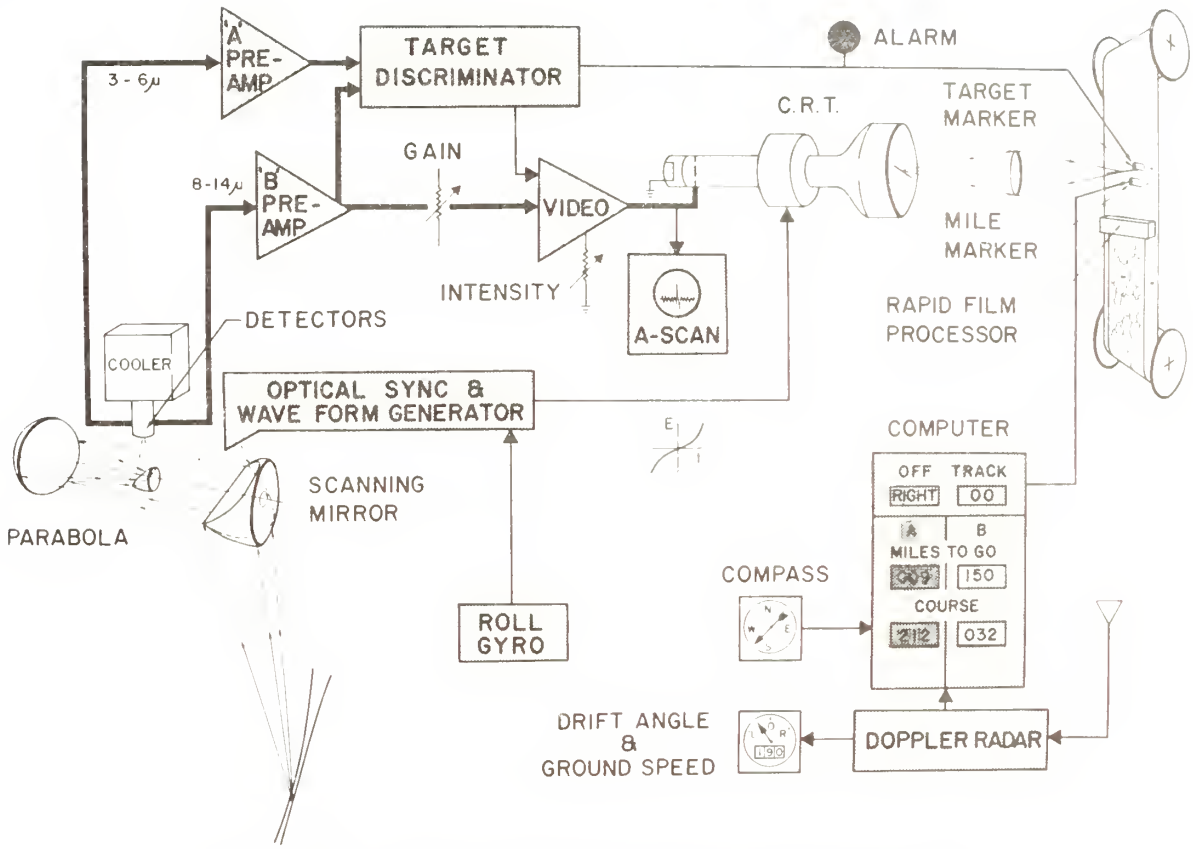


Figure 48. — Schematic of two-color IR fire detection system.

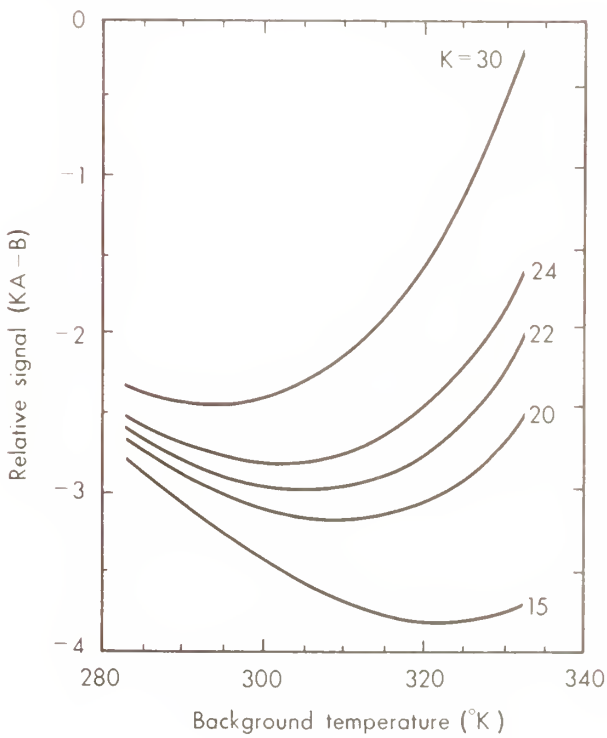


Figure 49. — Computed values of the relative signal (KA-B) as a function of background temperature for various values of K.

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY (Corporate author) USDA Forest Service Intermountain Forest & Range Exp. Station Northern Forest Fire Laboratory, Missoula, Montana	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b GROUP

3 REPORT TITLE

Airborne Infrared Forest Fire Detection System: Final Report

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final Report, April 1962 to December 1967

5 AUTHOR(S) (Last name, first name, initial)

Wilson, Ralph A. Madden, Forrest H.
Hirsch, Stanley N. Losensky, John B.

6 REPORT DATE	7a. TOTAL NO. OF PAGES	7b NO OF REFS
May 1971	99	38

8a CONTRACT OR GRANT NO. OCD-OS-72-174 b. PROJECT NO. ARPA ORDER #636 Work Unit 2521A c. d. ARPA Program Code No. 5860	9a. ORIGINATOR'S REPORT NUMBER(S) Research Paper INT-93, 1971 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10 AVAILABILITY/LIMITATION NOTICES

Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES Study Title: "THE EVALUATION OF AN AIRBORNE INFRARED MAPPER AS A TOOL FOR DETECTING AND MEASURING FIRES."	12 SPONSORING MILITARY ACTIVITY Dep. of the Army, Office of the Secretary Office of Civil Defense Washington, D. C. 20310

13. ABSTRACT

Outlines the basic requirements for an airborne infrared forest fire detection system and discusses the capability of the system to detect hot fire targets in natural forest backgrounds.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
airborne infrared line scanners detection probability target obscuration forest fire spectral response background noise						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2*a*. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2*b*. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7*a*. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7*b*. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8*a*. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8*b*, 8*c*, & 8*d*. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9*a*. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9*b*. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through ________________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through ________________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through ________________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

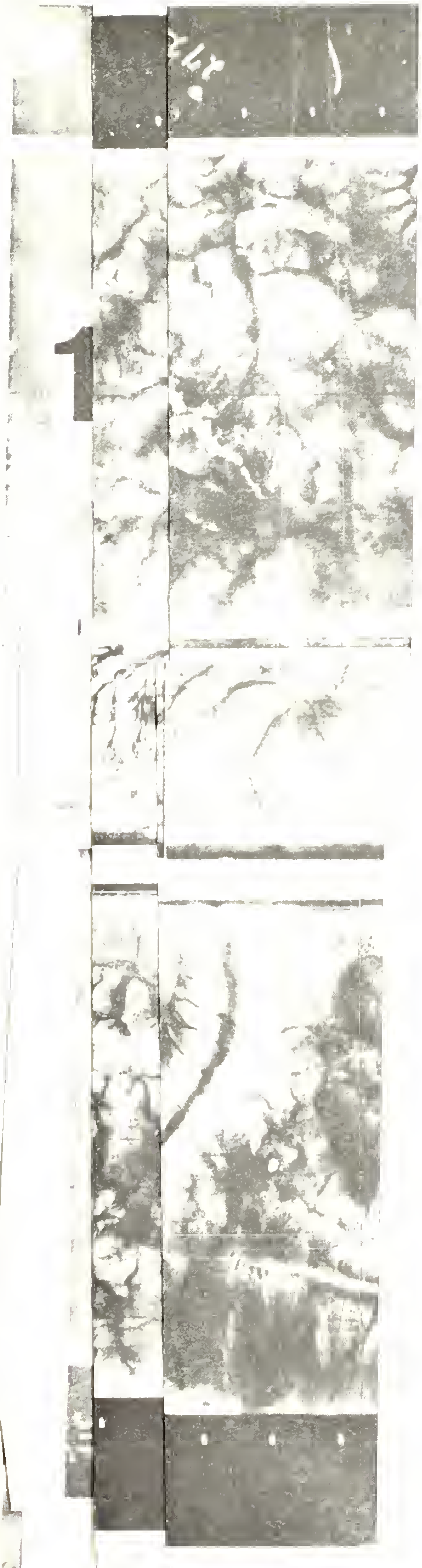
12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS)*, *(S)*, *(C)*, or *(U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.



Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

WOOD · WATER · FORAGE · WILDLIFE · RECREATION
FOREST SERVICE
U S
DEPARTMENT OF AGRICULTURE

USDA Forest Service
Research Paper INT-94
1971

SOIL STABILITY ON HIGH-ELEVATION RANGELAND IN THE INTERMOUNTAIN AREA

Richard O. Meeuwig

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Ogden, Utah 84401

THE AUTHOR

RICHARD O. MEEUWIG, Principal Soil Physicist in the Watershed Protection and Rehabilitation research work unit, joined the staff of the Intermountain Station in 1956. He holds B.S. and M.S. degrees in Forestry from the University of California, Berkeley; and a Ph.D. in Soil Physics from Utah State University. He is stationed at the Renewable Resources Center, University of Nevada, Reno.

USDA Forest Service
Research Paper INT-94
May 1971

SOIL STABILITY ON HIGH-ELEVATION RANGELAND IN THE INTERMOUNTAIN AREA

Richard O. Meeuwig

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U. S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

CONTENTS

ABSTRACT

Measurements were taken of the amount of soil eroded from small plots under the impact of a fixed amount of simulated rain. Under these conditions, erosion is more closely related to amount of cover than to any other site characteristic. However, the relation between erosion and cover is strongly influenced by slope gradient. Regression analyses indicated that erosion is about the same on a 5-percent slope with 40-percent cover as it is on a 35-percent slope with 80-percent cover. Organic matter is the most important soil parameter affecting erodibility, but the direction and magnitude of its effects depend on soil texture. Organic matter decreases erosion of clay soils, but tends to increase erosion of sandy soils.

INTRODUCTION

During the past decade, the author has studied infiltration and erosion potentials of seven diverse summer ranges and has related these to cover, soil, and topographic parameters by means of multiple regression analyses. Acceptable regression equations relating infiltration to site factors were developed for three of the areas (Meeuwig 1969, 1970a), but the regression equations developed for the other four lacked precision and contained anomalous relations.

Satisfactory regression equations relating erosion to site factors were developed for each of the seven areas (Meeuwig 1970b). Unlike the infiltration equations, the general relations defined by these equations did not differ greatly from area to area. In essence, these equations indicate that erosion potential (as measured in these studies) depends chiefly on cover and slope gradient; and that differences in the cover-slope-erosion relations, both within and among study areas, are attributable to variations in soil properties, notably organic matter content and texture of surface soils.

This paper reports the results of combining the data from all seven study areas to determine the general influences of cover, slope, soil texture, and organic matter on soil stability over the range of conditions encompassed by these studies.

STUDY AREAS

All the study areas have herbaceous cover and all are grazed by livestock during the summer, except the Davis County Experimental Watershed from which grazing has been prohibited for more than 30 years. Their locations are shown in figure 1. Areas studied were:

1. — *Great Basin Experimental Range*, Manti-LaSal National Forest, central Utah. Elevations of the 162 study plots varied from 7,000 to 10,000 feet. This sheep range has a wide variety of grass and forb species. Soils are mostly silty clay loams and clay loams derived from limestone, shale, and sandstone.

2. — *Davis County Experimental Watershed*, Wasatch National Forest, northern Utah. Elevations of the 80 study plots varied between 8,000 and 9,000 feet. This area was the source of serious floods during the period 1923 through 1930. Much of it was contour trenched and seeded with grass from 1933 through 1936. Grazing has been prohibited since 1933. Soils are mostly silt loams and loams derived from gneiss, schist, conglomerate, sandstone, and shale.

