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THINNING WESTERN LARCH

by

ARTHUR L. ROE and WYMAN C. SCHMIDT

DIVISION OF FOREST DISEASE AND
TIMBER MANAGEMENT RESEARCH

INTERMOUNTAIN FOREST & RANGE EXPERIMENT STATION
FOREST SERVICE
U. S. DEPARTMENT OF AGRICULTURE
OGDEN, UTAH

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INTRODUCTION

Overstocking threatens production on more than 1 million acres of western larch (Larix occidentalis Nutt.) in the northern Rocky Mountains. Dense stands have developed on favorable seedbeds found on many large burns and cutover areas in this region. The great number of stems in many of these stands precludes optimum growth and development of individual trees because growth is being distributed over too many stems per acre. These trees are likely to remain overcrowded for long periods if stands are unmanaged. Trees in such stands will not reach commercially desirable size within a reasonable time. The obvious solution to the overstocking problem is thinning.

Few western larch stands have been thinned, and little information has been published on thinnings in larch. Forest managers are now guided principally by information developed in other forest types. This paper reports results of two western larch thinning studies located on the Lolo National Forest in western Montana. Briefly, the results show that diameter, basal area, height, and cubic-foot volume growth can be improved by thinning. Concentrating growth on fewer trees per acre will produce larger trees earlier.

DESCRIPTION OF STUDIES

West Fork Plots [1]

Five plots were established in the West Fork of Petty Creek on the Lolo National Forest, at an elevation of about 4,200 feet. Slopes on plot locations range from 25 to 55 percent, and exposures are principally north to northeast. The average site index of the area, determined by using Cummings' site classification curves,[2] is 52 feet at 50 years, or site class III.

The stand originated following a burn and consists principally of western larch trees, with lesser numbers of lodgepole pine and Douglas-fir. Ponderosa pine, Engelmann spruce, grand fir, and subalpine fir are minor constituents only. The stand was about 50 years old when the study was established in 1949. Two crop-tree thinning treatments were applied on four randomly selected $\frac{1}{2}$-acre plots; the fifth plot was left unthinned as a check. Crop trees were chosen on all the plots at the rate of about 150 per acre, spaced roughly 15 feet apart. Preference was given to western larch, ponderosa pine, Douglas-fir, and lodgepole pine, and in that order. As far as possible, only dominant and codominant trees of good form and fair to good vigor were left. The treatments were:

1. On plots 1 and 2, the "D+4" rule of thumb was applied to individual crop trees. All trees were cut around each crop tree for a radial distance in feet equal to the diameter of the tree in inches plus 4.

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[1] Robert A. Smart, former District Ranger, Lolo National Forest, furnished valuable cooperation in this study; and Kenneth Boe, formerly with the Intermountain Forest and Range Experiment Station, prepared the study plan and installed the plots.

[2] Cummings, L. J. Larch--Douglas-fir board-foot yield tables. U.S. Forest Service, Northern Rocky Mountain Forest and Range Expt. Sta. Applied Forestry Note 78, 3 pp., illus. 1937.

2. On plots 3 and 4, trees were cut for a radius of 3 to 6 feet from the crown edge on at least three sides of each crop tree.

3. Plot 5 was left unthinned, but crop trees were marked for later comparison.

Trees were removed in October 1949 by cutting, axe girdling, and poisoning. Those smaller than 5 inches d.b.h. were cut with axes; those 5 inches and larger were girdled on plots 2 and 4, and poisoned on plots 1 and 3.

All larch and ponderosa pine crop trees were pruned with pole saws to a height of about 18 feet to include one log length.

Pattee Canyon Plots[3]

These three plots were located in Pattee Canyon east of Missoula, Montana, on the Lolo National Forest, at an elevation of about 4,600 feet. They were situated on a 15- to 20-percent north-facing slope. The average site index of the area, determined by using Cummings' site classification curves, is 44 feet at 50 years, or site class IV. This stand also originated following a burn and consists of nearly pure larch. Douglas-fir and ponderosa pine comprise less than 5 percent of the total number of trees. The stand was about 30 years old when the treated plot was thinned in 1932.

1. Plot 1, one-fourth acre in size, was thinned from below by removing all of the suppressed and part of the intermediate trees from the stand (grade B, low thinning). This left 876 of the original 2,468 trees per acre, at a spacing of approximately 7 by 7 feet.

2. Plots 2 and 3, one-twentieth and one-fiftieth acre, respectively, were laid out and trees were measured in 1949, because no control plots were established in 1932 when plot 1 was thinned. The locations of these plots in the stand had been considered in 1932, but no measurements were taken then. Growth for the previous 17 years was determined from increment borings in green trees and by recording dead trees in the stand. The numbers and diameters of trees on these unthinned plots in 1932 were calculated from the mortality, growth, and bark data obtained in 1949. We believe that a reasonably reliable estimate of the 1932 stand resulted.

Analysis

Thinning in the West Fork study was aimed at favoring individual trees. Therefore, the analysis was based upon records of individual crop trees. Multiple regression analysis was used to adjust for individual tree growth responses by treatments represented on the plots.

Analysis of the Pattee Canyon plots was based upon data from all trees because it was a uniform thinning.

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[3] The original thinning plot was established by Millard C. Evenson in 1932, while he was a student at the Forestry School, Montana State University, and two small control plots were established in 1949.

RESULTS

Results of thinnings in the moderately overstocked West Fork stand and the heavily overstocked Pattee Canyon stand are presented in tables 1 and 2. These two studies provide 10-year results of "crop-tree" thinning (West Fork) and 27-year results of uniform thinning (Pattee Canyon). Plot means on West Fork do not readily show relative growth responses because of initial inequalities in average d.b.h. However, individual tree analysis shows significant differences that are masked in the stand means. Growth response to thinning is obvious in the Pattee Canyon plots and is proportionate to the degree of stocking (table 2).

Table 1.--Total per-acre stocking in West Fork before thinning in 1949 and crop-tree stocking per acre after thinnings in 1949 and 1959

Treatment and plot number		Before thinning (all trees)			After thinning (crop trees only)									
		Mean d.b.h.	Trees	Basal area	Mean d.b.h. 1949	Mean d.b.h. 1959	Mean total height 1949	Mean total height 1959	Trees 1949	Trees 1959	Basal area 1949	Basal area 1959	Volume[1] 1949	Volume[1] 1959
		Inches	Number	Sq. ft.	- - Inches - -		- - - Feet - - -		- - Number - -		- - Sq. ft. - -		- - Cu. ft. - -	
D+4	(1)	3.4	1,586	103	5.3	7.0	44	55	198	188	34	50	610	1,077
D+4	(2)	3.8	1,386	111	5.6	6.7	50	60	188	176	33	43	664	963
Crown	(3)	3.9	1,410	118	5.8	6.8	48	59	168	168	32	42	656	945
Crown	(4)	3.2	1,886	106	5.7	7.0	47	56	174	172	34	46	665	1,026
Unthinned	(5)	3.9	1,668	135	6.0	7.1	52	62	164	164	36	45	753	1,069

[1] Cubic-foot volume on crop trees 2.4 inches d.b.h. and larger, peeled volume, including stump, stem, and top.

Table 2.--Total per-acre stocking in Pattee Canyon before thinning in 1932 and after thinning in 1932 and 1960

Treatment and plot number	Before thinning (all trees)				After thinning (all trees)									
	Mean d.b.h.	Trees	Basal area	Volume[1]	Mean d.b.h. 1932	Mean d.b.h. 1960	Mean total height 1949[2]	Mean total height 1960	Trees 1932	Trees 1960	Basal area 1932	Basal area 1960	Volume[1] 1932	Volume[1] 1960
	Inches	Number	Sq.ft.	Cu.ft.	- - Inches - -		- - Feet - -		- - Number - -		- - Sq. ft. - -		- - Cu. ft. - -	
Thinned (1)	([3])	2,468	([3])	878	3.3	5.1	42	50	876	824	57	132	660	2,666
Unthinned (2)	2.1	3,020	95	971	2.1	3.8	37	42	3,020	1,660	95	153	971	2,596
Unthinned (3)	1.4	7,500	102	742	1.4	2.6	31	37	7,500	3,050	102	140	742	1,894

[1] Includes all trees 0.6 inch d.b.h. and over, peeled volume, including stump, stem, and top.
[2] The unthinned plots were not measured until 1949.
[3] Data not available.

Diameter Growth

Diameter growth of individual trees in the West Fork plots increased promptly and significantly following thinning. Average diameter growth of trees on all four thinned plots either equalled or exceeded growth of trees on the unthinned plot (see table 3). Analysis of the individual trees shows that when trees of equal initial diameter are compared, the growth per tree was better on the thinned plots than on the unthinned. A multiple regression analysis relating basal area and diameter before thinning to 10-year growth after thinning, shows that growth response of individual trees is related to the basal area stocking of the plots prior to thinning (fig. 1). For example, 6-inch trees ranged from 0.64-inch d.b.h. growth per decade on the unthinned plot to a high of 1.06 inches for the same period on the heavily thinned plot (plot 1). Therefore, in this individual tree class, the trees in the heavily thinned plot showed a 65-percent greater d.b.h. growth than those on the check plot.

Table 3.--Ten-year growth per acre, crop trees only (West Fork)

Treatment and plot number		D.b.h.	Height	Basal area	Volume
		Inches	Feet	Sq. ft.	Cu. ft.
D+4	(1)	1.6	10.9	16.0	467
D+4	(2)	1.1	9.6	10.0	298
Crown	(3)	1.0	10.3	9.5	289
Crown	(4)	1.4	8.6	12.5	361
Unthinned	(5)	1.0	10.1	8.9	316

The individual tree relationship is not evident in the means because of the widely differing range and distribution of crop-tree initial diameters. The varied length of the curves in figure 1 shows the range of initial diameters. The broad range of crop-tree diameters on the unthinned plot (plot 5) results in a larger mean than the means of any of the thinned plots. The low means for plots 2 and 3 are the result of rather restricted distribution (short curves) shown for these two plots.

Diameter growth can be visualized in another way by considering the change in the range of plot means. For example, in 1949 the largest mean diameter (plot 5, unthinned) was 13 percent greater than the smallest (plot 1, D+4). In 1959, at the end of the 10-year growth period, the largest mean diameter (plot 5, unthinned) was only 6 percent greater than the smallest (now plot 2, D+4). Thus, the range of plot means had been narrowed from 13 to 6 percent. The difference between means of plots 1 and 5 was reduced from 13 percent in 1949 to 1 percent in 1959. Thus, the initial difference between the means of these two plots had virtually disappeared. The mean crop-tree diameter of the thinned plots will soon surpass the mean diameter for the unthinned plots if the present growth rates continue.

Diameter growth of trees in the thinned plots in Pattee Canyon increased much more obviously because of the extreme overstocking which existed in the stand before thinning. The unthinned plots show the marked effect of prolonged overstocking (table 4).