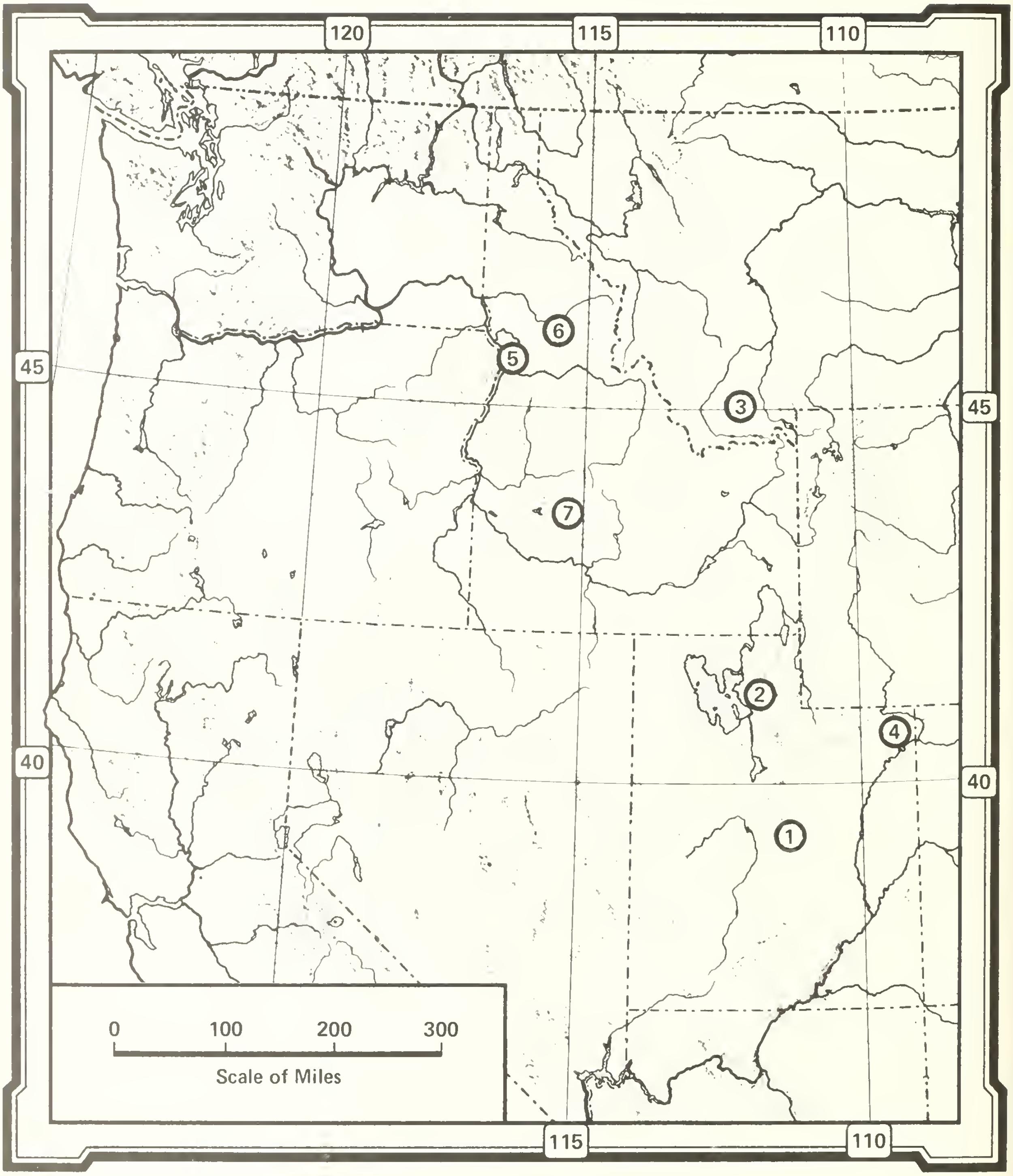


Figure 1. — Locations of study areas.

3. — *Vigilante Experimental Range and Monument Ridge* in the Gravelly Range, Beaverhead National Forest, southwestern Montana. Elevations of the 84 study plots varied between 7,000 and 9,500 feet. This is cattle and sheep range dominated in many parts by Idaho fescue (*Festuca idahoensis*) and in others by native forbs or seeded grasses (mainly *Agropyron desertorum*). Soils are mostly silt loams and silty clay loams derived from red shale, siltstone-shale, and glacial till.

4. — *Diamond Mountain Cattle Allotment* near Flaming Gorge, Ashley National Forest, eastern Utah. This is an experimental grazing area where portions of the native sagebrush-grass vegetation has been replaced by introduced grass species. Soils are loams and sandy loams derived from sandstone. Elevations of the 34 plots were about 8,000 feet.

5. — *The basalt study area* north of Seven Devils, Nezperce National Forest, central Idaho. Forty-five study plots were located in grassy openings in open ponderosa pine stands at about 5,000 feet elevation. Soils are loams and silt loams derived from basalt.

6. — *Coolwater Ridge*, Nezperce National Forest, central Idaho. Elevation of the 15 plots was about 6,000 feet. Vegetation on this deteriorated subalpine range is predominantly forbs of low value insofar as palatability and protection are concerned. The granitic soils are sandy loams and loams.

7. — *Trinity Mountains*, Boise National Forest, southern Idaho. Forty study plots were located in large and small openings in coniferous forest at elevations of about 7,000 feet. The granitic soils, typical of much of the Idaho Batholith, are sandy loams and loamy sands.

MEASUREMENTS

Uniform procedures were followed on all 460 plots involved in this analysis. The plots were 20 inches wide and 30.5 inches long; approximately 1/10 milacre in area. Dortignac's (1951) rain simulator was used to apply 2.5 inches of water to these plots at a constant intensity of 5 inches per hour for 30 minutes. The raindrops produced by this simulator tend to be larger than those of actual thundershowers, but have lower impact velocities. All runoff from the plots was collected and measured. All eroded mineral and organic material, including that deposited in the collecting trough at the bottom of the plot frame and that suspended in the runoff, was ovendried and weighed.

Density of cover on each plot was measured with a point frame (Levy and Madden 1933). First strikes at 100 evenly-spaced points were recorded as plants by species, litter, stone, or bare soil. A day or two after the simulated rain test, vegetation was clipped at the soil surface and litter removed. Vegetation and litter were air-dried and weighed.

The following soil parameters were among those measured:

1. — Antecedent moisture content of the surface 2 inches of soil;
2. — bulk density and capillary porosity of the surface 6 inches of soil;
3. — organic matter content of the surface inch of soil by the dichromate method (Peech 1947);
4. — particle-size distribution (Bouyoucos 1962) and aggregation (Middleton 1930) in the surface inch of soil.

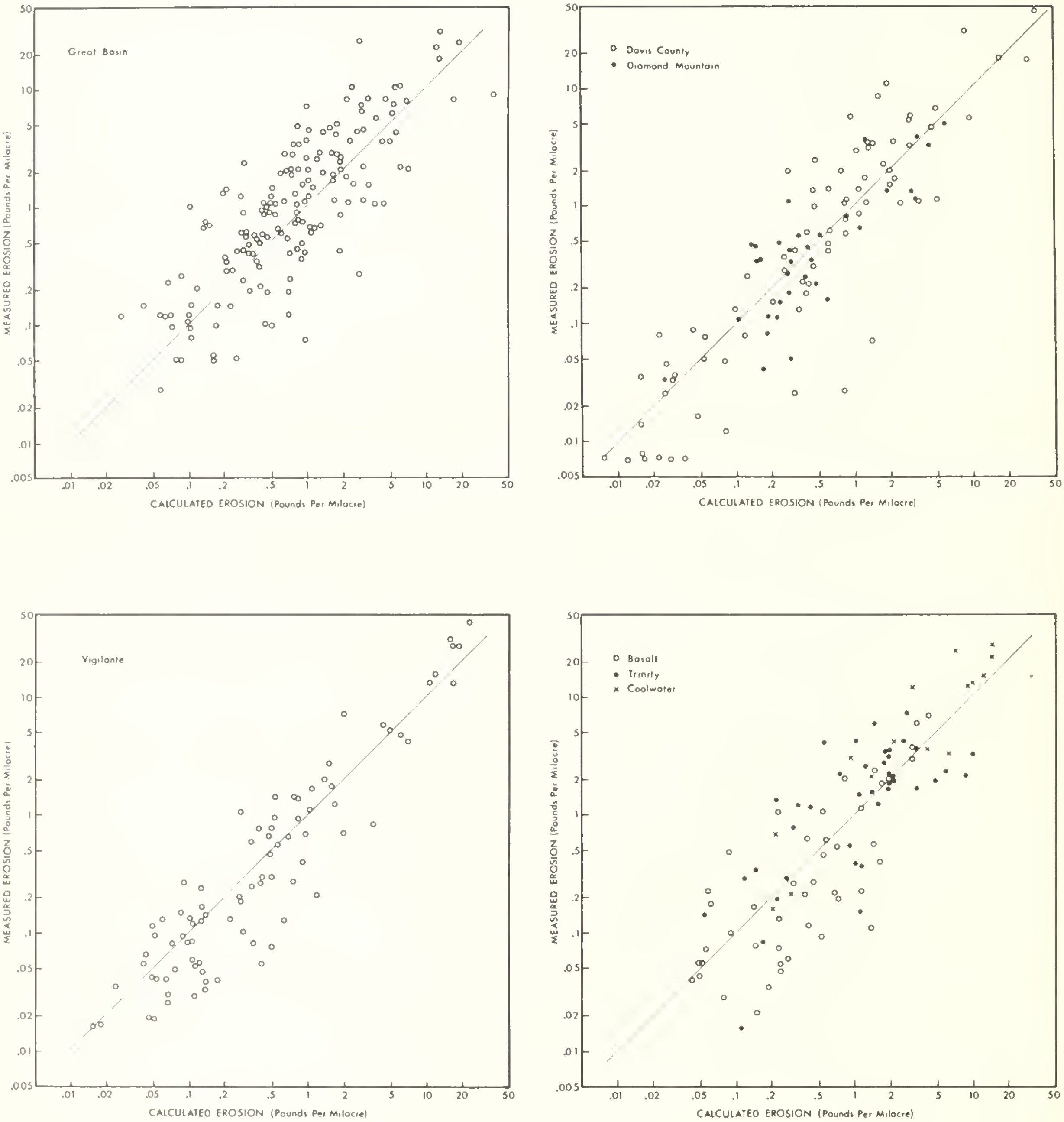


Figure 2. — Calculated and measured erosion of the 460 plots. Study areas are identified to show variation associated with each area.

ANALYSIS

Variables were subjected to preliminary screening during the development of the seven regression equations for the individual study areas. Several site variables that were expected to have a definite influence on erodibility (e.g., aggregation and antecedent soil moisture content) did not appear in any of these equations, and so were not included in the present analysis. Although stone cover materially affected erosion on some of the study areas, it did not prove to be important when the combined data were screened.

Final screening of the combined data was limited to the following parameters, their interactions, and transforms:

A. — Proportion of the soil surface covered by plants and litter, as determined by first strikes of the point analyzer. It is equivalent to the proportion of soil surface protected from direct impact by raindrops.

L. — Air-dry weight of litter in pounds per milacre.

G. — Slope gradient of plot in percent.

C. — Proportion of the surface inch of soil composed of clay.

D. — Proportion of the surface inch of soil composed of sand.

M. — Proportion of the surface inch of soil composed of organic matter.

Variable	Mean	Standard deviation	Correlation with Y
A	0.687	0.247	0.755
L	1.87	2.22	.533
G	18.4	8.5	.291
C	.240	.108	.063
D	.295	.210	.059
M	.075	.038	−.473
Y	−.239	.803	--

The dependent variable Y is the common logarithm of the weight (pounds per milacre) of material eroded from the plots during the 30-minute simulated rainstorm. Its average of −0.239 is equivalent to a geometric mean of 0.577 pound per milacre. The logarithmic transformation was used because the distribution of erosion values was skewed. The transformation resulted in a more nearly normal distribution and more nearly homogeneous variance.

Taking into consideration the curvilinear and interactive nature of the relations among the parameters as observed during preliminary analyses, the following regression model was assumed:

$$\hat{y} = \beta_o + \Sigma\beta_i X_i$$

in which the X_i were: A, A^2, A^3, A^4, A^5, A^6, L, L^2, AL, A^2L, A^3L, G, G^2, AG, A^2G, A^3G, C, C^2, D, D^2, M, M^2, CD, CM, DM, M/C, MD/C, MC^2, M^2C, MD^2, M^2D.

These components were screened in a computerized regression analysis designed to select those that contributed materially to the regression model. The following equation resulted:

$$\begin{aligned}\hat{y} = &-.6935 - 6.456\,A^3 + 17.483\,A^5 \\ &- 12.403\,A^6 - .0582\,A^3L + .0306\,G \\ &- .0217\,A^3G + 8.21C - 10.59C^2 \\ &- 8.45M + .651\,M/C - 1.38CD + 35.48\,M^2D.\end{aligned}$$

The equation explains 74 percent of the variance of the log of erosion. The standard error of estimate (0.42) is difficult to interpret because it is logarithmic. A clearer picture of the deviations from regression is derived when actual erosion and calculated erosion are plotted on logarithmic scales (fig. 2).

This empirical equation should not be applied indiscriminately to specific situations because, after all, it is derived from measurements of erosion caused by a fixed amount of simulated rain on small plots in a few selected areas. In spite of its limitations, this equation provides some indications as to the combined effects of cover, slope, and basic soil properties on soil stability.

COVER AND SLOPE

As found in other studies of a similar nature, erosion on the seven study areas is influenced more by cover than by any other site variable. The magnitude of the effect of cover on erosion depends on slope gradient. The curves in figure 3 are derived from the above regression equation; sand, clay, and organic matter contents of the surface inch of soil are fixed at their respective averages of 30, 24, and 8 percent. Unfortunately, it was necessary to ignore the litter weight term in calculating these curves, but the effects of litter weight will be quantified shortly.

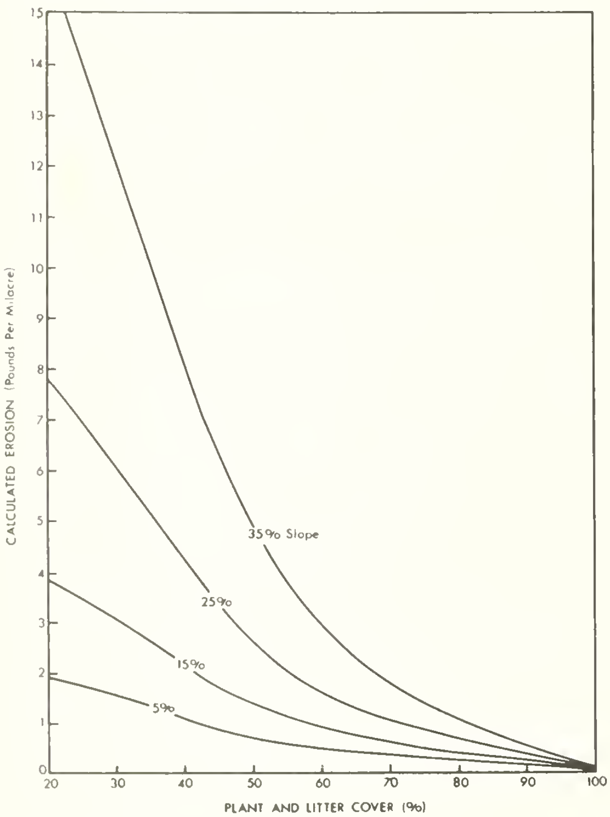


Figure 3. — Erosion calculated as a function of slope gradient and percentage of the soil surface protected by plants and litter. Sand, clay, and organic matter are fixed at their respective averages of 30, 24, and 8 percent.

The effects of cover are greater on steeper slopes. Similarly, slope becomes increasingly important as cover decreases. At less than 50-percent cover, erosion rates double for each 10-percent increase in slope. The amount of cover needed to hold erosion within some specified limit varies widely with variation in slope. For example, 40-percent cover on a 5-percent slope apparently is as effective as 80-percent cover on a 35-percent slope because calculated erosion is about 1 pound per milacre in both cases.

The regression term for litter weight ($-0.058A^3 L$) indicates that weight of litter is not important unless cover is virtually complete (table 1). At 60-percent cover, the presence of 1 pound of litter per milacre reduces estimated erosion to 97 percent of the value shown in figure 3. At 100-percent cover, the same amount of litter reduces erosion to 87 percent. Twelve pounds of litter per milacre with 100-percent coverage reduces estimated erosion to one-fifth that shown in figure 3. Thus, litter weight serves mainly to explain variations in erosion when cover is complete or nearly so. So far as soil stabilization is concerned, however, ground coverage provided by litter is much more important than its weight.

Table 1. — Correction factors for litter weight

Cover (percent)	Air-dry weight of litter — Pounds per milacre				
	1	2	4	8	12
	- - - Correction factors - - -				
60	0.97	0.94			
70	.96	.91	0.83		
80	.94	.87	.76	0.58	
90	.91	.82	.68	.46	0.31
100	.87	.76	.58	.34	.20

SOIL TEXTURE AND ORGANIC MATTER CONTENT

Sand, clay, and organic matter contents of the surface inch of soil were arbitrarily fixed at their average values to calculate the curves in figure 3. Variation within these parameters can cause estimated erosion to vary from less than half to more than twice the values shown in figure 3. Effects on erodibility are produced by these soil components operating together in a complex manner only approximated by the regression model presented in this paper. However, some general trends can be detected (see fig. 4) and are listed below:

1. — If organic matter is low, clay is more erodible than sand.
2. — Erodibility of clay is inversely related to organic matter content.
3. — Erodibility of sand tends to increase with increasing organic matter, especially if the soil contains less than 10-percent clay.
4. — If organic matter content is high, sand can be more erodible than clay.

Of particular interest is figure 4A which shows relative erodibility as a function of organic matter and sand contents at a constant clay content of 10 percent. Erodibility is about half that of average soil if organic matter does not exceed 8 percent or if sand does not exceed 30 percent. When both sand and organic matter exceed these percentages, a further increase in either sand or organic matter results in increased erodibility.

The apparent adverse effects that organic matter has on stability of sandy soils are believed to be real because comparable relations appeared in the three individual regression equations for Diamond Mountain, basalt, and Trinity Mountains study areas. This phenomenon is believed to be linked with water repellence, which has been observed to occur mostly in sandy soils and to be related to organic matter (Krammes and DeBano 1965). Organic coatings profoundly affect the interfacial energy of soil particles. Organic coatings on soil particles reduce the affinity those particles have for water to such a point that positive pressure may be required to force water into the soil (Fink 1970). These coatings may also reduce the forces of attraction between sand particles to such an extent that they repel one another and increase their erodibility.

Clay tends to reduce or eliminate the adverse effects of organic matter on sand. One or more of the following mechanisms may be responsible:

1. — Organic matter is known to favor aggregation of clay. Perhaps the stabilizing effects of organic matter on clay compensate for its deleterious effects on sand.
2. — Clay reduces the amount of organic matter available for binding to sand particles because it has a much greater surface area per unit weight than sand and a greater capacity to bind organic matter.
3. — Clay may form the necessary link for the aggregation of sand particles. Although the organic molecules on adjacent sand particles form no bonds with each other, they may form weak bonds with adjacent clay particles.

The foregoing is, of course, pure speculation but it points out the need for further research into these phenomena and suggests the possibility of the use of soil amendments to stabilize organic sands.

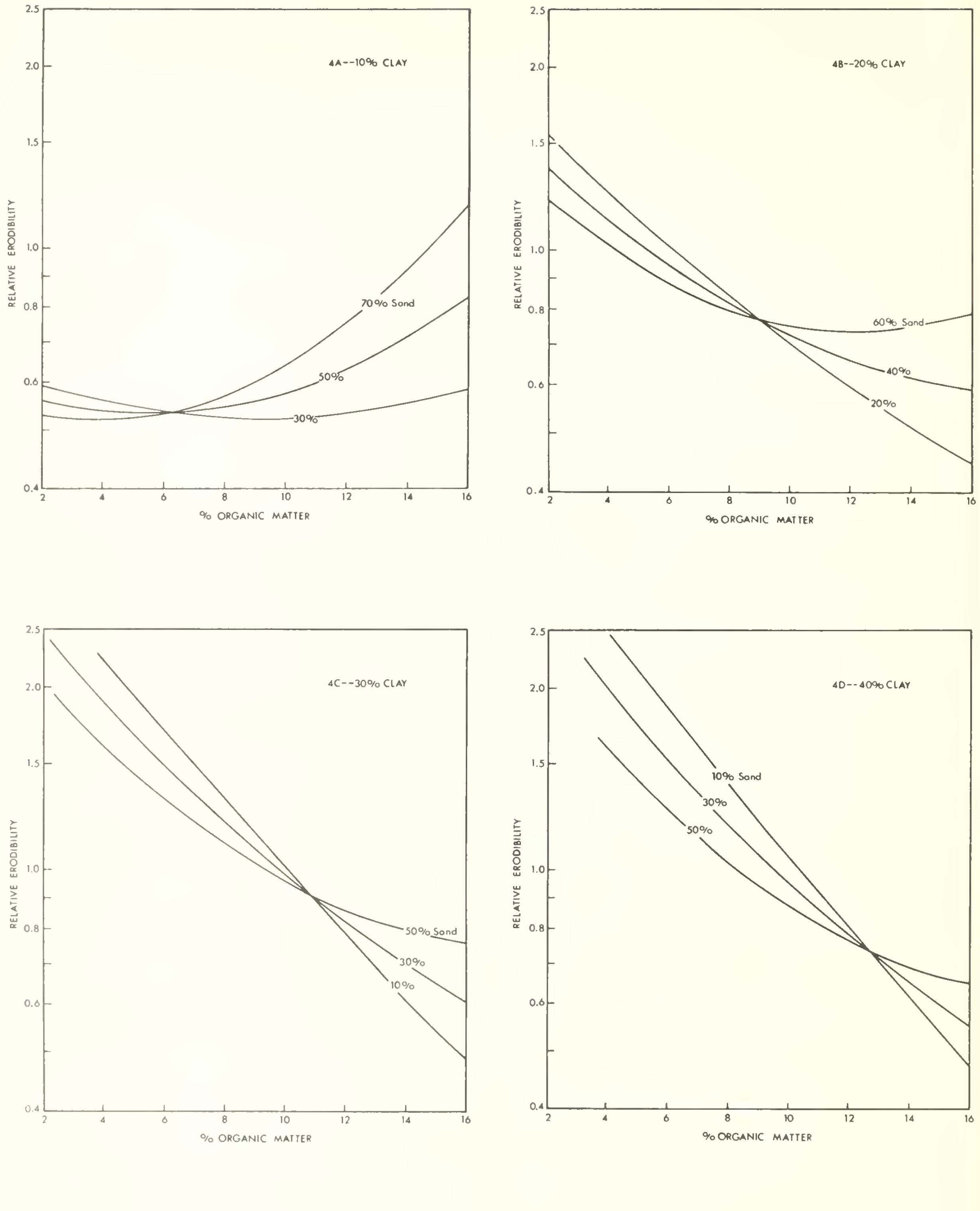


Figure 4. — Relative erodibility as influenced by variations in sand, clay, and organic matter content of the surface inch of soil. Relative erodibility is the ratio of calculated erosion corrected for sand, clay, and organic matter to calculated erosion at average sand, clay, and organic matter.

CONCLUSIONS

Unless plant and litter cover is virtually complete, erosion potential is strongly affected by slope gradient and the amount of cover required to limit potential erosion to some specified amount is substantially greater on steep slopes than on gentle slopes.

Soils vary in their susceptibility to erosion. The most erodible soils are those with high clay, low sand, and low organic matter contents. The combinations that appear to be least erodible are soils that have:

1. — High clay, low sand, and high organic matter contents;
2. — low clay, high sand, and <u>low</u> organic matter contents; or
3. — low clay and low sand contents, regardless of organic matter content.

Apparently, the generalization that organic matter favors soil stability is not universally true. Erodibility may increase with increasing organic matter content in very sandy soils. This poses a difficult problem for management of such soils; sufficient cover must be maintained but at the same time, excessive accumulation of soil organic matter discouraged.

LITERATURE CITED

Bouyoucos, G. J.
1962. Hydrometer method improved for making particle size analyses of soil. Agron. J. 54: 464-465.

Dortignac, E. J.
1951. Design and operation of Rocky Mountain Infiltrometer. U. S. Forest Serv., Rocky Mountain Forest and Range Exp. Sta., Sta. Pap. 5, 68 p.

Fink, D. H.
1970. Water repellency and infiltration resistance of organic-film-coated soils. Soil Sci. Soc. Amer. Proc. 34: 189-194.

Krammes, J. S., and L. F. DeBano
1965. Soil wettability: a neglected factor in watershed management. Water Resources Res. 1: 283-286.

Levy, E. B., and E. A. Madden
1933. The point method of pasture analysis. New Zealand J. Agr. 46: 267-279.

Meeuwig, R. O.
1969. Infiltration and soil erosion on Coolwater Ridge, Idaho. USDA Forest Serv. Res. Note INT-103, 5 p.

____
1970a. Infiltration and soil erosion as influenced by vegetation and soil in northern Utah. J. Range Manage. 23: 185-188.

____
1970b. Sheet erosion on Intermountain summer ranges. USDA Forest Serv. Res. Pap. INT-85, 25 p.

Middleton, H. E.
1930. Properties of soil which influence soil erosion. USDA Tech. Bull. 178.

Peech, M., L. T. Alexander, L. A. Dean, and J. F. Reed
1947. Methods of soil analysis for soil-fertility investigations. USDA Circ. 747, 25 p.

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

CONTOUR TRENCHING EFFECTS ON STREAMFLOW FROM A UTAH WATERSHED

Robert D. Doty

USDA Forest Service Research Paper INT-95, 1971

INTERMOUNTAIN FOREST AND RANGE
EXPERIMENT STATION
Ogden, Utah 84401

COVER PHOTO

Oblique aerial photograph of the Halfway Creek drainage.

USDA Forest Service
Research Paper INT-95
May 1971

CONTOUR TRENCHING EFFECTS ON STREAMFLOW FROM A UTAH WATERSHED

Robert D. Doty

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Joseph F. Pechanec, Director

THE AUTHOR

R. D. DOTY, Associate Research Forester, has been employed by the Intermountain Station since 1964. He holds a B. S. degree in Forestry from the University of Idaho and an M. S. degree in Watershed Management from Utah State University.

ACKNOWLEDGMENT

We of the Intermountain Forest and Range Experiment Station acknowledge with appreciation the valuable assistance of personnel of the Wasatch National Forest and the Intermountain Region headquarters in facilitating the design and supervision of the contour trench construction. This assistance substantially expedited the conduct of this study.

CONTENTS

ABSTRACT

Distribution and volume of streamflow from Halfway and Miller Creeks, two drainages on the Davis County Experimental Watershed, were evaluated. In 1964, about 15 percent of the Halfway Creek drainage was contour trenched. Twelve years of streamflow records before trenching and 4 years of records after trenching were analyzed.