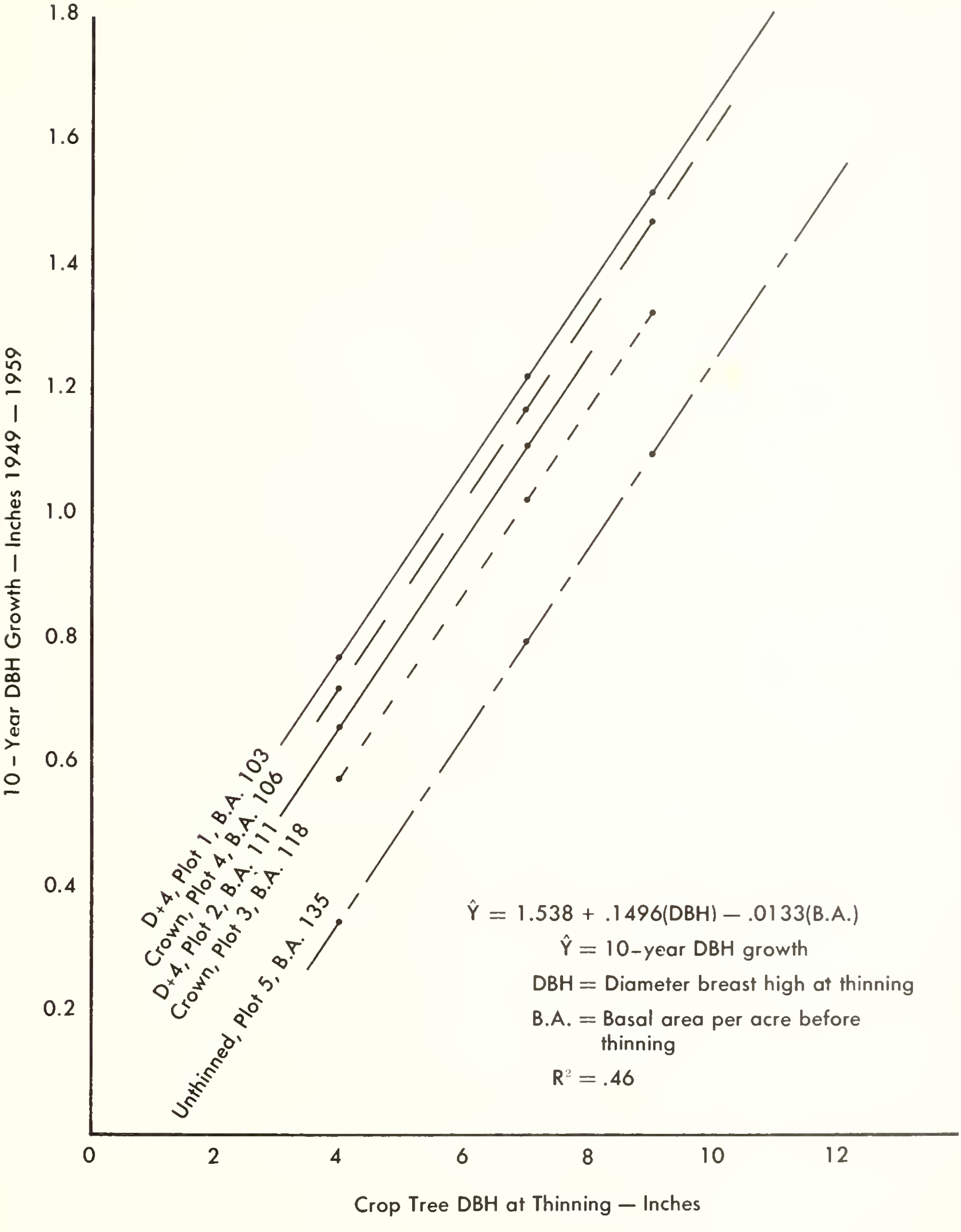

Figure 1.--Relation of 10-year DBH growth of western larch crop trees to DBH and basal area prior to thinning at West Fork.

Table 4.--Growth per acre of all trees in Pattee Canyon plots, 1932-1959

Treatment and plot number		D.b.h.	Height 1949-1960 [1]	Basal area	Volume
		Inches	Feet	Sq. ft.	Cu. ft.
Thinned	(1)	1.8	7.8	74.8	2,006
Unthinned	(2)	1.7	4.7	57.6	1,625
Unthinned	(3)	1.2	5.6	38.4	1,152

[1] Since check plots were not measured until 1949, height growth for 11 years only was available for comparison with the thinned plot.

The effect of thinning on diameter growth in the Pattee Canyon plots was even greater when comparison was based upon equivalent of the 150 largest trees per acre. This comparison showed 56 percent larger diameter growth on the thinned trees than on the unthinned. This indicated that the larger trees responded better to thinning than the smaller trees.

The effectiveness of thinning can be evaluated by comparing actual growth with potential growth for the proper site and age conditions and optimum stocking. A study of normal yield data for western larch has led to the development of a set of curves showing diameter growth of crop trees by age and site index and adjusted for optimum stocking.[4] These curves provide our best estimate of potential growth with a moderately intensive level of management in stands that have never been seriously suppressed.

By determining the section of curve covering the growth periods (age 50-60 in West Fork and age 30-57 in Pattee Canyon) involved in the thinning studies and adjusting to plot site index, the potential diameter curves for the growth period were developed. (See A and B, fig. 2.) For example, curve A in figure 2 is the potential diameter growth curve for crop trees (dominant and codominant trees) at site index 52 and an optimum level of stocking for age 50 to 60 years. Thus the potential 10-year d.b.h. growth for the growth period would be equal to the difference between the 50- and 60-year diameters, or 10.8 inches (60 years) minus 9.0 inches (50 years) = 1.8 inches. The ratio of $\frac{\text{actual d.b.h. growth} \times 100}{\text{potential d.b.h. growth}}$ equals the extent to which the stands have reached this potential.

By comparing actual growth on each plot to the potential growth, the relative improvement due to thinning is evident (table 5). For example, the D+4 treatment increased the diameter growth to 78 percent of the site potential in the first 10-year period following thinning--22 percent closer to the potential goal than the check. During this 10-year period, the trees responded to increased growing space by enlarging their crowns and root systems. About 3 years after thinning, ring width increased noticeably. If the trends continue, greater attainment of the potential goal is expected.

[4] Unpublished data, files of Intermountain Forest and Range Experiment Station.

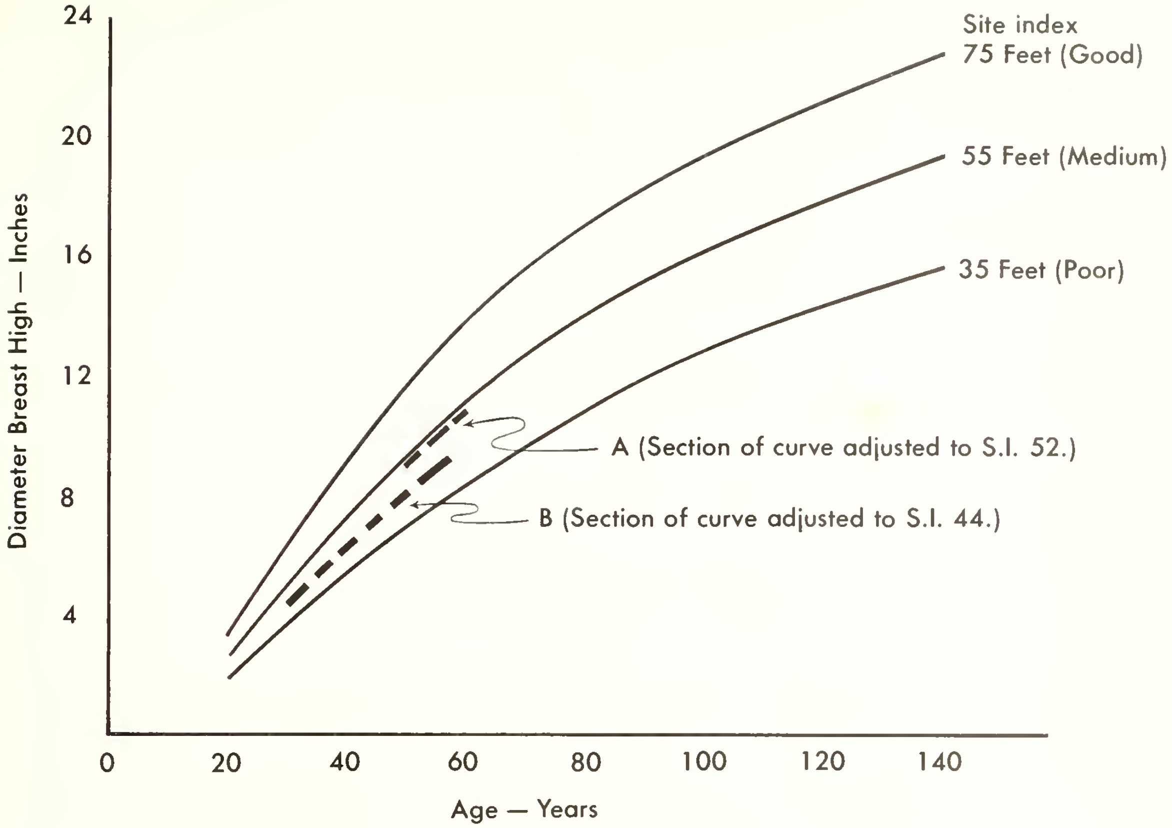

Figure 2.--Potential diameter breast high for western larch by age and site index, adjusted to optimum stocking.

Table 5.--Relation of actual to potential crop-tree diameter growth

Comparison of growth by treatments	West Fork: 10-year growth	West Fork: Percent of site potential	Pattee Canyon: 27-year growth	Pattee Canyon: Percent of site potential
	Inches		Inches	
Potential growth	1.8	100	4.9	100
Actual growth:				
D+4	1.4	78	--	--
Crown	1.2	67	--	--
Unthinned	1.0	56	--	--
Low thinning, "B" grade	--	--	2.8	57
Unthinned	--	--	1.8	37

The low thinning in Pattee Canyon was too light. Only 57 percent of the goal was attained over a 27-year growth period. However, this is 20 percent better than no treatment (unthinned). More than twice the number of trees per acre were present in the thinned plot at the end of the 27-year growth period than are desirable to obtain potential growth (fig. 3).

Figure 3.--Fifty-seven-year-old western larch on a medium site: A, Heavily overstocked unthinned stand. Both diameter and height growth are suppressed; B, comparable stand thinned from below, 27 years ago, to a 7- by 7-foot spacing. This stand is still overstocked (growing at one-half potential), but diameter and height growth are 50 percent greater than in the unthinned stand.

Basal Area

All thinned plots showed greater basal area increment than the unthinned plots (tables 3 and 4). Basal area relations closely parallel those of diameter growth. This similarity of growth is not unexpected because basal area is a function of diameter. The thinned plot on the Pattee Canyon area grew about 56 percent more basal area in 27 years than the unthinned plots, while the West Fork thinned plots averaged 35 percent more basal area increment than the unthinned plot during the 10-year growth period.

Height

Larch height growth responded to thinning only in the extremely overstocked stands in Pattee Canyon (table 4). The trees on the thinned plot added 48 percent more height during an 11-year growth period than did those on the dense unthinned checks. On the other hand, trees on the thinned plots (1-4) in the moderately overstocked West Fork stand did not show more height growth than those on the check plot (5). Although the rate of height growth varied somewhat in the four thinned plots, no significant trend appeared.