Peak spring flow and peak summer storm flow were reduced after trenching. However, neither annual water yields nor snowmelt runoff in spring and early summer were significantly altered in either volume or distribution over time as a result of trenching. This conclusion is substantiated by supplemental data of precipitation, soil moisture, snowpack water equivalent, and vegetation.

INTRODUCTION

Earlier in this century, the deteriorated condition of numerous high, mountain watersheds in the Western United States resulted in devastating mud-rock flows that flooded valuable lowlands, claimed several lives, and caused considerable property damage (Berwick 1962). These floods followed high-intensity summer rainstorms on the badly denuded areas. Overgrazing and burning of the protective vegetation were considered to be the primary causes of this deterioration (Cannon 1931).

To restore the watersheds, a rehabilitation program was undertaken in the early 1930's (Copeland 1960). Contour trenching, one of numerous practices applied, was so successful that it has become widely accepted (Bailey et al. 1947). By 1969, approximately 30,000 acres had been contour trenched in the States of Utah, Idaho, Nevada, Montana, and Wyoming. Through the years, contour trenches have evolved from small, handmade furrows, 1 or 2 feet deep, to large, bulldozed trenches, 3 or 4 feet deep.

It has been contended that annual streamflow is reduced by trenching. This contention is supported by studies of contour terracing and water-spreading techniques on agricultural land (Branson et al. 1966; Mickelson 1968; Zingg and Hauser 1959).

However, little research has been conducted to determine what effects trenching has on streamflow from high, mountain watersheds. Bailey and Copeland (1960) compared streamflow records from a trenched and an untrenched watershed in Utah. The trenches, which were dug in 1935, were spaced about 25 feet apart. Each had a capacity of 1.5 area inches of water. A gradual decrease of 2.7 inches (23 percent) in average annual streamflow from the trenched watershed developed over a 22-year period. Most of this decrease occurred during the high-flow months, March, April, and May. This decrease in annual flow apparently was due to revegetation, resulting from the stabilizing effect of trenches and the prohibition of grazing by domestic livestock.

Contour trenches in the Western United States are designed to regulate the peak streamflow from the high-intensity summer rainstorm by intercepting overland flow and allowing it to infiltrate into the soil mantle. Total streamflow from these storms represents less than 1 percent of the total annual yields. Therefore, the effect of contour trenching on annual yields would be minimal even if all runoff from these storms were trapped on the mountainside and lost to evapotranspiration. However, contour trenches may have influences that extend beyond control of summer torrents. The effects of trenching on snow catch and areal distribution, on snowmelt and runoff, on soil moisture and vegetation, and on runoff from long-lasting, low-intensity rains are integrated and reflected in annual water yields, in spring snowmelt runoff, and in base streamflow.

Comparisons of the effects of contour furrowing, pitting, and ripping on rangelands from Montana to New Mexico were made by Branson et al. (1966). These treatments added to soil moisture and forage production by increasing infiltration and delaying runoff. These rangelands have a low annual precipitation, most of which occurs during summer rainstorms.

The effect that trenches might have on snowpack accumulation was suggested by Martinelli (1965), who showed that natural barriers contribute significantly to snow accumulation in the alpine zone. I followed this up with two winters' measurements of snow accumulation, distribution, and water content in the contour-trenched area of Halfway Creek (Doty 1970). The effect of trenches on wind movement of snow was to increase snow accumulation slightly, which probably affected revegetation more than water yields.

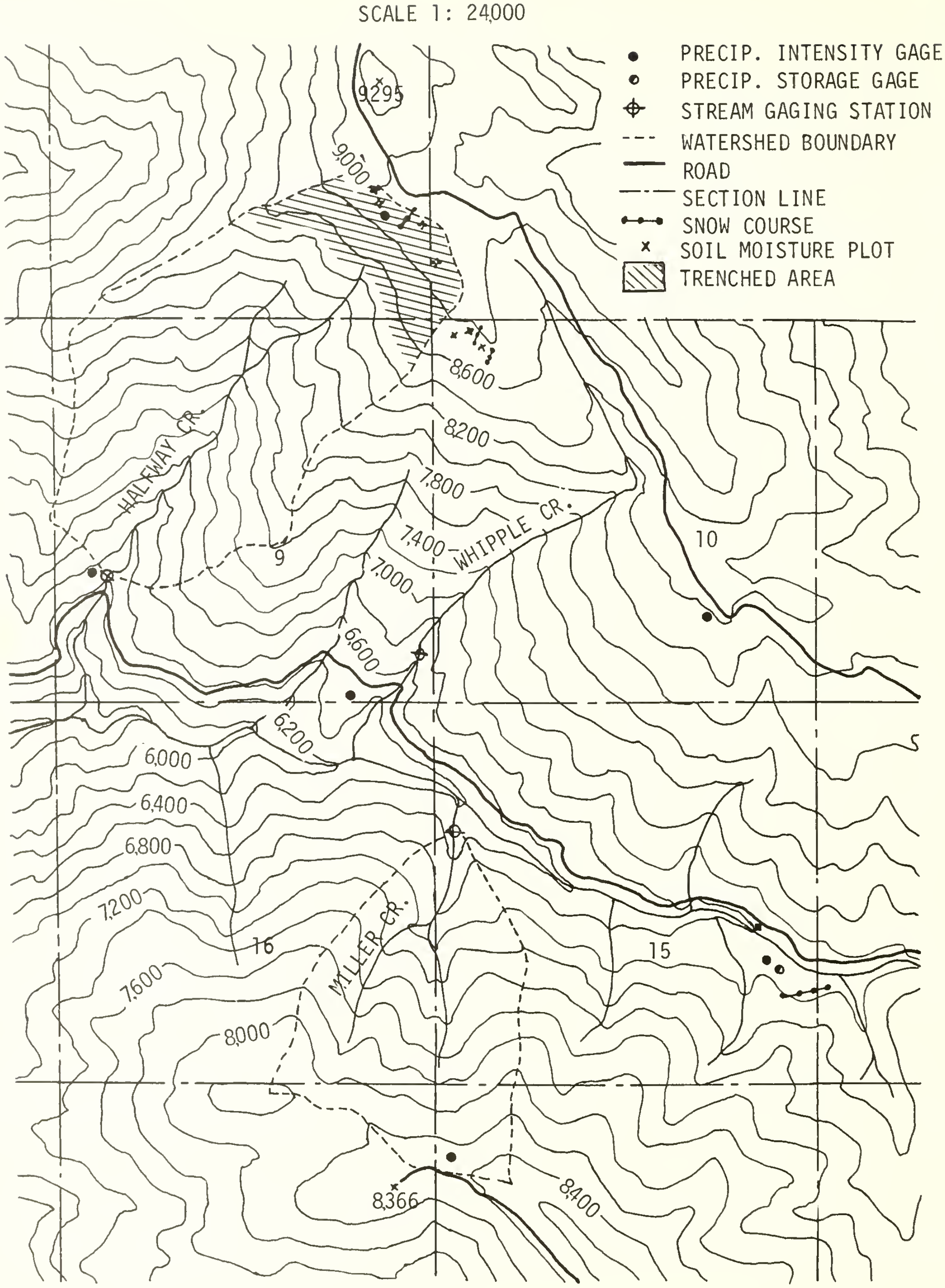


Figure 1.--Topographic map of a portion of the Farmington Canyon watershed showing locations of instruments on the Halfway Creek and Miller Creek drainages.

From this review it becomes apparent that several causal relationships may exist between contour trenching and water yield. A more thorough understanding of trenching effects is necessary to adequately determine what changes, if any, in water yield or water quality occur when a watershed is trenched. The results reported here are the outcome of research conducted on two Utah watersheds, Halfway Creek and Miller Creek. Contour trenching is evaluated in terms of:

(1) Total annual streamflow;

(2) Characteristics of spring streamflow (total and peak volumes and recession); and

(3) Low streamflow (July through February) with respect to total volume of streamflow from these watersheds.

DESCRIPTION OF AREA

The contour trenches used in this study are in Halfway Creek drainage, a tributary of the 10-square-mile Farmington Canyon watershed northeast of Farmington, Utah (fig. 1). Within Farmington Canyon are a couple of snow courses, a network of precipitation gages, and small watersheds which have streamflow records of varying lengths. Of these, Miller Creek drainage was selected as the control. The Halfway Creek drainage produced floods from summer storms in 1926, 1936, and 1947 because of the badly denuded condition of portions of its headwaters area. This drainage and those adjacent to it have been closed to livestock grazing since the late 1930's.

Topography, Geology, and Soils

On this west face of the Wasatch range, the transition is abrupt from the Great Basin valley floor (elevation 4,200 feet) to the peaks of the Wasatch Mountains. Within the 464-acre Halfway Creek drainage, elevation ranges from 6,200 feet at the mouth to 9,000 feet near Francis Peak (9,547 feet). Elevation within the Miller Creek drainage ranges from 6,500 feet to 8,500 feet. The steep stream gradients (approximately 38 percent) for the two drainages are illustrated in figure 2. Halfway Creek's main channel is slightly over 1 mile long, Miller Creek's is approximately two-thirds of a mile long.

A comparison of the Halfway Creek and Miller Creek drainages is given by the dimensionless area-elevation curve (Aronovici 1966) in figure 3. Had the two drainages been similar in configuration, the two curves would have coincided along their entire length. The departure of the curves reflects the greater percentage of Miller Creek drainage at the higher elevations.

Halfway Creek faces southwest and Miller Creek north, and their contrasting aspects contribute to differences in precipitation patterns and vegetation. However, as extremely different as the two watersheds appear to be, their hydrographs react quite similarly as will be shown later in the analysis.

The Halfway Creek drainage has a fine network of tributaries. Many of these are headed by perennial springs that originate along the broad contact zone just below the trenched area. Numerous intermittent stream channels extending into the trenched area are deeply incised. Major channels in the Halfway Creek drainage are V-shaped (10 to 20 feet deep, 40 to 60 feet in width) and usually eroded down to bedrock. Stream channels in Miller Creek do not reflect this degree of cutting, being less than 10 feet deep and 20 feet wide.

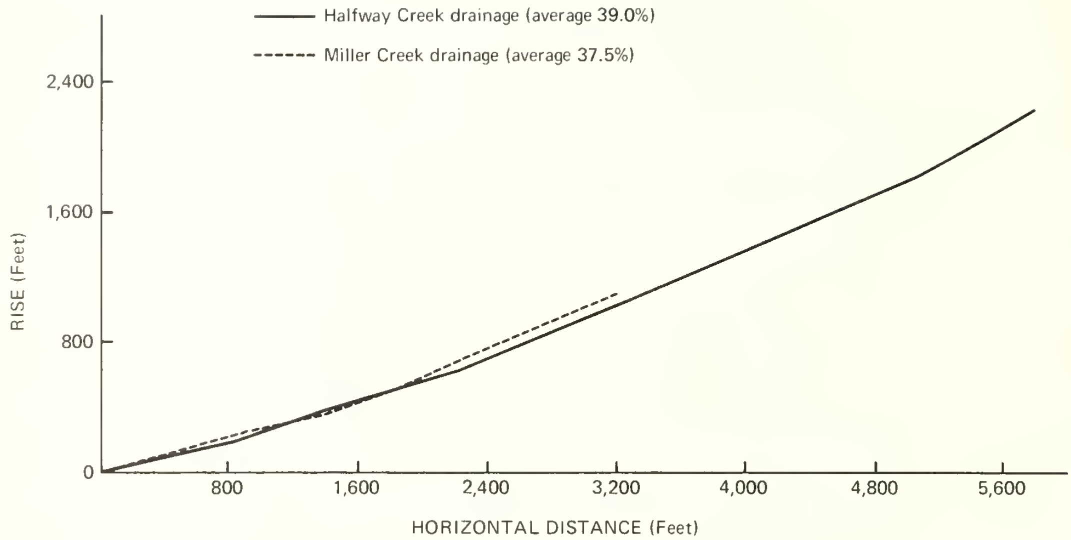


Figure 2.--Stream gradient curves of the Halfway Creek and Miller Creek drainages.

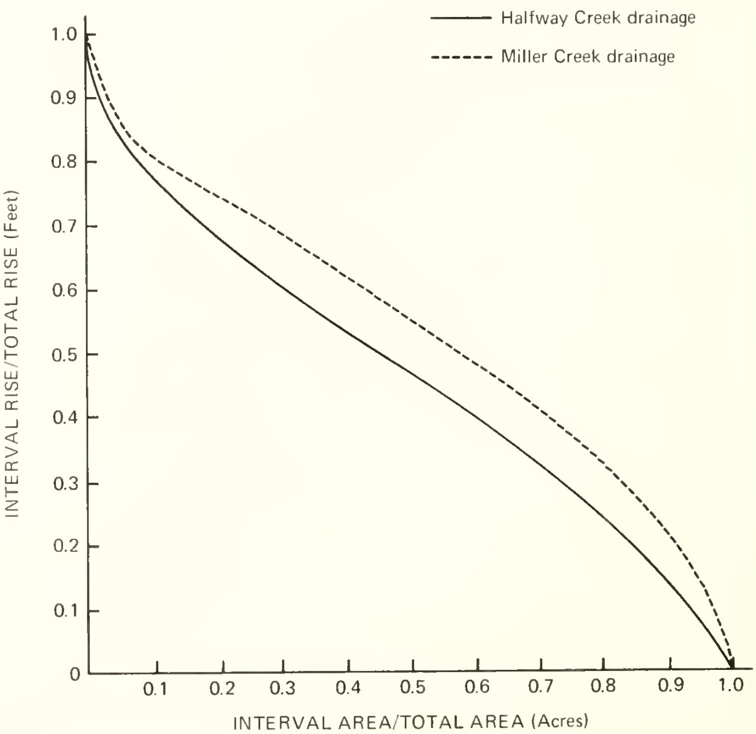


Figure 3.--Dimensionless area--elevation curves for the Halfway Creek and Miller Creek drainages.

Some important geologic features may influence the results of this study. With the use of a detailed geologic map (Bell 1952), a comparison of fault lines with stream locations and strike and dip information with contour lines explains the occurrence of the contact zone in the Halfway Creek drainage. Prevailing winds move considerable snow out of the Halfway Creek drainage. Springs, fed by the large accumulation of snow in the cirque basin immediately to the east and from seepage along the fault zone, return some of this moisture to the Halfway Creek drainage.

Soils are generally coarse textured, immature, rocky, and shallow. Parent material was disintegrated in place by frost action and the resulting surface material in the trenched area is approximately 7 feet thick.

Vegetation

Halfway Creek drainage may be divided into five major vegetation zones (fig. 4). Aspen (*Populus tremuloides*) occupies the wetter sites along stable stream courses just below the contact zone. Adjacent to the aspen, on slightly drier sites, are the ceanothus (*Ceanothus velutinus*) and mixed browse (*Amelanchier utahensis*, *Prunus virginiana*, *Symphoricarpos* sp., *Alnus tenuifolia*) zones. The ceanothus and mixed browse zones form dense thickets of brush with little understory. The two are separated because ceanothus completely dominates sites on which it occurs and forms a much shorter type of cover. Along the upper ridges and drier midslopes, two species of sagebrush (*Artemisia tridentata*, and *Artemisia scopulorum*) predominate. A variety of grasses and forbs form the ground cover.

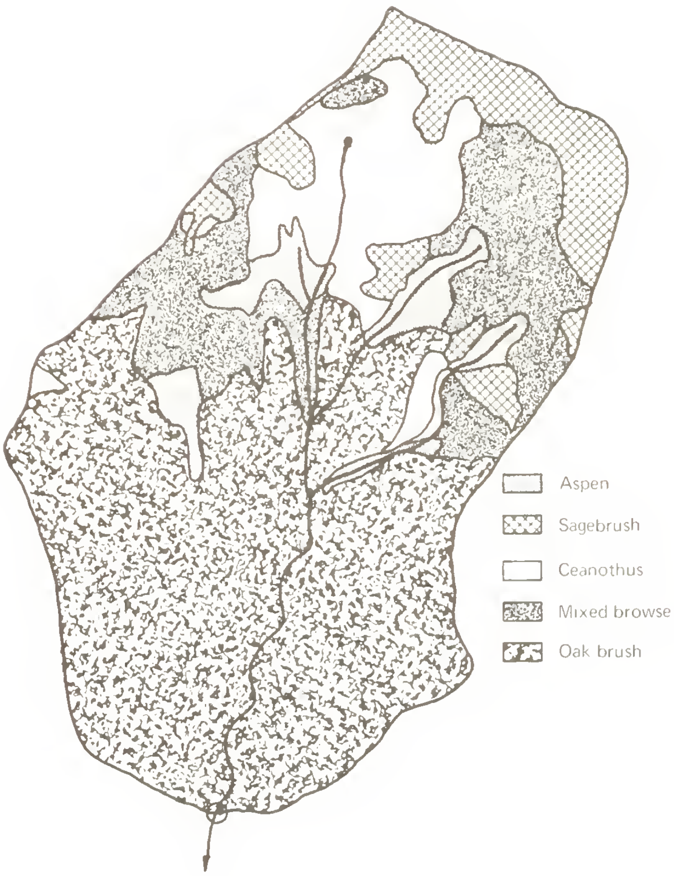
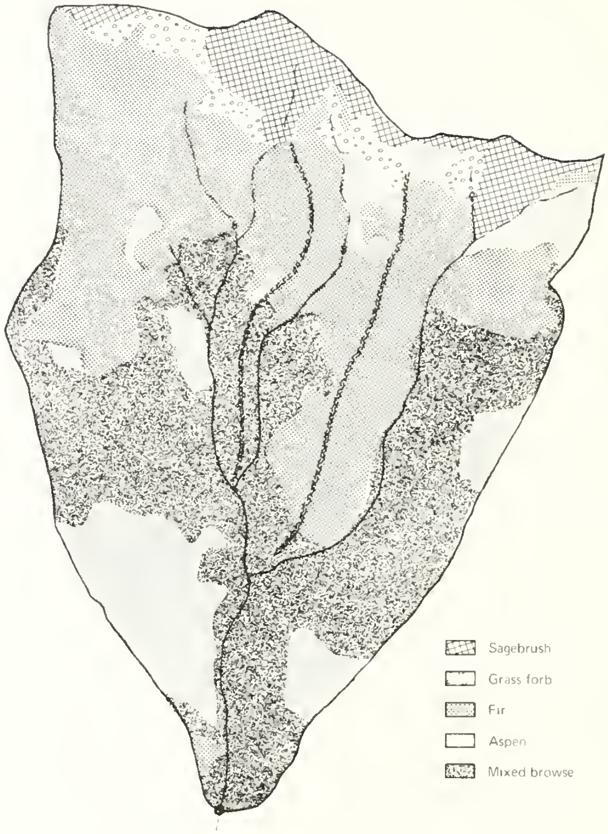


Figure 4.--Halfway Creek drainage showing five major vegetation zones.

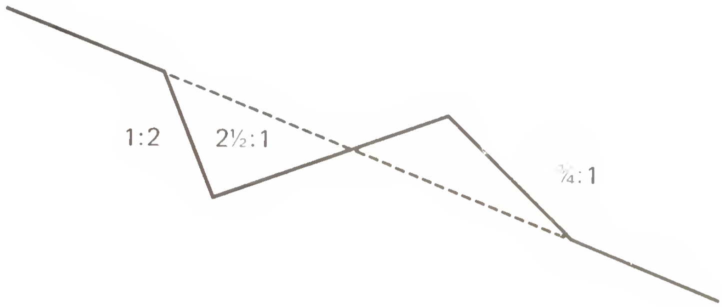
Figure 5.--Miller Creek drainage showing five major vegetation zones.



Because this zone includes the harshest sites and areas of least vegetation, it was the zone trenched for this study. The fifth, or oakbrush (*Quercus gambelii*) zone, occupies more than 50 percent of the drainage. This zone ranges from sparsely vegetated dry slopes where mountain mahogany (*Cercocarpus ledifolius*) also is common to wetter sites, areas covered with dense oakbrush intermixed with maple (*Acer glabrum*).

The Miller Creek drainage tends more toward forest and is generally much more densely vegetated than Halfway Creek drainage (fig. 5). Here, subalpine fir (*Abies lasiocarpa*) occupies much of the upper middle part of the drainage, the ceanothus zone on the Halfway Creek drainage. Fir is interspersed with clones of quaking aspen. Because of the exposure and the wetter site, aspen is also found well down into the bottom of the drainage in the mixed browse zone. Sagebrush grows along the tops of both drainages. An additional zone, the grass-forb, occurs on those areas where snowbanks persist late into the summer.

Figure 6.--Typical contour trench cross-section showing cut and fill grade slopes.



METHOD OF INVESTIGATION

Trench Construction

During the summer of 1964, contour trenches were constructed on the upper 15 percent of the Halfway Creek drainage according to standards outlined in Forest Service Handbook 2569.11 (U.S. Dep. Agr. 1959). These trenches were designed to hold 50 percent of precipitation from a 2-inch storm lasting 1 hour, plus allowing an additional 1.5 feet freeboard.

Because of variations in slope gradient, the slope distance between trenches ranges from 40 to 120 feet. The vertical height from trench bottom to fill crest was maintained at 4.5 feet. The profile is shown in figure 6. This gave approximately 10 cubic feet of storage capacity per linear foot.

When the trenches were completed they were seeded with a mixture of yellow clover (*Melilotus officinalis*), smooth brome (*Bromus inermis*), mountain brome (*Bromus carinatus*), intermediate wheatgrass (*Agropyron intermedium*), and tall oatgrass (*Arrhenatherum elatius*).

Instrumentation

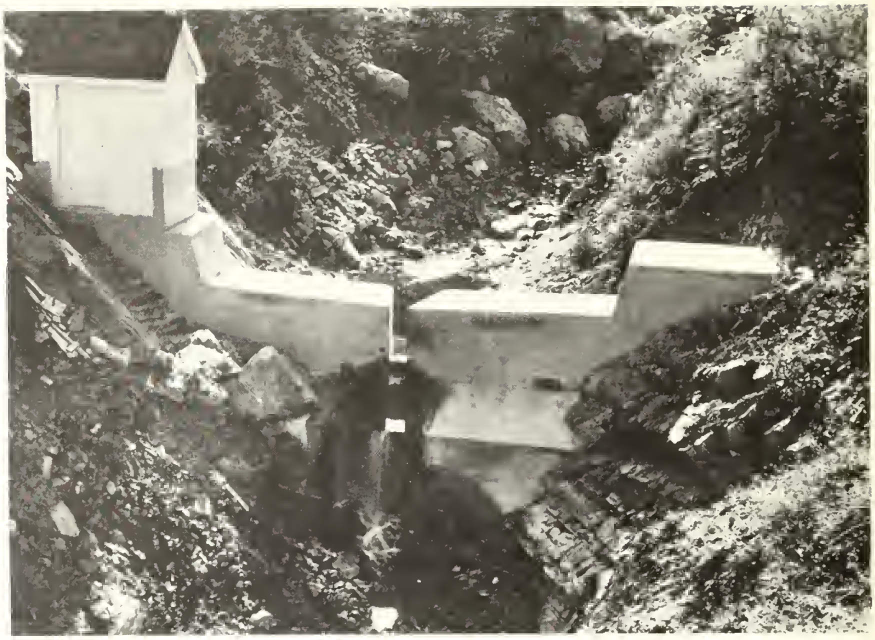
The locations of most instruments used in this study are shown in figure 1.

Modified Venturii-trapezoidal flumes were installed on the Halfway Creek and Miller Creek drainages in the 1930's. The trapezoidal section was built into the bottom of a broad-crested weir (fig. 7).

Except for a brief period following the 1947 flood when operation of the Halfway Creek gage was disrupted, both structures have been maintained and continuous strip chart records of streamflow gathered since their construction.

A network of recording precipitation gages has been maintained and operated during the summer months in the Farmington Canyon area since 1942. A comprehensive report on these data has been published by Farmer and Fletcher (1969). In addition, two precipitation storage gages are maintained on the Farmington Canyon watershed, the Rice Climatic Station gage (since 1940), and the Farmington Guard Station gage (since 1951). Summer precipitation intensity data, air temperature data, and snow course data are also available from Rice Climatic Station. Fifteen years of snow measurements can be obtained from the Farmington Guard Station.

Figure 7.--Modified Venturii-trapezoidal flume in a broad-crested weir section constructed in the late 1930's on the Davis County Experimental Watershed.



In addition to the streamflow and precipitation records, other data have been collected in Farmington Canyon that contributed to the conclusions reached here. Soil moisture measurements have been made on the trenched area and on an adjacent untrenched area since 1965. Vegetation measurements were taken as point samples along permanent transects. Two 100-foot transects were located in the trenched area and two others in an adjacent untrenched area. In addition to the regular snow courses, four snow courses were established in conjunction with the contour trenches in the Halfway Creek drainage. Two of the courses were so located in the trenched area that each course crossed one trench.