In contrast to western larch, lodgepole pine crop trees in the West Fork plots responded significantly to thinning by a reduction in height growth. Lodgepole pine crop trees in the thinned plots average 30 percent less height increment than those in the unthinned plots (table 6). The response agrees with findings in an earlier lodgepole pine study.[5]

Table 6.--Mean 10-year height growth of western larch and lodgepole pine on West Fork

Treatment and plot number		Western larch	Lodgepole pine
		Feet	Feet
D+4	(1)	11.7	8.9
D+4	(2)	9.7	6.6
Crown	(3)	11.4	5.8
Crown	(4)	8.9	7.5
Unthinned	(5)	10.7	10.3

Cubic-Foot Volume

Cubic-foot volume increment increased following thinning in both studies. This increase was much more obvious in the more densely stocked Pattee Canyon area. Trees on the thinned plot grew from a volume 23 percent smaller than the average of those on the check plots in 1932 after thinning, to a 19-percent greater volume than the trees on the check plots in 1960 (table 2). The volume increase on the West Fork thinned plots is much more subtle, since the smaller initial total crop-tree volumes on the thinned plots have only approached the crop-tree volume on the unthinned plot during the 10-year growth period. Two of the thinned plots now have about

[5] Tackle, D., and R. C. Shearer. Strip-thinning by bulldozer in a young lodgepole pine stand. Mont. Acad. Sci. Proc. 19: 142-148. 1959.

the same volumes as the unthinned plot, while the other two have nearly caught up. To do this, it was necessary for the thinned crop trees to grow faster than those in the unthinned plot. It is expected that this trend will continue, and all the thinned plots may exceed the unthinned plot 10 to 15 years hence.

Cost

The cost of thinning by the D+4 rule in the West Fork area amounted to 20.1 man-hours per acre as contrasted with 15.0 for the crown thinning. These costs are further broken down as follows:

Cutting	-	64.3 trees per man-hour (trees less than 5 inches d.b.h. only)
Girdling	-	23.6 trees per man-hour (trees more than 5 inches d.b.h. only)
Poisoning	-	18.4 trees per man-hour (trees more than 5 inches d.b.h. only)

The D+4 thinning cost more because it resulted in removing more trees than the crown thinning.

Western larch and ponderosa pine trees were pruned to a height of one log at an average rate of 14 trees per hour. This cost was obtained on the $\frac{1}{2}$-acre plots in the West Fork study. Consequently, it may not completely represent practical average rates for such work on larger areas. The crew was better than average; consequently the cost estimate is probably conservative.

No cost records were kept for the low thinning in the Pattee Canyon plots.

DISCUSSION AND RECOMMENDATIONS

These studies show that the main benefit from thinning is obtained by concentrating the growth on fewer stems. The net result is that trees grow to a larger size earlier, and usable volume is realized earlier in the life of the stand. For example, if the present growth rates continue on the Pattee Canyon plots, the thinned trees will reach a 10-inch average diameter at stand age 135 years. The unthinned trees, on the other hand, will not reach this average size in less than 200 years, or $1\frac{1}{2}$ times as long.

Recommendations for thinning western larch:

1. Early thinning should be the rule in managing larch stands. Growth response of thinned stands is related to stand structure and stocking prior to thinning. Growth that is lost on individual trees through years of overstocking cannot be regained by thinning. In fact, response to thinning will be slow until the thinned trees develop good crown and root systems. Therefore, stands should be thinned early, before serious competition for moisture and light occurs.

2. The best results are obtained from larch thinnings when first consideration is given to selecting good crop trees. Correct spacing is important, but secondary to crop-tree selection. Dominant and codominant trees consistently show the greatest response to thinning. Therefore, the best practice is to thin from below and reserve the more dominant trees with well-developed vigorous crowns.

3. Where crop-tree thinning is desirable, the D+4 rule applied to individual crop trees as a spacing guide is suggested. If the management objective is to grow sawtimber on a 140-year rotation, crop trees should be selected at the rate of 120 to the acre for site index 65 or more, and 140 to the acre for under site index 65.

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Project headquarters are also at:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State College)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with Montana State University)
- Moscow, Idaho (in cooperation with the University of Idaho)
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RESULTS OF REGENERATION CUTTING IN A SPRUCE-ALPINE FIR STAND

A. L. Roe and G. M. DeJarnette

INTRODUCTION

Development of the Engelmann spruce (Picea engelmannii Parry)-subalpine fir (Abies lasiocarpa (Hook) Nutt.) forest in the northern Rocky Mountains has posed many problems for the forest manager. Because the forest grows at high elevations and is costly to develop, it presents many silvicultural problems, particularly in designing cutting practices and in working out the best regeneration process. A low level of utilization, until recent years, meant limited experience in spruce management. Recently, however, forest managers have begun to utilize Engelmann spruce to supplement the short supply of other quality species, and also to control insect epidemics that threaten the overmature stands.

One of the principal problems in developing the spruce type is to convert dominant old-growth stands to stands comprised of young growing stock. Harvest cutting and natural regeneration present one solution. One such cutting was attempted in northern Idaho from 1916 through 1925. Observations of this area were made in 1921, 1929, and 1954; this paper reports the establishment and development of regeneration and changes in the residual stand.

STUDY AREA

The study area is located in Spruce Creek on the Kaniksu National Forest in northern Idaho at an elevation ranging from about 4,200 to 6,000 feet. The stand varied from a white pine type on the slopes at the lower end to a pure spruce-fir stand on the upper slopes and in the basin at the head of the stream (fig. 1). The stand on the slopes was composed of a mixture of species with a predominance of Engelmann spruce but with white pine in the mixture where the white pine and Engelmann spruce-subalpine fir types merged. The basin supported a nearly pure spruce-subalpine fir stand. Age of the residual trees ranged from 118 to 140 years. The whole area can be classified as a Picea-abies/menziesia ecological habitat type.[1]

Logging started in the summer of 1916 and was completed by the end of 1925. Area logged each year varied from a high of 133 acres in 1917 to a low of 43 acres in 1918. Area cut in the other years ranged between these extremes, and a total of about 800 acres was cut over. The total yield amounted to approximately 23.5 million board feet. The volume removed was comprised of 56 percent spruce, 31 percent subalpine fir, 5 percent western white pine, and 8 percent mixed western larch, Douglas-fir, and lodgepole pine.

Except for a tract of 30 acres, the total area was clearcut, leaving seed-tree groups, strips, and blocks. On the clearcut area, seed-tree groups were composed of 15 to 20 trees each; strips were 1 chain wide and of different lengths; and two blocks were of 1-acre size. The 30-acre tract was partially cut, reserving 27 percent of the original volume. Locations of the partial cutting, seed-tree groups, strips, and blocks are shown in figure 1.

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[1] Daubenmire, R. Forest vegetation in northern Idaho and adjacent Washington and its bearing on concepts of vegetation classification. Ecol. Monog. 22: 301-330, illus. 1952.

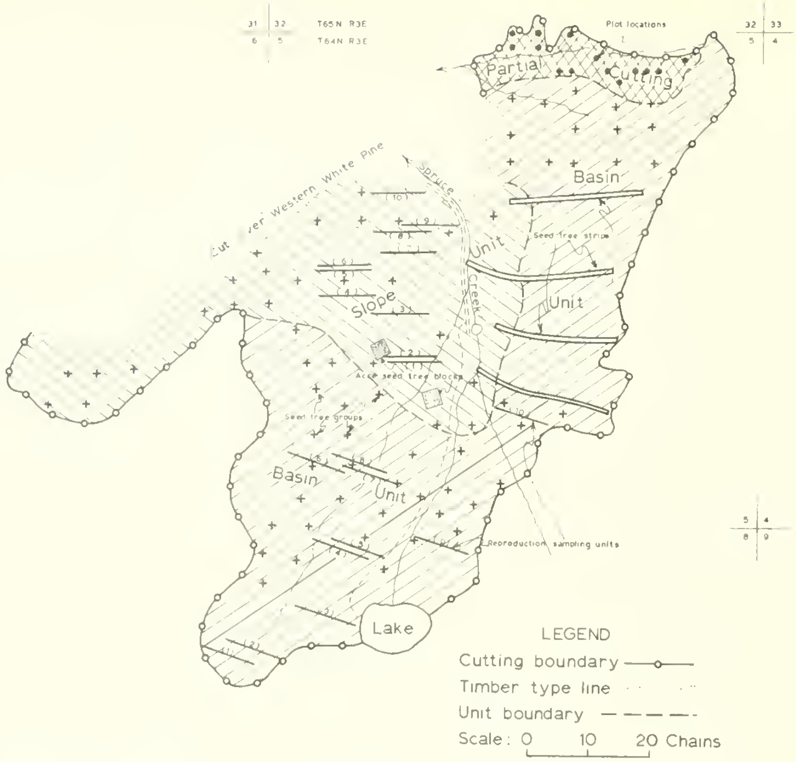

Figure 1.--Study area.

STUDY METHODS

Partial cutting.--Volume and growth of the residual trees in the partial cutting were measured in 1954 by means of temporary sample plots at 14 randomly selected locations. At each location data were collected on three different-sized concentric plots as follows:

1. Residual trees 9.6 inches d.b.h. and larger were recorded on a 1/5-acre circular plot, and trees 3.6 inches to 9.5 inches d.b.h. were recorded on a 1/10-acre plot. Diameter at breast height, total and merchantable height, dominance, external traits of vigor, defect, growth by 5-year periods before and after logging (from increment cores), and mortality since logging were determined and recorded for each tree.

2. The reproduction (trees to 3.5 inches d.b.h.) was tallied by height and diameter on a 4-milacre circular sample plot.

Clearcutting.--Reproduction counts on the group seed-tree cuttings were made in 1954 on randomly located sampling units. Each sampling unit was five 4-milacre circular sample plots spaced 1 chain apart along a 5-chain segment of a line (fig. 1). On each plot, species were recorded by height and diameter classes. Earlier reproduction counts had been made on milacre plots[2] in 1921 on the lower portion of the area, and in 1929[3] counts were made over all of the area except the 30-acre partial cutting.

[2] Lowdermilk, W. C. The management of Engelmann spruce--the basis for marking and slash disposal rules. U.S. Forest Service. Unpublished typewritten report. 40 pp. 1922.

[3] DeJarnette, G. M. Report on cut-over area examination. U.S. Forest Service. Unpublished typewritten report. 18 pp. 1931.

ANALYSIS OF THE DATA AND RESULTS

RESIDUAL STAND GROWTH

In addition to providing a large controlled seed source and shade protection for the site, partial cutting makes available high-quality, selected growing stock. Because part of the trees are removed by logging, the success of the growing stock hinges to a large degree upon the ability of the residual trees to accelerate and maintain good growth rates and to remain windfirm. The following analysis evaluates the growing stock in the partial cutting on the basis of these criteria.

Gross and net growth.--The original stand volume on the partial cutting averaged about 29,000 board feet Scribner per acre; about 7,000 feet per acre, chiefly Engelmann spruce, remained in the residual stand in 1924. Subalpine fir was the principal associate, and only minor quantities of other species were present.

In partial cuttings, foresters aim to leave trees that can respond to release and make good growth. The Engelmann spruce residual made a good net gain of 3,035 board feet per acre in the 30-year period 1924-1954, but the subalpine fir sustained a net loss of 62 board feet (table 1). Deductions for defect were not made from the volumes in table 1 because a quantitative value for this factor was not available for the residual stand in 1924. However, defect as determined by increment borings in 1954 was 6 percent of the volume in Engelmann spruce and 48 percent of the subalpine fir. Heart rot was chiefly responsible for the defect. The large volume of defect in subalpine fir further accentuates the difference in the growth between the two species shown in the table.

Table 1.--Thirty-year gross and net growth and mortality [1]

Species	Residual volume in 1924	Volume in 1954	30-year growth		Periodic annual growth		Annual mortality
			Net	Gross	Net	Gross	
	Board feet						
Engelmann spruce	5,906	8,941	3,035	4,255	101	142	41
Subalpine fir	1,082	1,020	–62	729	–2	24	26

[1] Values rounded to the nearest board foot; no deductions made for defect.

Although Engelmann spruce usually is not windfirm, mortality in the residual stand in this study was not unduly high. This may have been because the stand was situated below the crest of a ridge in a reasonably well-protected location. The annual mortality of 41 board feet per acre of Engelmann spruce was caused primarily by windthrow, while much of the mortality in subalpine fir appeared to be caused by sunscalding and insects. The following tabulation shows the estimated percent volume loss by cause for both species.

Cause of loss	Engelmann spruce	Subalpine fir
Windthrow	81	11
Windbroken	4	--
Root rot and windthrow	7	--
Insects	8	19
Sunscalding	--	56
Unknown	--	14

Response of residual trees in relation to time.--One of the chief reasons for reserving trees on a cutover area, besides providing a seed source, is to obtain additional growth on quality trees. This concept implies that the remaining trees will increase their increment when the stand is thinned by cutting. The residual trees responded significantly to logging release with acceleration in diameter growth, beginning in the second 5-year period after logging (fig. 2). The diameter increment remained high through the 6- to 30-year period after logging but fell off slightly during the last 5-year period. DeJarnette[4] reported no evident increase in diameter growth after an examination of the cutting in 1929; this confirms the lack of response depicted in the first 5-year period in the 1954 data.

Changing climatic conditions as well as release by logging can bring about accelerated diameter growth rates in trees. To help eliminate the effect of climatic factors and isolate the effect of logging release in the analysis, growth rates in an adjacent uncut stand were compared with those in the cutover residual stand. The trees in the cutover stand grew considerably more than those in the uncut stand; and the substantial difference between the two represents the response attributable to release.

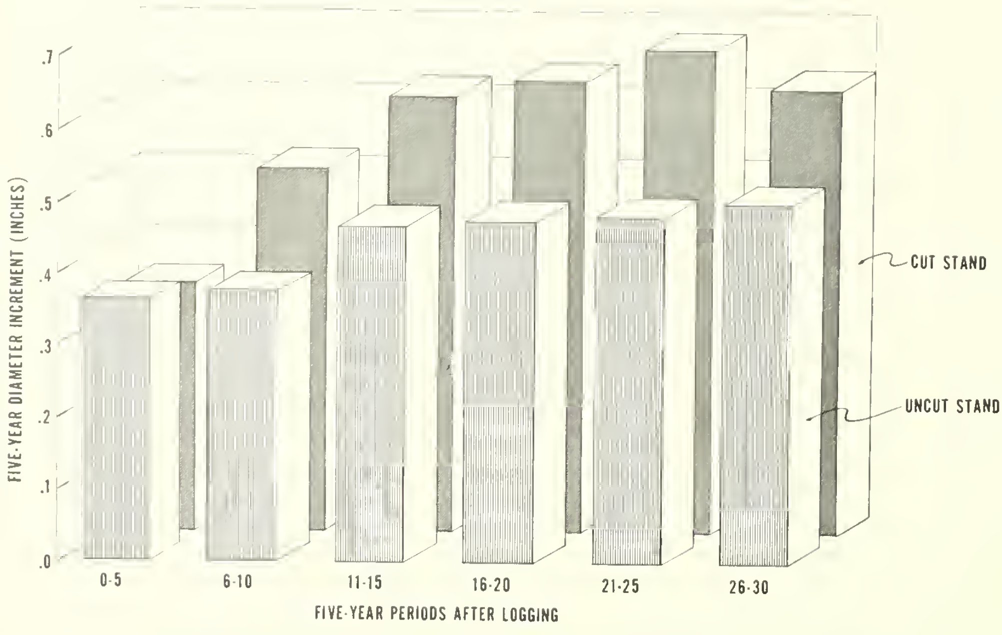

Figure 2.--Average diameter increment of trees in relation to time since cutting.

[4] Ibid.

Response of residual trees in relation to tree size.--Stand structure and size and vigor of trees influence stand growth. In this study, growth response was related to initial tree size. Table 2 shows that an Engelmann spruce tree 8.1 inches d.b.h. at logging reached 10 inches d.b.h.--a 1.9-inch increase in diameter--in 30 years. On the other hand, a 20.6-inch tree at time of logging grew to 25 inches in 30 years--a 4.4-inch diameter increase. Thus a preponderance of large trees in the residual stands helps to develop good stand growth. The same relationship is shown for subalpine fir in table 3.

Response of residual trees in relation to tree vigor.--A preponderance of good and fair vigor trees also influenced the diameter growth of the residual trees (table 4). More than two-thirds of the spruce trees in the cutover stand showed fair to good vigor. Differences between mean growth for vigor classes were significant at the 1-percent level. Further, a covariance analysis showed that the regression coefficients of 5-year diameter increment on crown length were significantly different among dominance classes. Vigor classes used in the field were based upon a vigor classification developed previously for western larch and Douglas-fir trees.[5] Since bark characteristics shown in the classification did not apply, they were not used; however, all other criteria were applied and proved useful in classifying the Engelmann spruce and subalpine fir trees.

Table 2.--Diameter breast high outside bark of Engelmann spruce trees 30 years before logging and at 5-year intervals after logging[1]

30 years before logging	Years after logging						
	0	5	10	15	20	25	30[2]
	Inches						
7.4	8.1	8.2	8.4	9.0	9.4	9.6	10
8.1	8.9	9.0	9.3	9.9	10.3	10.5	11
8.7	9.8	9.9	10.2	10.8	11.2	11.5	12
9.3	10.6	10.7	11.1	11.7	12.2	12.5	13
10.0	11.4	11.6	12.0	12.6	13.1	13.5	14
10.6	12.3	12.5	12.9	13.5	14.0	14.4	15
11.3	13.1	13.3	13.8	14.4	14.9	15.4	16
11.9	13.9	14.2	14.6	15.3	15.9	16.4	17
12.6	14.8	15.0	15.5	16.2	16.8	17.4	18
13.2	15.6	15.9	16.4	17.0	17.7	18.3	19
13.8	16.4	16.8	17.3	17.9	18.6	19.3	20
14.5	17.3	17.6	18.2	18.8	19.5	20.3	21
15.1	18.1	18.5	19.1	19.7	20.4	21.3	22
15.8	18.9	19.3	20.0	20.6	21.4	22.2	23
16.4	19.8	20.2	20.8	21.5	22.3	23.3	24
17.1	20.6	21.0	21.7	22.4	23.2	24.2	25
17.7	21.4	21.9	22.6	23.3	24.1	25.2	26
18.4	22.2	22.7	23.5	24.2	25.0	26.1	27

(See footnotes at end of table, page 6)

[5] Roe, Arthur L. A preliminary classification of tree vigor for western larch and Douglas-fir trees in western Montana. U.S. Forest Serv., North. Rocky Mountain Forest & Range Expt. Sta. Res. Note 66, 6 pp., illus. 1948.

Table 2.--(con.)

30 years before logging	Years after logging						
	0	5	10	15	20	25	30[2]
	Inches						
19.0	23.1	23.6	24.4	25.1	25.9	27.1	28
19.7	23.9	24.5	25.3	25.9	26.8	28.0	29
20.3	24.7	25.3	26.2	26.8	27.8	29.0	30

[1] This table was derived from regression equations based on the following constants:

Years after logging	b coefficient	a constant	r^2
0	0.833	−0.209	0.876
5	0.859	−0.441	0.899
10	0.888	−0.467	0.929
15	0.890	+0.149	0.961
20	0.919	+0.221	0.950
25	0.975	−0.159	0.996
30 years before logging	0.645	+0.971	0.681

[2] Diameter class at year of measurement (1954) is also the independent variable in the regression equation.

Table 3.--Diameter breast high outside bark of subalpine fir trees at 5-year intervals after logging[1]

Years after logging						
0	5	10	15	20	25	30
Inches						
8.0	8.2	8.4	8.6	8.8	9.3	10.0
8.6	8.9	9.2	9.6	9.8	10.4	11.0
9.3	9.7	10.1	10.5	10.8	11.4	12.0
10.0	10.4	10.9	11.4	11.9	12.4	13.0
10.7	11.2	11.7	12.3	12.9	13.5	14.0
11.4	11.9	12.5	13.2	13.9	14.5	15.0
12.1	12.6	13.3	14.1	14.9	15.5	16.0
12.8	13.3	14.1	15.0	16.0	16.6	17.0

[1] This table was derived from regression equations based on the following constants:

Years after logging	b coefficient	a constant	r^2
0	0.685	+1.125	0.810
5	0.736	+0.824	0.854
10	0.811	+0.329	0.933
15	0.903	+0.375	0.970
20	1.026	−1.451	0.980
25	1.026	−0.915	0.992

[2] Diameter class at year of measurement (1954) is also the independent variable in the regression equation.

Table 4.--Five-year diameter growth breast high and average crown length by vigor and crown class

Crown class	Good vigor		Fair vigor		Poor vigor	
	Average crown length	Average increment	Average crown length	Average increment	Average crown length	Average increment
	Percent	Inches	Percent	Inches	Percent	Inches
Dominant and codominant	68.5	0.827	61.1	0.666	55.7	0.468
Intermediate and suppressed	--	--	51.2	.482	34.0	.345

Gross volume increment in relation to time.--Because volume of trees is dependent upon diameter and height, it is expected that volume increment will respond to treatment the same as diameter growth has. As shown in table 5, 5-year periodic annual volume increment increased substantially in the second 5-year period (6 to 10 years after logging). The periodic annual increment continued to increase in all but the last 5-year period, when it began to fall off slightly. The study shows that in partial stands of this kind, residual spruce can be expected to accelerate its increment and continue to grow well for 25 to 30 years after logging.

Table 5.--Gross volume increment per acre of surviving residual trees and ingrowth

Species and tree class	Periodic annual increment						Total 30-year increment	P.A.I. 30-year period
	Years after logging							
	0-5	6-10	11-15	16-20	21-25	26-30		
	Board feet							
Engelmann spruce:								
Residual [1]	64.6	113.0	133.0	158.2	190.2	189.0	4,240	141.3
Ingrowth [2]	--	--	--	--	2.8	.2	15	.5
Total	64.6	113.0	133.0	158.2	193.0	189.2	4,255	141.8
Subalpine fir:								
Residual	7.6	10.4	15.2	18.4	16.2	13.4	406	13.5
Ingrowth	--	5.6	14.0	2.0	3.2	39.8	323	10.8
Total	7.6	16.0	29.2	20.4	19.4	53.2	729	24.3

[1] Trees 9.6 inches d.b.h. and larger at time of logging.

[2] Trees reaching 9.6 inches d.b.h. and larger size after logging.