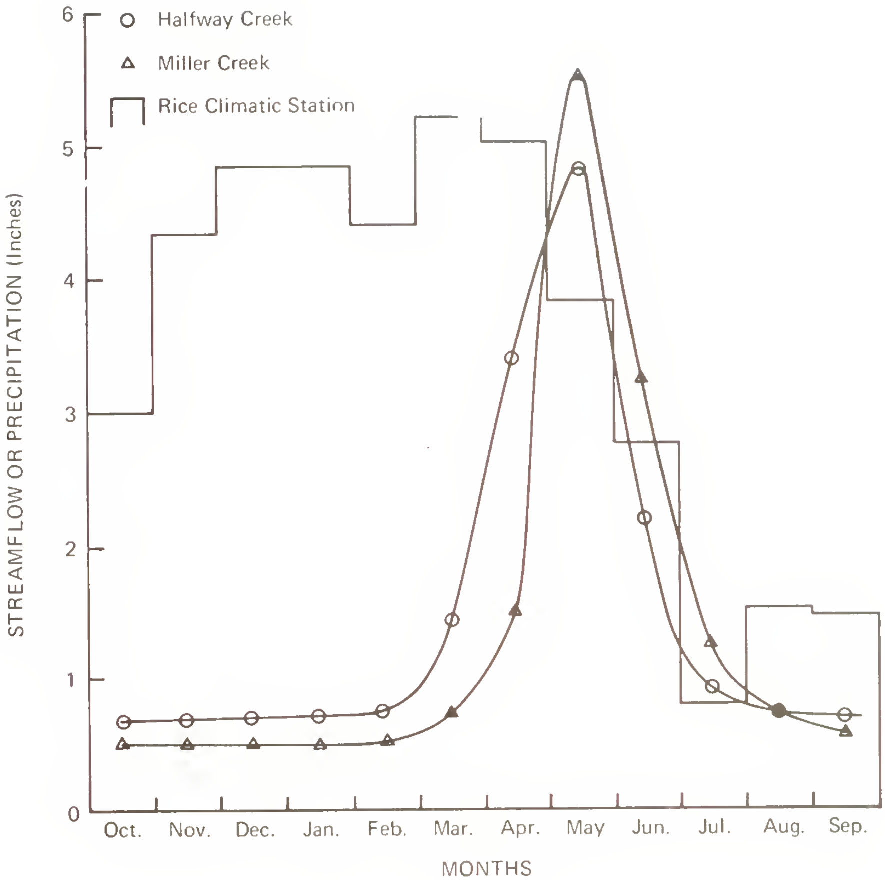
RESULTS AND DISCUSSION

The relationship of three factors, streamflow from the Halfway Creek drainage, streamflow from the Miller Creek drainage, and precipitation at the Rice Climatic Station, was determined from records for the 12 years immediately prior to trenching. Correlations of these factors for different streamflow and precipitation periods were the basis used to evaluate effects of contour trenching.

The general nature of the relationship before trenching of the Halfway Creek streamflow, the Miller Creek streamflow, and the Rice Climatic Station precipitation is shown in figure 8. Precipitation catch at Rice Climatic Station tended to be greater than that on Halfway Creek drainage and less than that on the Miller Creek drainage. The extent of this error was accentuated in wet years, primarily because wet years are the result of more snow. Wind generally carries snow out of the Halfway Creek drainage but into the Miller Creek drainage. The movement of snow from Halfway Creek drainage into adjoining drainages is a significant factor in the actual distribution of precipitation available for streamflow.

Streamflows from Halfway Creek and Miller Creek drainages are closely correlated. Based on monthly streamflow patterns, the primary difference is a shift in the spring streamflow. Miller Creek streamflow is somewhat delayed relative to Halfway Creek because snowmelt begins later on this north exposure.

Figure 8.--The 12-year average monthly streamflow from Halfway Creek and Miller Creek drainages and the monthly precipitation at the Rice Climatic Station (1952-1964).

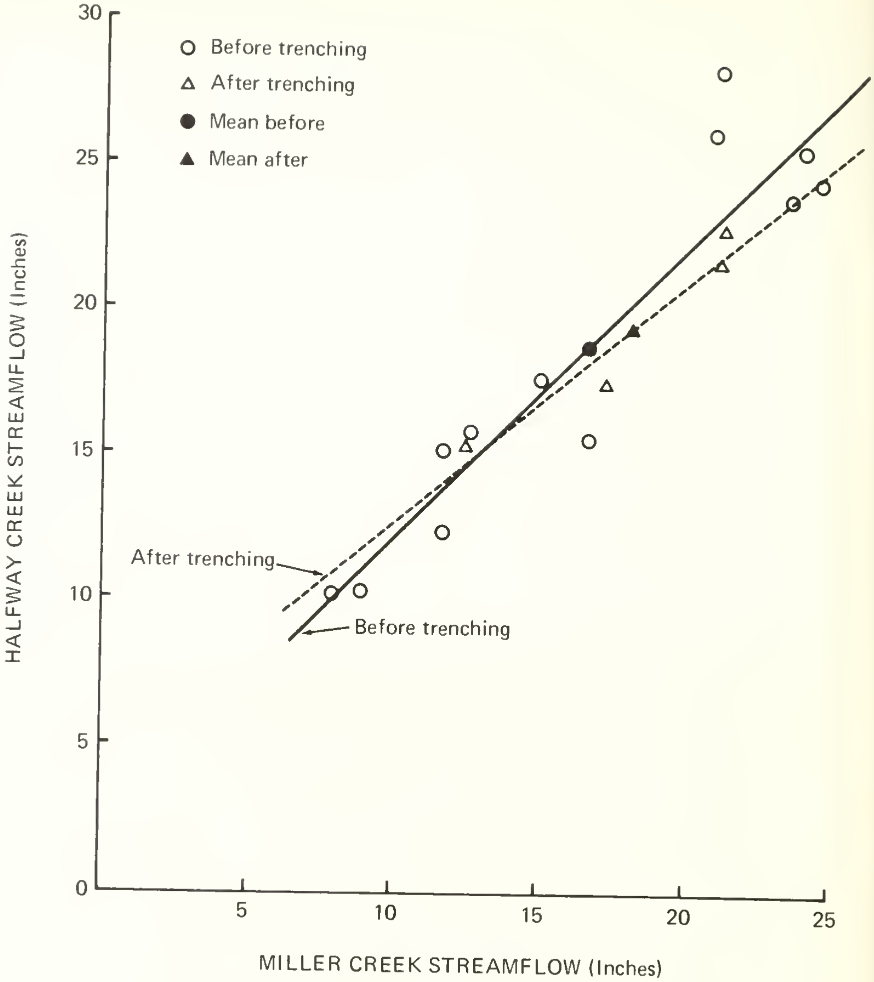


Because of its southwest exposure, the Halfway Creek drainage shows a rapid release of water from the snowpack in the spring. Timing of the peak spring flow fluctuates considerably from year to year, a reflection of the influence of temperature. Table 1 illustrates the relationship between seasonal streamflow from the Halfway Creek and Miller Creek drainages prior to trenching.

Table 1.--*Average streamflow from the Halfway Creek and Miller Creek drainages before trenching*

Streamflow period	Months	Streamflow			
		Halfway Creek		Miller Creek	
		Inches	*Percent*	*Inches*	*Percent*
Low streamflow (July through February)	8	6.25	33.2	5.51	33.1
Spring snowmelt (March through June)	4	12.59	66.8	11.12	66.9
Water year (October through September)	12	18.84	100.0	16.63	100.0

Figure 9.--The regression line comparing annual streamflow from Halfway Creek drainage with that from Miller Creek drainage, 1952-1968.

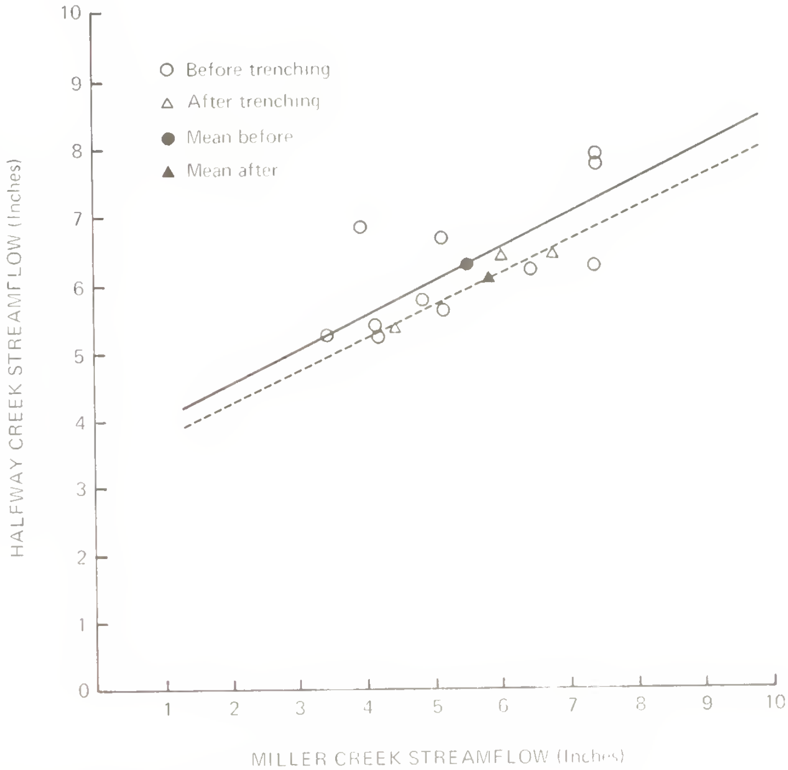


Annual Streamflow

A high degree of correlation (r^2 = 0.878) existed between the water-year (October through September) streamflow from the Halfway Creek drainage and that from the Miller Creek drainage prior to trenching. A covariance analysis compared the regression obtained before trenching with that after trenching. That analysis indicated no significant change in the slope of the regression line after trenching and no significant shift in the data either above or below the original regression line (fig. 9). Years of below average streamflow come closer to conforming to the before-trenching regression line than years of high streamflow. Apparently, years of low streamflow are closely alined by such relatively constant factors as consumptive use and watershed characteristics, whereas years of high streamflow are influenced more by such variable factors as precipitation storm patterns and snowpack distribution prior to runoff (Gartska et al. 1958). A slight reduction observed in streamflow from Halfway Creek in wetter years is indicated by triangles that represent the 4 years since trenching.

Some of the scatter of points in figure 9 are explained by multiple regression analysis that includes Rice Climatic Station precipitation data. With this precipitation included, the r^2 increased to 0.932, but did not alter the previous conclusion that trenching had no significant effect on annual flow.

Figure 10.--The relationship between seasonal low streamflow from the Halfway Creek drainage and that from the Miller Creek drainage, 1952-1968.



Low Streamflow Period

As defined for this analysis, the low streamflow period includes the streamflow for July through February. Streamflow during this period is almost exclusively baseflow, water from deep seepage and interflow. Precipitation occurring during the period contributes little water directly to streamflow. Summer storms are generally light and less than 2 percent of their precipitation results in direct runoff (Croft and Marston 1950). Fall and winter precipitation recharge the soil mantle and build the snowpack, but do not appreciably affect streamflow until snowmelt and spring runoff, March through June. Consequently, the low streamflow period reflects the watershed's drainage characteristics while the influence of concurrent precipitation is negligible (Hall 1968).

Soil moisture data collected at various places on the Davis County Experimental Watershed (Johnston, Tew, and Doty 1969) and the fact that two-thirds of the annual streamflow consistently occurs during the spring flow period indicate that the soil mantle is fully recharged at the beginning of each growing season. Fluctuations in streamflow, particularly on Miller Creek, sometimes occur at the beginning of the low flow period due to delayed snowmelt. For the most part, however, this is a rather stable streamflow period.

The relationship between the low flow of Halfway Creek and that of Miller Creek was determined for the pretreatment years (fig. 10). This resulted in an r^2 of 0.46, a low correlation apparently due to events on Miller Creek that effect streamflow while not effecting streamflow on Halfway Creek. The most probable influence was low temperatures, May through June, that delayed snowmelt longer on the Miller Creek drainage with its northern exposure than on Halfway Creek with its southwest exposure. A covariance analysis comparing before and after trenching data indicated no significant change in either the slope of the regression line nor any shift in position of the line. However, a slight decrease in streamflow after trenching is indicated (table 2).

Table 2.--*Annual streamflow during July through February from Halfway and Miller Creeks after trenching*

Year	Halfway Creek Y	Miller Creek	Halfway Predicted (Ŷ)	Halfway Difference (Y-Ŷ)
	Inches	*Inches*	- - - *Inches*	- - - -
1965-66	6.39	6.29	6.59	-.20
1966-67	5.31	4.43	5.78	-.47
1967-68	6.35	6.86	6.83	-.48

As already noted, precipitation during the low flow period has little influence on streamflow. Correlations between Halfway Creek streamflow and Rice Climatic Station precipitation, as well as between Miller Creek streamflow and Rice Climatic Station precipitation, verified this lack of relationship. Since the trenches have been completed, summer precipitation amounts have varied from near-record lows to extreme highs, yet streamflow yields do not reflect such extremes.

Spring Streamflow Period

Spring streamflow (March through June) is extremely variable and represents the net effect of many variables (Croft 1944). Total streamflow from Halfway during this period has ranged from a low of 4.78 inches to a high of 19.61 inches in 1964 just before trenching. The extremely variable streamflow from the Halfway Creek drainage is matched by that from the Miller Creek drainage. When streamflows from the two were compared, 88 percent of the variation in Halfway Creek was explained by Miller Creek streamflow (fig. 11). The lack of change in streamflow after trenching was confirmed by a covariance analysis that compared before and after trenching results. This analysis showed no significant change in either the slope nor the position of the regression line.