Ingrowth.--Another important source of volume increment in partially cut stands is contained in trees smaller than merchantable size (9.6 inches d.b.h.) at logging that subsequently grow into merchantable size. These trees are not measured in board-foot volume until they reach the 10-inch d.b.h. class. Ingrowth contributed very little volume increase for Engelmann spruce, but comprised nearly half of the gross volume increment for subalpine fir. Ingrowth of Engelmann spruce did not appear until the 21- to 25-year period after logging, but the ingrowth of subalpine fir became part of the merchantable stand within 6 to 10 years after logging and continued to increase over the period. The subalpine fir, although small, were old and had approached or passed their peak vigor.

STATUS AND PROGRESS OF NATURAL REPRODUCTION

The primary objective of regeneration cutting is to establish a new stand by natural regeneration. This entails providing an adequate seed source, an effective seedbed, and other site and climatic conditions favorable to seedling establishment. In discussion of natural regeneration the area will be referred to in three units, namely: (1) partial cutting, (2) clearcut basin unit, and (3) clearcut slope unit (fig. 1).

Seed source.--A seed source may be provided by leaving scattered seed trees, shelterwood in partial cuttings, or uncut timber margins surrounding clearcut blocks, strips, or patches. In this study a shelterwood remained in the partial cutting. The seed source in the clearcuttings was contained in groups of 15 to 20 seed trees, 1-chain-wide strips, and two 1-acre blocks of seed trees. In 1929, about 5 years after the last cutting, DeJarnette[6] carefully examined the condition of the seed source. He reported very heavy mortality, largely windfall, of mature trees in the strips and seed-tree groups. Of the total number of seed-tree groups left, only 38 percent retained one or more live trees. Out of 30 groups which were identified and examined in detail, about half had one-fourth or fewer of original trees surviving, one-third of the groups had between one-fourth and one-half of the trees surviving, and only one-sixth of them had as many as one-half or more of the original number surviving. DeJarnette also reported similar results in the strips. By 1954 it was practically impossible to identify any of the seed-tree groups or the strips. However, enough surviving trees were present to identify the two 1-acre blocks.

Analysis of the 1954 data shows evidence of seeding in the clearcut units from the surrounding uncut timber. The mean number of trees per acre in reproduction 2.6 feet and taller was 369, based upon plots that fell within 10 chains of the timber edge--as compared with only 250 trees per acre beyond 10 chains from the timber edges. The difference of 119 trees was significant at the 5-percent level in "t" tests. Because of the early loss of much of the seed source left within the clearcut areas after logging, it is doubtful whether that source contributed much seed for reproduction.

Seedbed.--Differences among seedbeds after 30 years could not be readily distinguished in 1954. Some skidroads and soil bared by upturned roots were still discernible. Skidroads could be identified by the reproduction on them and impressions in the ground. However, most of the areas disturbed by the logging operations had been completely clothed by trees and other vegetation, particularly *Menziesia ferruginea*, commonly known as buckbrush, which is the predominant shrub now.

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[6] Op. cit.

In 1921, Lowdermilk[7] examined a portion of the area that had been cut in 1916 and 1917; slash had been piled and burned in 1918. He reported the following condition of the seedbed:

	Percent
Burned seedbed (burning of slash piles, etc.)	13.1
Mineral soil (exposed by mechanical disturbance)	13.3
Natural undisturbed forest floor	73.6
	100.0

Although these values represent only the lower slopes, they nevertheless indicate the proportions of mineral soil and burned seedbed that were exposed by the logging and slash disposal operations. No additional seedbed was prepared. It seems safe to assume that these figures may apply reasonably well to the whole area.

The superiority of mineral soil seedbed as opposed to undisturbed natural forest floor was established by Lowdermilk's studies in 1921. The following tabulation compares the percentages of stocked milacre plots by surface conditions as he found them:

Seedbed	Engelmann spruce	Subalpine fir and other
Burned surface	20.4	30.6
Mineral soil	95.0	100.0
Natural forest floor	9.0	9.0

Lowdermilk pointed out that the stocking on burned areas was disappointing. He theorized that the hot fires caused by burning piles sterilized the soil; such sterilization may explain why the centers of the burned spots did not stock satisfactorily. Even so, the burned surface was two or three times better stocked than the natural forest floor. The number of trees per acre shows a similar trend, as illustrated by the following tabulation:

Seedbed	Engelmann spruce	Subalpine fir and other
Burned surface	405	356
Mineral soil	2,300	1,405
Natural forest floor	109	118

Although Lowdermilk's observations were limited to cutting before 1919, comments in reports of later examinations bear out the same trends in other parts of the area.

Stocking of reproduction.--In both 1929 (DeJarnette)[8] and 1954, a fair stocking of Engelmann spruce and subalpine fir on the clearcut areas was found despite the heavy loss of seed source shortly after logging and the limited amount of favorable seedbed (table 6). These examinations dealt with three units based upon physiography and method of cutting, and made no attempt to recognize seedbed condition that was no longer discernible or to distinguish between the kinds of the seed source (i.e., 15 to 20 tree groups or strips) in the clearcutting.

[7] Op. cit.
[8] Op. cit.

Table 6.--Four-milacre plots stocked with one or more seedlings

Year	Partial cutting		Clearcutting with seed-tree groups			
			Basin unit		Slope unit	
	Engelmann spruce	Subalpine fir	Engelmann spruce	Subalpine fir	Engelmann spruce	Subalpine fir
	Percent					
1954	[1] 64(43)	43(29)	58(34)	84(48)	56(48)	52(52)
1929	--([2])	--([2])	35	39	60	71

[1] Numerals in parentheses include only trees 2.6 feet and taller that were considered well established and able to compete with other vegetation.

[2] Reproduction counts in the partial cutting area were not made in 1929.

However, stocking by well-established reproduction in the clearcut area in 1954 did not increase substantially after the 1929 examination (table 6). The increase in stocked quadrats in the 1954 figures may be attributed to 1-year-old seedlings and to older seedlings so badly suppressed by other vegetation that their survival is doubtful. Many 1-year seedlings start even under very heavy shrub cover, but very few survive long enough to become established trees. After careful examination of the 1954 stand, only those seedlings that had reached the 3-foot height class were judged to have a fair probability of becoming a part of the productive stand within a reasonable period of time. On the basis of seedlings 2.6 feet or taller, it appears that the well-established seedlings are mainly those that were established by 1929; and accretion in numbers of new seedlings very nearly balanced losses. On the slope unit, the stocking in 1929 considerably exceeded that of the basin unit, but by 1954 the difference in stocking on the two areas was much less. The means of both total number of seedlings and seedlings 2.6 feet and taller on the slope and basin units were not significantly different in 1954 as revealed by "t" tests.

Composition of the reproduction stand.--The highest ratio of spruce to subalpine fir occurred in the reproduction established under the partial cutting. This is best illustrated in table 7, which shows more than $1\frac{1}{2}$ times as many spruce as subalpine fir trees. This favorable ratio may be attributed to the greater number of spruce than subalpine fir seed trees in the residual stand of the partial cutting. On the other hand, in the clearcuttings the subalpine fir outnumber spruce in the reproduction by about four to one. The greater incidence of spruce seedlings in the partial cutting reflects the better seed control achieved by the partial cutting.

Table 7.--Composition of reproduction by cutting areas and species

Area	Engelmann spruce	Subalpine fir
	Trees per acre	
Clearcut basin	580	2,190
Clearcut slope	450	1,980
Partial cutting	838	519

Development of the seedling stand.--Although a larger proportion of spruce to subalpine fir seedlings was established in the partial cutting, the best growth and development of seedlings after they were established occurred in the clearcutting. None of the spruce seedlings in the partial cutting had attained a measurable diameter at breast height in 1954, but in the clearcutting the spruce seedlings attained mean diameters of 1.56 and 1.93 inches in the basin and slope units, respectively. Subalpine fir, on the other hand, attained mean diameters at breast height of 1.50, 1.59, and 2.22 inches in partial cutting, basin, and slope units, respectively. Height growth is also much better in spruce seedlings in the clearcuttings than in the partial cutting (see table 8). The tallest spruce seedlings in the partial cutting fell in the 5-foot height class, while 30 percent of the seedlings in the basin unit and 50 percent of those in the slope unit exceeded the 5-foot height class. Subalpine fir height growth, in contrast to the spruce development pattern, was much better in the partial cutting, where 38 percent of the seedlings were taller than the 5-foot height class, and only 6 and 10 percent of the seedlings exceeded the 5-foot height in basin and slope units, respectively. This relationship indicates that despite the protected conditions and preponderance of spruce seed source that favor seedling establishment in the partial cut, the best environment for later growth was in the clearcut areas.

Table 8.--Distribution of reproduction by total height classes

Height class (feet)	Engelmann spruce			Alpine fir		
	Clearcutting		Partial cutting	Clearcutting		Partial cutting
	Basin unit	Slope unit		Basin unit	Slope unit	
	Percent					
1	34	22	43	82	77	50
2	10	7	26	6	10	7
3	7	7	15	3	2	3
4	8	9	8	1	1	0
5	7	6	8	2	1	3
6	12	6	0	1	2	17
7	3	2	0	1	2	0
8	6	4	0	1	1	3
9	1	4	0	0	0	3
10	9	18	0	2	2	11
20	2	10	0	1	2	3
30	1	5	0	0	1	0
Total	100	100	100	100	100	100

DISCUSSION

Partial cutting is useful in Engelmann spruce management as a reproduction method. Although the partially cut stand observed in this study is small, it shows both advantages and disadvantages of the method.

On the credit side, both spruce and subalpine fir responded well to release even at the advanced ages represented by the trees in this study. The spruce residual increased its gross volume at a 2.4 percent per annum rate for 30 years. These residual trees during the regeneration period not only furnished an adequate, well-distributed seed source, but also provided natural shade to aid seedling survival in the early years and good protection for the site. At the same time, the residual trees returned a substantial increment. As illustrated in the results, the selection of good, vigorous spruce seed trees provided good control of the species composition in the reproduction.

On the debit side, however, the spruce residual presents the problem of risk from loss by windthrow. Windthrow is not an insurmountable problem because, under proper conditions of exposure, skillful cutting, and deep soil, spruce residuals can produce good net gains, as shown by this study. Studies on the east side of the Canadian Rockies[9] have shown that the blow-down problem can be alleviated by light selection cutting where reasonable reserve stands of 3,000 board feet or more per acre have been left. Further, these partially cut stands make possible another cut on the area in 30 to 40 years.

Subalpine fir, despite its good growth response to release by logging, is highly sensitive to damage and mortality from sunscalding and insect attack, and suffers a high incidence of heart rot. These facts make subalpine fir an extremely high risk in the residual stand unless the trees are very young and vigorous.

Suppression of the spruce reproduction by the residual stand, which is held for many years beyond seedling establishment, constitutes another disadvantage of partial cutting. Diameter and height growth of well-established spruce seedlings were retarded when compared with seedling growth and development in the clearcutting. The extent to which the suppressed reproduction may respond and fill the gap of lost increment when the old stand is removed is not known.

A further disadvantage of partial cutting is found in the difficulty of preparing seedbeds under the residual trees. Mechanical scarification around the bases of spruce trees very often damages roots close to the surface and, consequently, decreases vigor and increases the risk of windthrow. Prescribed burning also often damages the shallow roots of spruce and sometimes causes death by damaging the cambium. The extent to which scarification and prescribed burning may be modified to reduce their damaging effects is not known, but further investigation is highly desirable.

On the basis of this study and present experience, clearcutting with seed-tree groups, strips, or small blocks is not recommended. Seed sources of this kind are highly vulnerable to wind damage. The transitory nature of the seed sources is a serious disadvantage not only

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[9] DeGrace, L. A. Management of spruce on the east slopes of the Canadian Rockies. Canada Dept. of Resources and Development. Forest Res. Div. Silv. Res. Note 97, 55 pp. 1950.

because the volume contained in the trees is lost early through windthrow, but also because the trees may not remain upright long enough to produce useful quantities of seed. Further, such seed sources offer only a minimum opportunity to control species composition. The groups possess the same composition, usually, as the harvested stand.

Clearcutting in blocks or strips with seeding from the side or uncut timber edge is now widely practiced as a reproduction method. It was not included as a method in the cuttings described; yet, the early loss of the seed-tree groups and a fair degree of stocking throughout the clearcut area suggest that side seeding helped effect successful regeneration. Evidence in the study shows that side seeding was a significant factor within 10 chains of the timber edge.

The type of reproduction cutting to use in harvesting spruce stands should be selected carefully and the advantages and disadvantages of each method must be considered. Blind faith in any single method is not justified, but careful consideration of the site conditions and requirements will help the forest manager to select. Partial cutting under some conditions and clearcutting under others are both useful methods.

RECOMMENDATIONS

A few simple guidelines for spruce cutting are enumerated below:

Partial cutting

1. Partial cutting should be practiced only on deep, well-drained soils, away from crests of ridges or other locations in the paths of high winds. Moist, poorly drained areas are a poor risk for partial cuttings and consequently should be clearcut.

2. Trees of good vigor should be left. Select only trees in the upper dominance classes--preferably trees having long, medium-to-wide crowns.

3. A uniform canopy should be left with as little variation as possible in tree height. Making large holes in the canopy should be avoided whenever possible.

4. Subalpine fir should be removed unless the trees are very young and have long crowns. Trees with a history of long, early suppression should be avoided in the residual because of the high incidence of heart rot, and also because of their sensitivity to sunscalding.

5. Seedbed preparation that exposes mineral soil and removes competitive vegetation is required for early seedling establishment and growth.

Clearcutting

1. Clearcut blocks or strip cutting should be practiced especially in areas having moist soils or in sites that lie in the paths of high winds.

2. While block or clearcut strips can be expected to receive seed from the side (timber edge), side seeding should not be depended upon beyond 10 chains from the timber edge. The size and shape of the opening should be planned to provide standing timber within 10 chains of any part of the cutover area.

3. Planting or seeding should be planned as a supplemental measure on those areas beyond 10 chains from the timber wall. Small groups or islands of seed trees within the cut-over area are not recommended.

4. Seedbed should be prepared either by mechanical scarification or broadcast burn. A cool, moist microenvironment is required for successful seedling establishment on the seedbed and can be accomplished by leaving sufficient scattered material, such as logs and branches to provide shade and protection.

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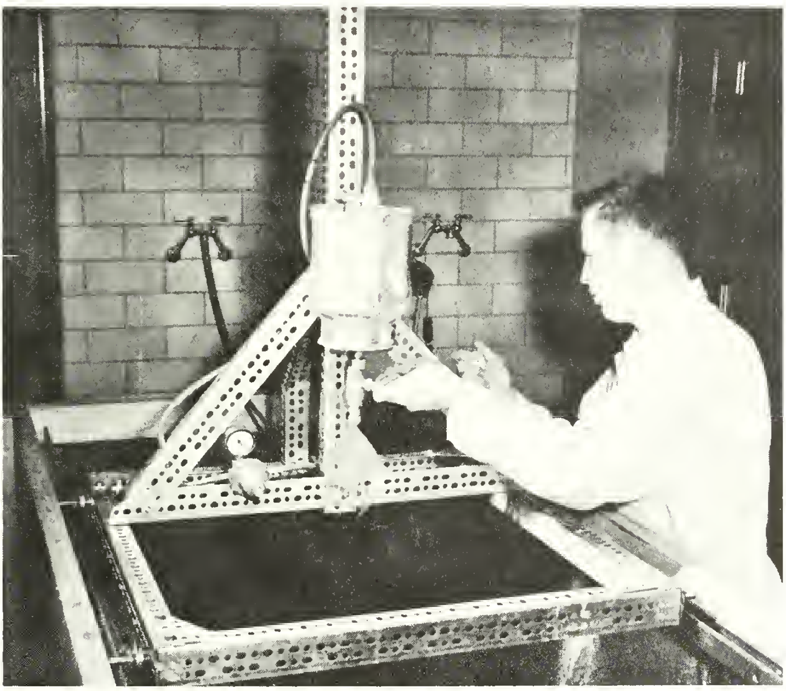

by

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INFLUENCE OF MOISTURE ON EFFECTIVENESS OF FIRE RETARDANTS

Richard C. Rothermel and Charles E. Hardy

INTRODUCTION

The Problem

Application of fire-retardant chemicals is fast becoming an integral part of control procedures on forest, range, and brushland fires. Each year new fire-retardant chemicals or combinations of chemicals are introduced, and existing retardants are improved. Fire-control personnel urgently need more information about the effectiveness of present types of retardants as influenced by the environment.

A complete series of tests for each new or modified product is not economically feasible. Instead, procedures are being developed to classify fire-retardant chemicals so that a minimum number of tests will make it possible to list each one within a group having similar characteristics.

All research reported in this publication was performed at the Northern Forest Fire Laboratory, Missoula, Montana. It explored the relation between effectiveness of each fire retardant and fuel moisture content as influenced by such environmental conditions as wind velocity, humidity, and temperature.

Fire retardants may be classified generally as short-term or long-term retardants. Short-term retardants rely entirely upon the water they contain to prevent combustion. Long-term retardants contain, in addition to water, a chemical that effectively prevents flaming combustion even after the water has evaporated.

Much conjecture surrounds the question of comparative evaporation rates among the various retardant materials. If differences do exist, the slowest drying material is the most desirable one to use in fire control. Determination of evaporation rates in this study is important not only as a prerequisite to the burning tests, but also as an aid in selecting the most effective retardant thickening or water-holding material.

Results from earlier research at the Northern Forest Fire Laboratory[1] indicated that long-term retardants--those containing fire-retarding salts--are markedly more effective than short-term retardants. The present study was more concerned with how wind and relative humidity affect the rapidity of moisture loss from retardant-treated fuels than on how moisture affects the burning characteristics of retardant-treated fuels.

Both experience and previous research show the superiority of long-term over short-term retardants. However, the short-term retardants continue to be used because they cost less and some of them are easier to mix and use. Results of this study should help the fire-control

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[1] Hardy, C. E., R. C. Rothermel, and J. B. Davis. Evaluation of forest fire retardants--a test of chemicals on laboratory fires. U.S. Forest Serv., Intermountain Forest and Range Expt. Sta. Res. Paper 64, 33 pp., illus. 1962.

officer determine what environmental conditions justify use of short-term retardants, and wha conditions force him to apply the more costly, but more effective, long-term type.

Objectives

The major objective of this study was to learn the extent to which environment affects the ability of retardants to slow or stop an advancing fire (1) when the degree of retardant dryness changes, (2) when different amounts of retardant material are applied to the fuel bed, and (3) when ammonium salts should be included in the retardant formulation.

The experiments were of two sorts:

Drying test.--Determination of drying rates of several fire-retardant formulations.

Burning test.--Determination of effectiveness of a particular retardant in a controllec fire situation.

The study was designed to yield information that could ultimately be used in developing operational guidelines. These guidelines would assist fire-control officers in choosing the proper type of retardant, and in determining how much to use, according to the fuel and enviror mental situation at hand.

INITIAL CONSIDERATIONS

Three major elements received primary consideration in developing the study plan:

1. Retardant chemicals--selection of types, amounts, and methods of application.
2. The composition of fuel beds upon which each retardant would be applied.
3. Environmental regimes within which the drying and burning tests would be conducted.

Chemicals

Retardants now being used against wildfire consist of water thickened by either a natural organic gum, a synthetic organic gum, or a swelling clay. Use of the thickened material assures that a large percentage of the original volume will reach the ground instead of breakin up into a mist and drifting off, that it will cling to all parts of the fuel surface, that it will buil up a thick layer of moisture that will be a barrier between the fuel and the flame, and that this moisture barrier will evaporate more slowly than would a thin film of plain water.

The ability of the thickened material to retard fire is increased substantially by adding a salt--usually an ammonium salt such as ammonium sulfate or diammonium phosphate. The ammonium salt alters the combustion characteristics of the fuel, causing it to char rather than flame; this reduces heat transfer which, in turn, inhibits spread of the fire. The inhibiting actic persists even though the retardant's moisture has evaporated from the surface of the fuel.

Representative retardants selected for this study are classified by effective life and thick ening agents (table 1).

Table 1.--Classification of retardants by effective life and thickening agents

Retardant[1]	Effective life		Thickening agent	
	Short-term	Long-term	Clay	Gum
Gelgard	X			X
Algin-gel	X			X
Bentonite	X		X	
Phos-Chek 202		X		X
Fire-Trol		X	X	

NOTE: Table 7, p. 28, shows composition, mixing quantities, and method of mixing.

[1] Mention of trade or brand names is solely for convenience in identification. Such mention does not imply endorsement by the U.S. Forest Service of the products mentioned, nor does it imply nonendorsement of unnamed products.

All five retardants and water were used in the drying test. Water, however, penetrated through the fuel instead of adhering to it, and formed puddles on the bottom of the drying pans. This caused spurious drying rates; hence we eliminated water from further consideration in the present study.

We used only one short-term and one long-term retardant in the burning test on the assumptions that:

1. Short-term retardants have similar fire-inhibiting characteristics.

2. Long-term retardants, as now manufactured, have similar fire-inhibiting characteristics.

3. The fire-inhibiting characteristics of long-term retardants as a group are significantly different from those of short-term retardants.

Fuel

We used ponderosa pine needles for fuel bed material in all tests because of their natural organic composition and also because pine-needle beds can be reproduced with reasonable accuracy;[2] also, pine needles are readily available. Earlier research analyzed the burning of untreated ponderosa pine fuel beds under a wide range of fuel and air moisture content and environmental conditions; the results were the basis for comparison of the burning phenomena of treated and untreated fuels.[3]

Needles from the current year's cast were cleaned, mixed, and stored in bins. At least 2 weeks prior to use the needles were place in 10-pound-capacity wire baskets on open shelves in the fuel preparation room, where the ambient environmental conditions caused the moisture

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[2] Schuette, Robert D. Preparing reproducible pine needle fuel beds. U.S. Forest Serv. Research Note INT-36, 7 pp., illus. 1965.

[3] Rothermel, R. C., and Hal E. Anderson. Fire spread characteristics determined in the laboratory. (In preparation.)

content of the needles to lie between 6.0 and 7.0 percent of their ovendry weight. Further conditioning of the needles to bring them into equilibrium moisture content with the environment in which they would be burned was not necessary because the entire fuel bed was to be coated with a moisture-laden retardant.

Pine needles were distributed over each fuel bed to a loading density of 0.5 pound per square foot. Thus, each 18- by 24-inch drying pan contained 1.5 pounds of needles, and each 18- by 96-inch burning tray contained 6 pounds. To build reproducible 8-foot-long fuel beds with uniform compactness, we followed Schuette's[4] published instructions. A similar procedure was followed in preparing the 2-foot-long drying pans and the 3-foot-long "igniter" fuel beds.