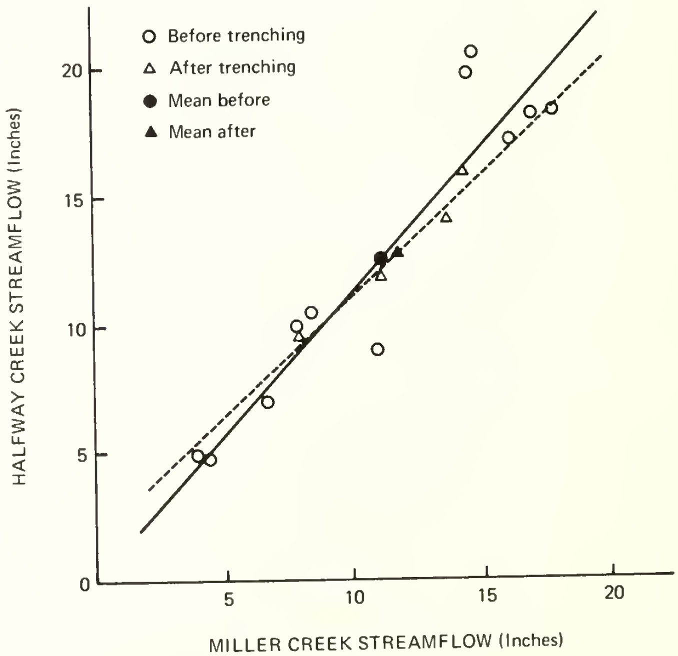
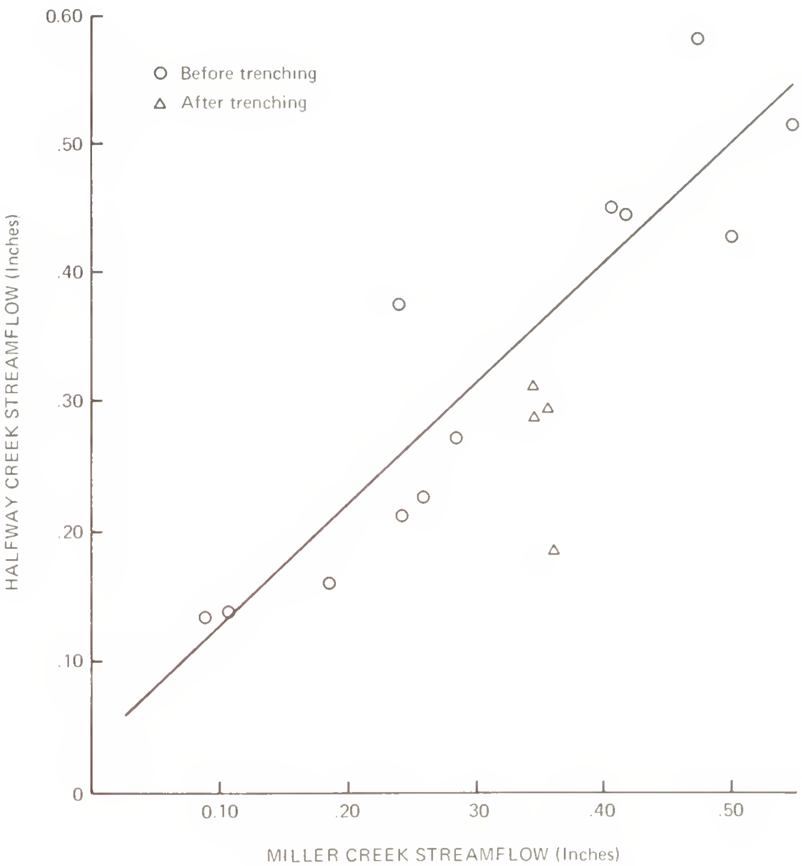


Figure 11.--The relationship between the snowmelt period streamflow from the Halfway Creek drainage and that from the Miller Creek drainage, 1952-1968.

Figure 12.--The relationship between the spring peak streamflow from the Halfway Creek drainage and that from the Miller Creek drainage, 1952-1968.



Although, for this period, no apparent change in streamflow resulted from trenching, it is possible that redistribution of the streamflow did occur. Peak streamflow during the period reflects the most change.

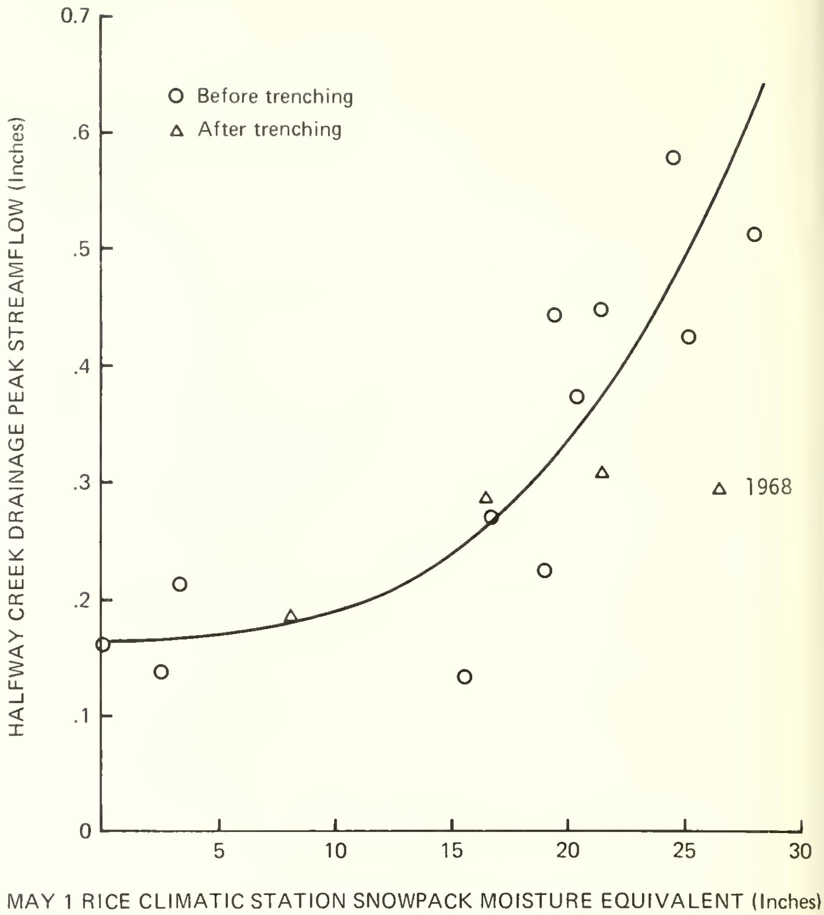
Based on daily streamflow measurements, a comparison was made of the highest single day of streamflow from Halfway Creek each year and the highest single day of streamflow from Miller Creek each year. Thus compared, the 2 days of each year do not necessarily coincide, but do reflect the peak of snowmelt-generated streamflow each year. An analysis of the 12 years of records prior to trenching resulted in 86 percent of the variance of Halfway Creek streamflow being explained by Miller Creek streamflow (fig. 12). After trenching, all peaks were lower than predicted by the regression line.

A comparison of peak flows and snowpack water content indicated that after trenching the peak flows closely followed the regression they followed before trenching; only a slight reduction was noted (fig. 13). For the year 1968, the peak flow, compared to snowpack conditions, was less than expected on both drainages.

Less obvious changes in peak streamflow since trenching include less fluctuation in the peak height and a shift of the peak to a later date. Of interest, too, is the fact that peak flow each year on Miller Creek usually occurs within a week of May 21; on Halfway Creek, it can take place any time between March 24 and May 27 (mean, April 24), nearly a month ahead of the peak Miller Creek flow.

Peak streamflow cannot be influenced without showing some change in the subsequent recession. Recession streamflow is characteristic of a particular watershed and more or less independent of current precipitation. Consequently, a change in the recession

Figure 13.--The annual peak daily streamflow from the Halfway Creek drainage plotted against the May 1 Rice Climatic Station snowpack moisture equivalent, 1952-1968.



flow should be a good indicator of any alteration of watershed characteristics due to trenching. A rapid recession in Halfway Creek streamflow follows the peak. After 60 days, the recession curve flattens to a slight downward gradient until sometime in August or September.

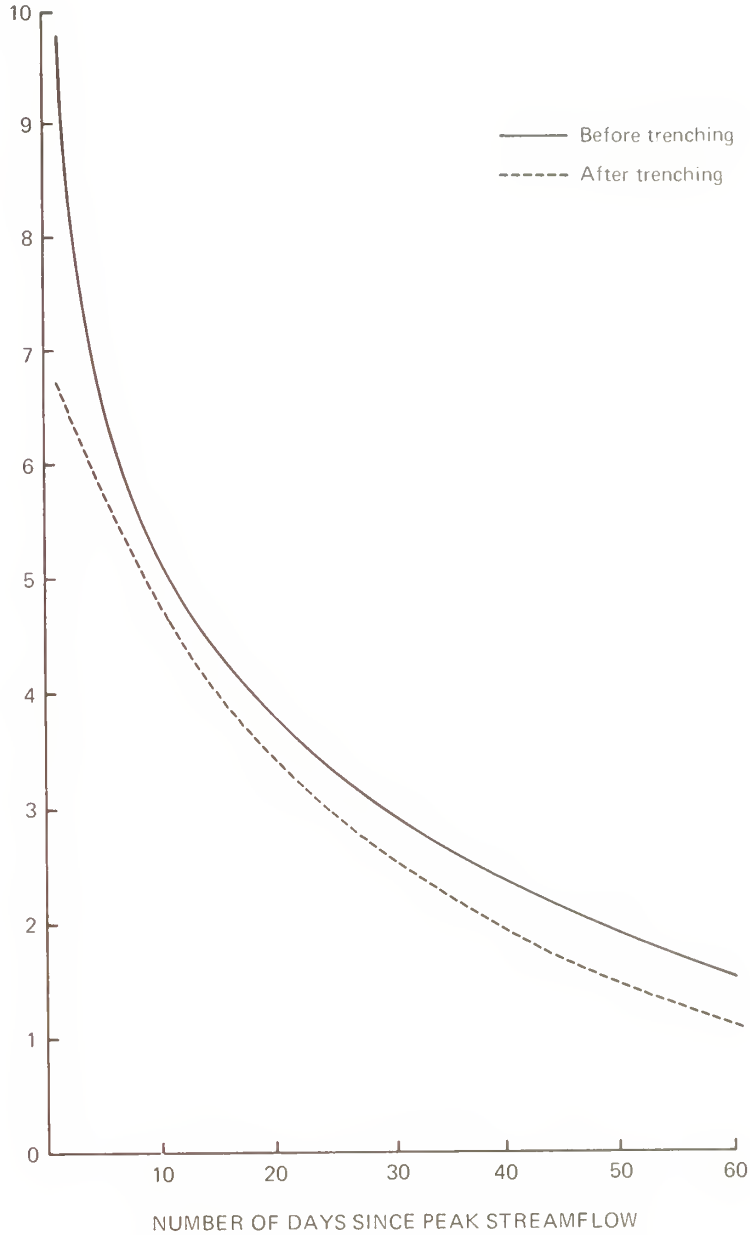
Evaluation of the recession flow was made by plotting daily flows for the 60-day period following the peak. The average of the 12 years prior to trenching was plotted as was the 4-year average after trenching and smooth curves were drawn through these data (fig. 14). A greatly reduced peak and a flattened recession curve followed trenching. Also, a general, but slight, reduction in the flow is shown.

Summer Storms

Runoff from summer storms does not represent a significant portion of the total annual runoff. However, since control of such storms is the primary reason for trenching, a limited analysis of their relationship to trenching was made.

More than 100 storms were studied to determine total surface runoff, time of that runoff, peak flow, and storm patterns. No two storms were alike and, more important, no storm affected the two watersheds in the same manner. However, a few conclusions can be drawn from the precipitation-runoff relationships studied so far. It was noted that less than 2 percent of the precipitation in a storm generally left the watershed as overland flow or was intercepted by the stream channel. Most of the storms analyzed produced less than a half-inch of precipitation each; only a small percentage produced more than an inch.

Figure 14.--The recession streamflow from the Halfway Creek drainage based on daily flow periods before and after trenching.



Hydrographs of two storms are illustrated (figs. 15 and 16) to show the relation between precipitation and runoff from summer storms on the Halfway Creek and Whipple Creek drainages. Figure 15 is the hydrograph of a storm that produced a total of 1.3 inches of precipitation, but had a maximum 5-minute intensity of 6.0 inches. Peak runoff exceeded 18 c.s.m. from Halfway Creek within an hour. Whipple Creek peaked an hour later at 11 c.s.m. The initial smaller peak on Whipple Creek is the result of a rainburst lower on the watershed. This also occurred on Halfway Creek and appeared on that portion of the hydrograph not shown. Figure 16 illustrates a storm 1 year after trenching. This storm produced 1.6 inches of precipitation, but had a maximum 5-minute intensity of 2.5 inches. Halfway Creek peaked at 6.7 c.s.m. Whipple Creek peaked at 7.5 c.s.m. an hour later. In comparison to pretrench conditions, the peak on Halfway Creek was greatly reduced. Also, the flow was distributed over a longer period of time, whereas the untrenched Whipple's flow period was about the same as before. How many of these differences can be attributed to trenching and how many to storm patterns is difficult to say.