Environment

All testing reported here was performed in the laboratory's large wind tunnel. Test objectives specified three variations of environment for both drying and burning tests; to achieve these, we combined two relative humidities and two wind velocities at a temperature of 90° F. (table 2).

Table 2.--Environmental conditions

Condition	Temperature	Relative humidity	Wind velocity: Height above fuel: 1 foot	Wind velocity: Height above fuel: 20 feet[1]	National spread index equivalent[2]
	Degrees F.	Percent	M.p.h.	M.p.h.	
I	90	50	2	6	36
II	90	20	2	6	40
III	90	20	5	15	68
Tolerance	±1.0	±1.0	±0.25		

[1] A 3-to-1 difference in windspeed between the fuel surface and an anemometer at 20 feet is assumed. This value may change drastically according to the boundary layer created by the surface vegetation.

[2] National Fire-Danger Rating System, Fine Fuel Moisture--Cured Herbaceous Stage, U.S. Dept. Agr. Forest Serv. Form 5100-24 (2/64).

CHEMICAL APPLICATION

Essential Features

Immediately before impact with the fuel, physical characteristics vary greatly among retardant formulations--even within a specific drop of a single retardant. Viscosity may be much less while a retardant is falling through the air than when it is at rest; this change in viscosity influences droplet size, both in average diameter and in range of diameters; in turn, the droplet's velocity is affected. All these factors, along with the total amount applied, affect the retardant's penetration into the fuel bed. The following six essential features were incorporated into the application technique to produce a retardant drop pattern that would most closely simulate actual drop conditions:

[4] Schuette, op. cit., p. 3.

1. Application of the total specified amount of retardant on the upper surface of the completed fuel bed. (Preliminary burning tests had shown this to be feasible.)

2. Use of an application device that would not aerate the retardant. This was done by pressurizing the supply tank just enough to force the liquid out the bottom into a manageable spray pattern.

3. Selection of a nozzle and pressure combination that effectively prevents formation of fine mist and large globs.

4. Use of a flat or single-plane nozzle to obtain a uniform lateral spray pattern over the full width of the fuel bed.

5. Reduction of particle velocity to as near terminal rate as possible without sacrificing requirements of droplet size, spray pattern, or flow rate.

6. Increasing application time to permit better control of application amount by reducing flow rate as much as practicable. The rate achieved was between 1.7 and 2.0 gallons per minute.

Equipment

Application equipment consisted of a 12-foot-long spray chamber with tracks along each side to support the carriage containing the pressurized applicator (fig. 1).

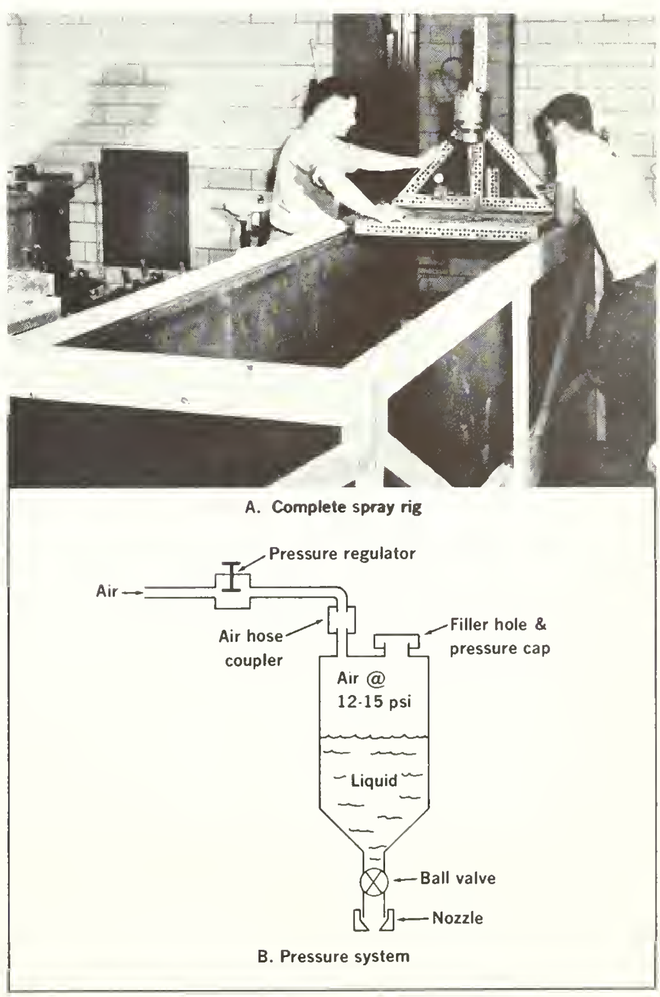


Figure 1.--Application equipment.

Calibration

Each retardant was calibrated to determine its total flow rate, lateral pattern uniformity, and usable flow rate.

Total Flow Rate

Flow rates were measured at tank pressures between 3 and 21 p.s.i., and at five orifice sizes of 5/64 to 11/64 inch, by timing the discharge of 1 gallon of each retardant and converting the information to gallons per minute.

Lateral Pattern Uniformity

We achieved optimum uniformity of retardant amount at all points across the 18-inch tray width by: (1) spraying each retardant for 10 seconds into plastic ice cube trays arranged across the spray chamber floor to intercept the spray, using varied nozzle heights and the array of pressures and orifices described above in Total Flow Rate (also see fig. 2); (2) weighing each tray; and (3) after examining results, choosing the nozzle type, nozzle height, and tank pressure that produced the best pattern for each retardant across the usable 18-inch span.

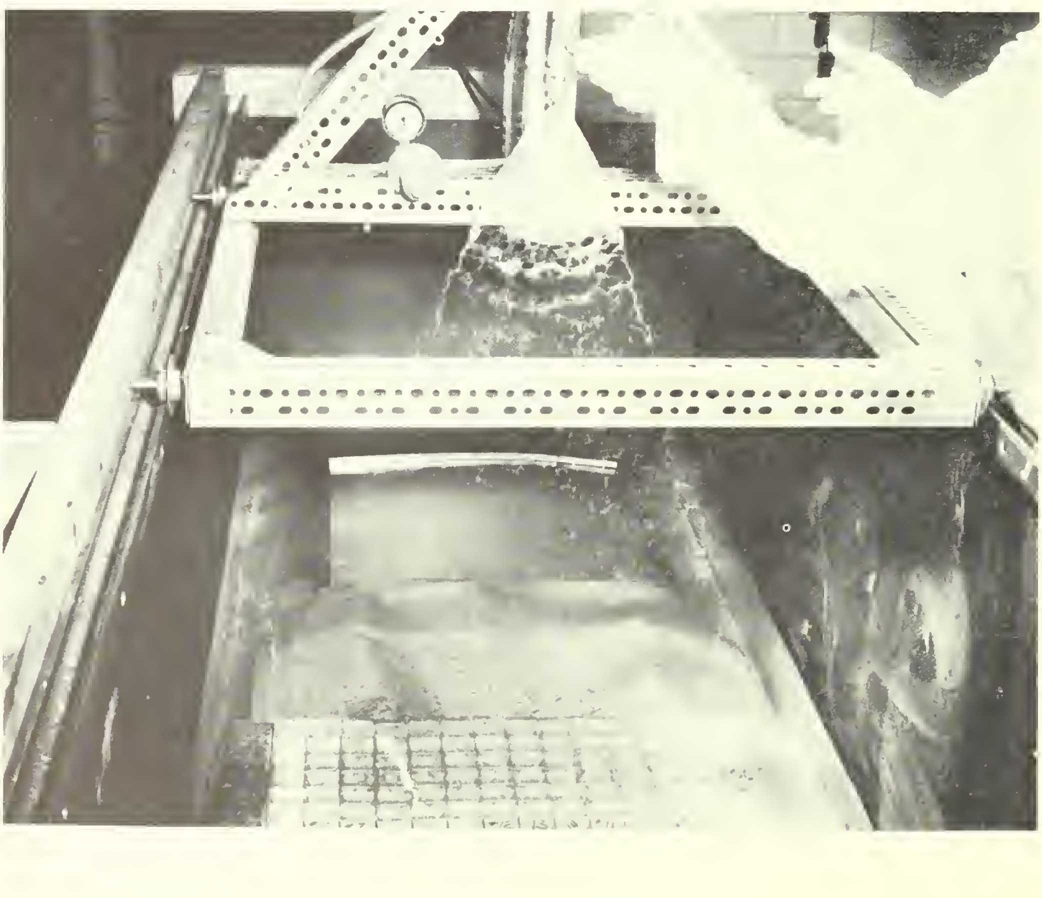


Figure 2.--Pattern calibration.

Usable Flow Rate

While the above procedure laterally oversprayed and lost considerable volume to each side of the fuel bed, it produced a uniform pattern over the 18-inch fuel bed width. The actual amount of material falling into the fuel bed per second was determined by spraying directly into 18-inch-wide pans for a given time period, then weighing the pans and computing the rate. Table 3 shows the resultant usable flow rates.

Table 3.--Retardant calibration and application data (based on rate of 1 gallon per 100 square feet)

Retardant	Calibration: Measured density[1]	Flow rate[2]	Viscosity[3]	Time[4]	Application amount[5]				
					Chemical		Water		Total
	Lb./gal.	G.p.m.	C.p.s.	Sec.	Grams	Percent	Grams	Percent	Grams
				Drying Pans					
Gelgard	8.36	1.82	--	2.4	1	1	114	99	114
Algin-gel	8.33	1.92	1,360	2.5	1	1	113	99	113
Bentonite	8.76	2.00	5,090	1.9	10	8	109	92	119
Phos-Check 202	8.83	1.85	2,610	1.9	14	11	106	89	120
Fire-Trol	9.49	2.00	2,637	2.5	32	25	97	75	129
				Burning Trays					
				Sec.	Lbs.	Percent	Lbs.	Percent	Lbs.
Short-term			3,505	7.8	0.09	8	0.96	92	1.05
Long-term			2,780	10.0	.29	25	.85	75	1.14

[1] Residual bubbles may have caused minor errors, even though at least 18 hours elapsed between mixing and measuring.
[2] Nozzle tip diameter: 9/64 inch; tank pressure: Phos-Check 202 - 15 p.s.i.; all others - 12 p.s.i.
[3] See table 7, p. 28.
[4] Nozzle height above fuel bed: Phos-Check 202 - 110 cm.; all others - 100 cm.
[5] By volume: 0.01 gal./sq.ft. for all retardants.

Retardant Application

Selection of Amounts

Retardant dropped from an air tanker does not form a uniform lateral layer on the ground. The amount may vary from less than 0.5 gallon per hundred square feet (0.5 gal./100 sq.ft.) to more than 5.0 gal./100 sq.ft. Seldom does a continuous strip of air-dropped retardant contain more than 3.0 gal./100 sq.ft. From this range of field-attainable amounts we used the quantities of 1, 2, and 3 gal./100 sq. ft. for the series of drying and burning tests. Preliminary burning tests verified that these amounts would produce a satisfactory range of results.