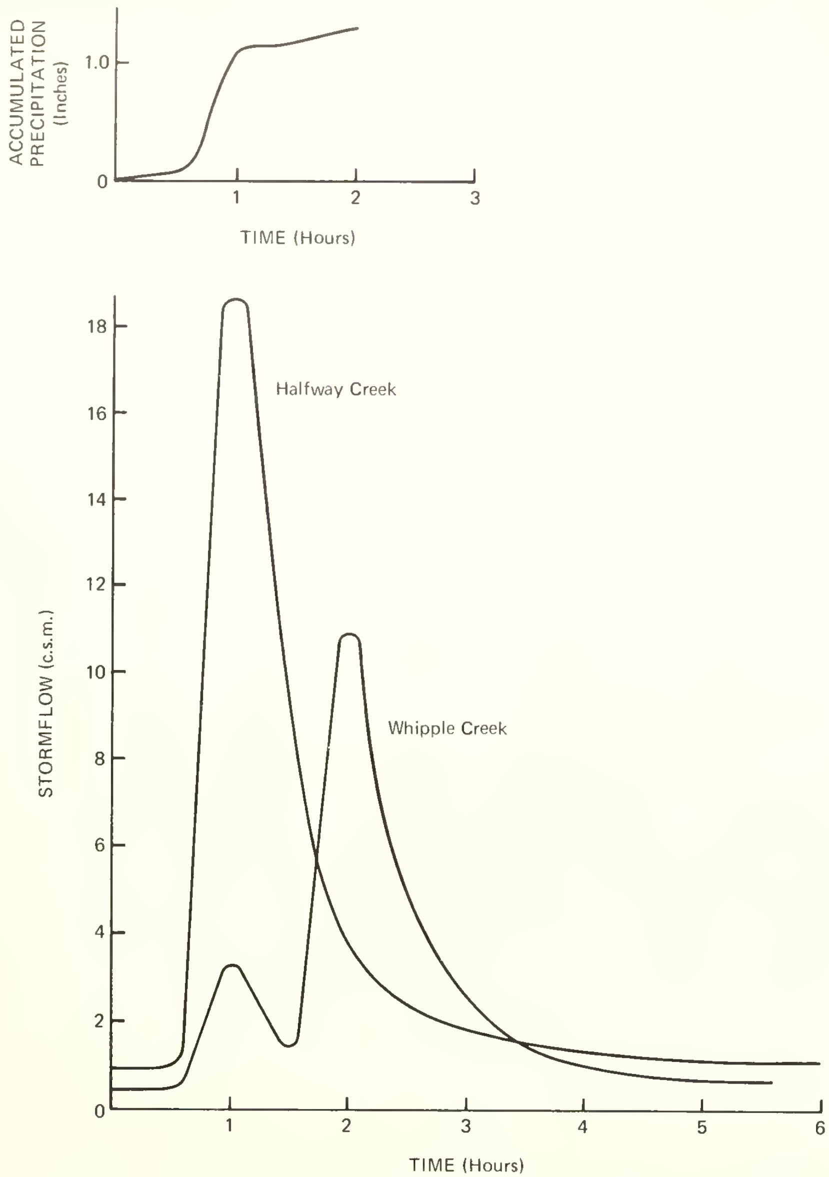


Figure 15.--A hydrograph representing a storm on the Halfway Creek and Whipple Creek drainages before trenching.

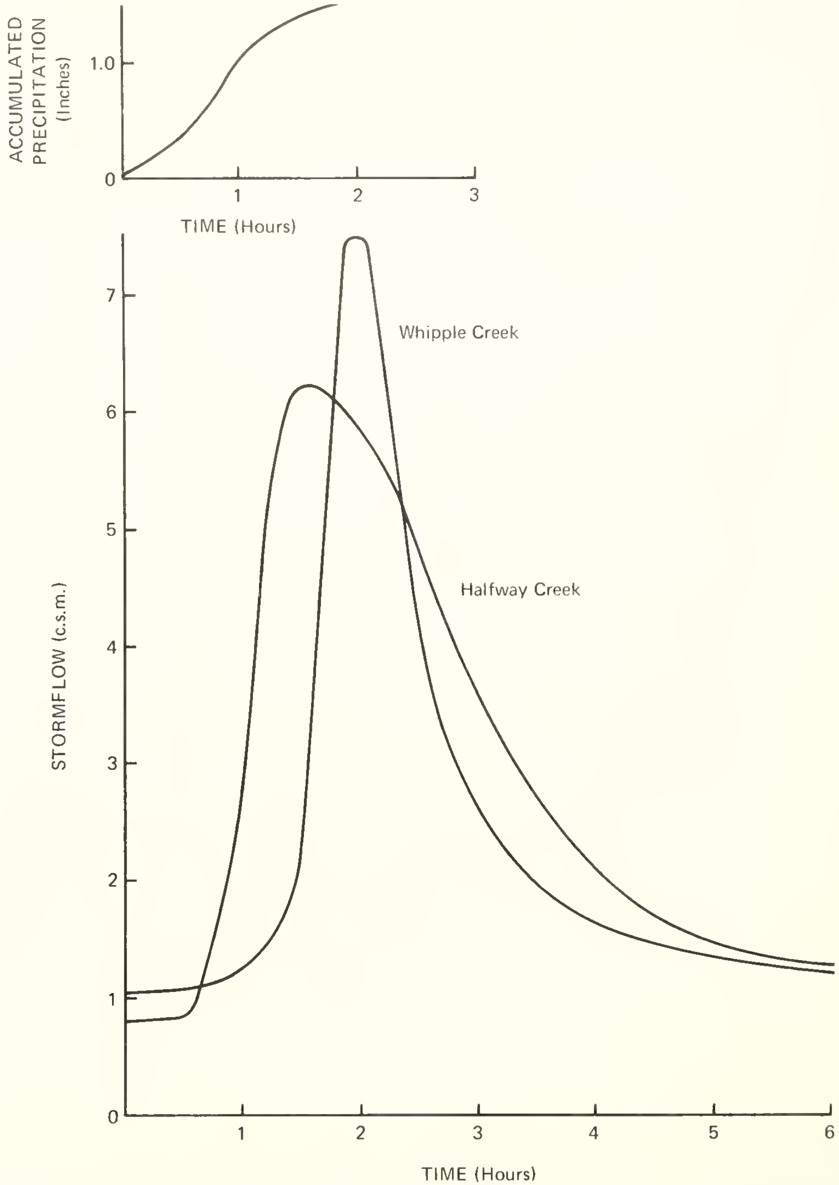


Figure 16.--A hydrograph representing a storm on the Halfway Creek and Whipple Creek drainages after trenching.

CONCLUSIONS

The streamflow and precipitation data analyzed from Halfway and Miller Creek watersheds show no statistically significant change in streamflow patterns as a result of contour trenching. This conclusion is based on 4 years of records after trenching and 12 years of records before trenching. The slight decrease in streamflow since trenching is perhaps due to chance variation in the data or to a slight increase in consumptive use due to a delay in streamflow from the trenched area. The possibility that any change is due to trenching is further reduced by supplemental data that show no appreciable change in the distribution of moisture available as potential streamflow. Snow distribution remains approximately the same, except for some on-site redistribution (Doty 1970). The consumptive use of soil moisture by vegetation has not shown appreciable change to date, although a trend similar to that reported by Bailey and Copeland (1960) may be developing.

The streamflow characteristics of the two drainages before and after trenching are summarized in table 3.

After an examination of streamflow regimen and watershed characteristics, such as soil type and vegetation, it is concluded that contour trenching has not significantly affected streamflow patterns of the Halfway Creek drainage.

Table 3.--*Summary of Halfway Creek and Miller Creek streamflow*

a. AVERAGE STREAMFLOW BEFORE TRENCHING

Streamflow period	Months	Halfway Cr. streamflow		Miller Cr. streamflow	
		Inches	*Percent*	*Inches*	*Percent*
July thru February	8	6.25	33.2	5.51	33.1
March thru June	4	12.59	66.8	11.12	66.9
Water year	12	18.84	100.0	16.63	100.0

b. ANNUAL STREAMFLOW SINCE TRENCHING

Year	Streamflow from Halfway Cr.	Streamflow from Miller Cr.	Predicted* Streamflow Halfway Cr.	Difference (actual-predicted)
	- - - - - - -	- - - - - - - *Inches*	- - - - - - -	- - - - - - -
1964-65	21.58	21.35	22.04	-0.46
1965-66	15.29	12.45	15.06	+ .23
1966-67	17.30	17.27	21.47	-4.17
1967-68	22.91	21.31	23.23	- .32

*Prediction based on regression: $\hat{Y} = -8.876 + 0.506\ X_i + 0.487\ X_{ii}$
Where: $\hat{Y}$ = Halfway Creek streamflow, X_i = Miller Creek streamflow, and X_{ii} = Rice Climatic Station precipitation.

c. SNOWMELT STREAMFLOW SINCE TRENCHING

Year	Streamflow from Halfway Cr.	Streamflow from Miller Cr.	Predicted* Streamflow Halfway Cr.	Difference (actual-predicted)
	- - - - - - -	- - - - - - - *Inches*	- - - - - - -	- - - - - - -
1965	14.05	13.78	15.52	-1.47
1966	9.42	7.88	9.02	+ .40
1967	11.77	11.24	12.72	- .95
1968	15.80	14.44	16.25	- .45

*Prediction based on regression: $\hat{Y} = 0.325 + 1.103\ X$
Where: $\hat{Y}$ = Halfway Creek streamflow, X = Miller Creek streamflow.

d. LOW STREAMFLOW PERIOD SINCE TRENCHING

Year	Streamflow from Halfway Cr.	Streamflow from Miller Cr.	Predicted* Streamflow Halfway Cr.	Difference (actual-predicted)
	- - - - - - -	- - - - - - - *Inches*	- - - - - - -	- - - - - - -
1965-66	6.39	6.29	6.59	-0.20
1966-67	5.31	4.43	5.78	- .47
1967-68	6.35	6.86	6.83	- .48

*Prediction based on regression: $\hat{Y} = 3.87 + 0.432\ X$
Where: $\hat{Y}$ = Halfway Creek streamflow, X = Miller Creek streamflow.

LITERATURE CITED

Aronovici, V. S.
1966. The area-elevation ratio curve as a parameter in watershed analysis. J. Soil and Water Conserv. 21:226-228.

Bailey, R. W., and O. L. Copeland
1960. Low flow discharge and plant cover relations on two mountain watersheds in Utah. I.A.S.H. Comm. of Surface Waters 51:267-278.

________, G. W. Craddock, and A. R. Croft
1947. Watershed management for summer flood control in Utah. U.S. Dep. Agr. Misc. Pub. 630, 24 p.

Bell, G. L.
1952. Geology of the northern Farmington Mountain, 38-51, in: Marsell, R. E., (ed.), Guidebook to the Geology of Utah, No. 8, Utah Geological Society, Salt Lake City, Utah.

Berwick, V. K.
1962. Floods in Utah, magnitude and frequency. U.S. Geol. Surv. Circ. 457, 24 p.

Branson, F. A., R. F. Miller, and I. S. McQueen
1966. Contour furrowing, pitting, and ripping on rangelands of the Western United States. J. Range Manage. 19:182-190.

Cannon, S. Q., (Chmn.)
1931. Torrential floods in northern Utah. Report of special flood commission. Utah Agr. Exp. Sta. Circ. 92, 51 p.

Copeland, O. L.
1960. Watershed restoration, a photo-record of conservation practices applied in the Wasatch Mountains of Utah. J. Soil and Water Conserv. 15:105-120.

Croft, A. R.
1944. Some recharge-and-discharge-phenomena of north-and-south-facing watershed-lands in the Wasatch mountains. Trans. Amer. Geophys. Union 25:881-889.

________, and R. B. Marston
1950. Summer rainfall characteristics in northern Utah. Trans. Amer. Geophys. Union 31:83-93.

Doty, R. D.
1970. Influence of contour trenching on snow accumulation. J. Soil and Water Conserv. 25(3):102-104.

Farmer, E. E., and J. E. Fletcher
1969. Precipitation characteristics of summer storms at high-altitude stations in Utah. (Abstr.) Trans. Amer. Geophys. Union (EOS) 50(11):615.

Gartska, W. U., L. D. Love, B. C. Goodell, and F. A. Bertle
1958. Factors affecting snowmelt and streamflow (at the Fraser Experimental Forest, Colorado). U.S. Bur. Reclam. and U.S. Forest Serv., 189 p.

Hall, F. R.
1968. Base-flow recessions--a review. Water Resources Res. 4:973-983.

Johnston, R. S., R. K. Tew, and R. D. Doty
1969. Soil moisture depletion and estimated evapotranspiration on Utah watersheds. USDA Forest Serv. Res. Pap. INT-67, 13 p.

Martinelli, M., Jr.
1965. Accumulation of snow in alpine areas of central Colorado and means of influencing it. J. Glaciol. 5(41): 625-636.

Mickelson, R. H.
1968. Conservation bench terraces in eastern Colorado. Trans. Amer. Soc. Agr. Eng. 11:389-392.

U.S. Department of Agriculture
1959. Land treatment measures handbook, FSH 2509.11, Forest Serv. Handb., 124 p.

Zingg, A. W., and V. L. Hauser
1959. Terrace benching to save potential runoff for semi-arid land. Agronomy J. 51:289-292.

AFLC/HAFB, Ogden

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Headquarters for Research Work Units are also at:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)

8