Penetration

Application of all the retardant onto the upper surface of the 3-inch-deep fuel bed created a situation similar to what occurs in field application--an unequal vertical distribution of the retardant. The greatest amount lay near the fuel bed surface; progressively lesser amounts penetrated the fuel toward the bottom. Virtually no retardant reached the bottom of the fuel bed when the 1 gal./100 sq.ft. rate was applied. Application procedures described in an earlier test[5] required use of only one-third of the retardant after each 1-inch layer of needles was placed in the fuel bed, creating a sort of three-layered sandwich of fuel and retardant. This system was not practicable for the present test series because the rigid drying schedules did not allow for the time involved in the layered application method. The one-application method used in the present tests was closer to what is encountered under field conditions, and fires smoldered along the bottom of the fuel bed much as they do under field conditions.

Operation of Retardant Application Equipment

After weighing, the fuel beds were placed in the spray chamber, where the applicator tank had been set at the correct pressure and height above the fuel bed. The operator opened the ball valve and began spraying retardant beyond the end of the fuel bed. The retardant flow was timed as the carriage crossed above the end of the fuel bed. The carriage continued to move back and forth above the fuel until the time required for applying the desired amount had elapsed. To prevent buildup when the carriage movement stopped or was reversed, the operator sprayed beyond the end of the fuel bed before changing directions. When the amount estimated to be proper had been applied, we reweighed the fuel bed to determine the exact amount of application. If when reweighed the fuel bed was more than 5 percent too light, the carriage operator applied an additional light layer; if it was more than 5 percent too heavy, we discarded the fuel bed and started over. (See fig. 14, p. 27, for sample record sheet.) We weighed fuel beds in the drying rate pans to the nearest gram on a solution balance, and fuel beds on the large burning trays were weighed on a platform scale that enabled the weight to be determined to the nearest 0.01 pound. Immediately after final weighing, the operator hoisted the pan or tray into position in the environmentally preconditioned wind tunnel for the drying or burning test (figs. 3, 4, and 5).

[5] Hardy et al., op. cit., p. 1.

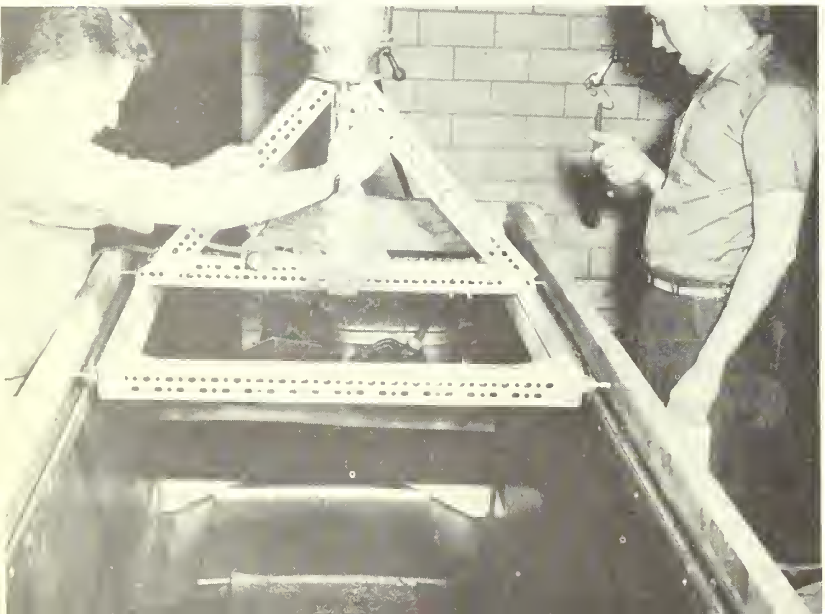


Figure 3.--Applying retardant--note spray pattern.

Figure 4.--Weighing drying pan.

TESTING PROCEDURE

Drying Test

To determine the drying rates of the various retardants, each sample was weighed at 15-minute intervals until it was essentially dry. The results were then plotted as drying curves.

Nine runs were made, each with 18 treated samples:

Variable	Number of treatments
Chemicals, including water	6
Environments	×3
Application amounts	×3
Replications	×3
Total samples	162

Before running any tests, we positioned a 20-compartment rack across the wind tunnel test section to expose the treated pans to the environmentally conditioned airflow. The treatment sequence and order of placement in the rack were determined by random number selection before the test series began.

Figure 5.--Weighing burning tray.

During a run (1 day's operation) we applied a specified amount of each of the six retar ants (1, 2, or 3 gal./100 sq.ft.) to each of three 3- by 18- by 24-inch pans. The entire gr of 18 pans was then subjected to one of the three environmental conditions (I, II, or II described in tables 2 and 3.

The operator reweighed each pan to the nearest gram on a direct-reading balance afte brought it into the wind tunnel and before placing it in its assigned cell. Weighing continued 15-minute intervals until the loss in moisture showed a difference of 2 grams or less betwe any three readings. After each weighing the pans were rotated in sequential order from cell cell to reduce any effect of possible unequal airflow through the wind tunnel's cross secti (fig. 6).

Burning Test

Burning Plan

The burning plan held the total number of test fires to a minimum by restricting t number of considerations. The considerations to be covered were two retardant types, thre environmental conditions, three drying times, three application amounts, and three replicati of each test. Complete coverage of all these would have required 162 fires, plus reruns in t event of instrument failure. Such complete coverage was beyond the scope of our time, budg and fuel supply; however, the number of tests finally chosen covered the most pertinent d and answered our questions satisfactorily.

The total number of fires actually burned was held to 73 by reducing the number of dry conditions from three to two and by adjusting the application amounts as dictated by the conditions. The short-term retardants were tested when they were 33- and 67-percent d the long-term retardants, when they were 67- and 95-percent dry. Since previous testing[6] shown that short-term retardants were ineffective after severe drying, there seemed to be need to test short-term retardants when they were 95-percent dry. The same report clearl showed long-term retardants to be superior to short-term retardants under any given condit and thus eliminated need for extensive comparative testing now.

[6] Hardy et al., op. cit., p. 1.

Figure 6.--Drying test equipmen in wind tunnel. Rack in back ground has screen and baffle on upwind side to establis uniform airflow over the pans

In this study, fires on which the retardants were judged to be effective continued to burn ep within the fuel bed where there was little or no retardant. These fires could have been opped easily by a heavier application of retardant or by deeper penetration, or by a break in el continuity such as is found in wildland fuels.

The amount of retardant to be applied was determined by using first the median amount at ch new condition, and then adjusting the next amount of application according to the success failure of the first amount. The amounts applied thus varied from 1 to 3 gallons per 100 sq. If the retardant was judged to be effective, even with the minimum application, the environ- ental conditions were increased to a higher Spread Index for the next series of tests. If dged ineffective, the quantity of retardant applied was increased.

Positioning of Tray

Immediately after the 3- by 18- by 96-inch burning tray had been treated, the operator ted it into the large wind tunnel and placed it on the strain gage weighing system attached to e fixed support frame (fig. 7). An untreated 3- by 18- by 36-inch fuel bed (igniter tray) placed wind from the longer, treated bed afforded the fire a chance to approach a steady rate of ad- nce before it came in contact with the retardant-treated fuel--a situation comparable to what ght occur in nature. End and side ground plane aprons designed to produce uniform airflow er the needle surface were placed on all sides of the treated and igniter trays. The final eparation included placing the alcohol ignition trough at the upwind end of the igniter tray.

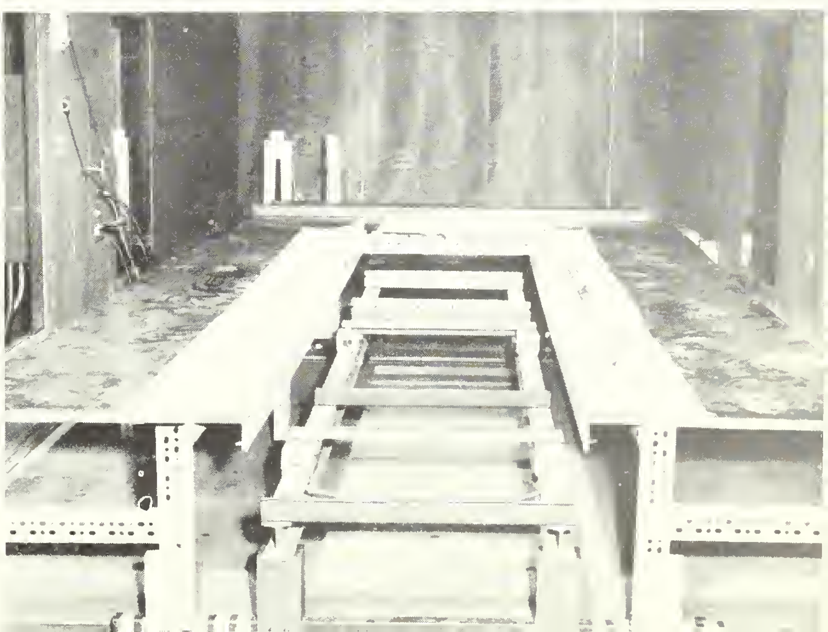
Drying

The fuel bed was ready to be burned as soon as the designated amount of retardant- sociated moisture had evaporated. The evaporation was monitored on the same weighing stem used to measure rate of fuel consumption during the fire.

Ignition

Just before test time, an observer poured 15 cc. of alcohol into the ignition trough. A motely controlled electric spark ignited the alcohol, which in turn set afire the igniter tray untreated needles. The fire in the untreated fuel bed established a strong flame front, which rned into the retardant-treated fuel bed.

Figure 7.--Instrumented support frame in wind tunnel. Note the side and front ground planes in place.



Measurements

Records began when needles on the treated fuel bed first caught fire.

Rate of spread.--A marker board lay alongside the untreated fuel bed. An observer with a stopwatch recorded the length of time required for the fire front to travel each 6-inch increment of fuel bed. He also noted any unusual or erratic behavior.

Weight loss.--The loss of weight as the flame front advanced was measured by a system of strain gages used as the sensing element; it transmitted the information onto a strip chart recorder. The record was continued after the flames reached the end of the fuel bed until no more appreciable loss was encountered.

Radiation.--A radiometer mounted 8 feet above the fuel bed measured and transmitted to a strip chart recorder the radiant energy released between the 5- and 7-foot marks of the burning fuel bed.

RESULTS

Drying Test

Results of the drying test are shown in figures 8a, 8b, and 8c. These uncorrected data clearly show that the retardants dry according to the environmental conditions as well as the initial amount of retardant applied. Contrary to popular belief, all retardants dry at practically the same rate. Retardants applied in heavier application amounts than the mean stayed high in the grouping; conversely, those that were applied lighter than the mean stayed low. Any real difference in drying rate would be shown by crossing lines and definite trends away from the mean; to be significant, such divergences would have to exist in all nine conditions tested. No such trends are apparent.

The data shown in all three parts of figure 8, when plotted on semilog paper, produce straight lines until the retardant is almost dry. The deviation at the dry end of the curve is attributed to the depletion of surface water and the slower release of water from within the fuel itself. An equation for the straight portion of the line is:

$$M = M_o e^{-rt} \qquad (1)$$

where: M = moisture at any time (grams)

M_o = initial amount of moisture (grams)

r = drying rate constant

t = time (minutes)

e = the base of natural logarithms

Equation (1) is the integrated form of the classical differential equation: [7]

$$\frac{dM}{dt} = rM \qquad (2)$$

Equation (2) shows that the change of M with time depends upon a constant r and the amount M that is present at that time.

[7] The form of equations (1) and (2) is used to describe the discharge of a capacitor, the growth of bacteria, or, as Sir Isaac Newton showed, the cooling of a cannonball.

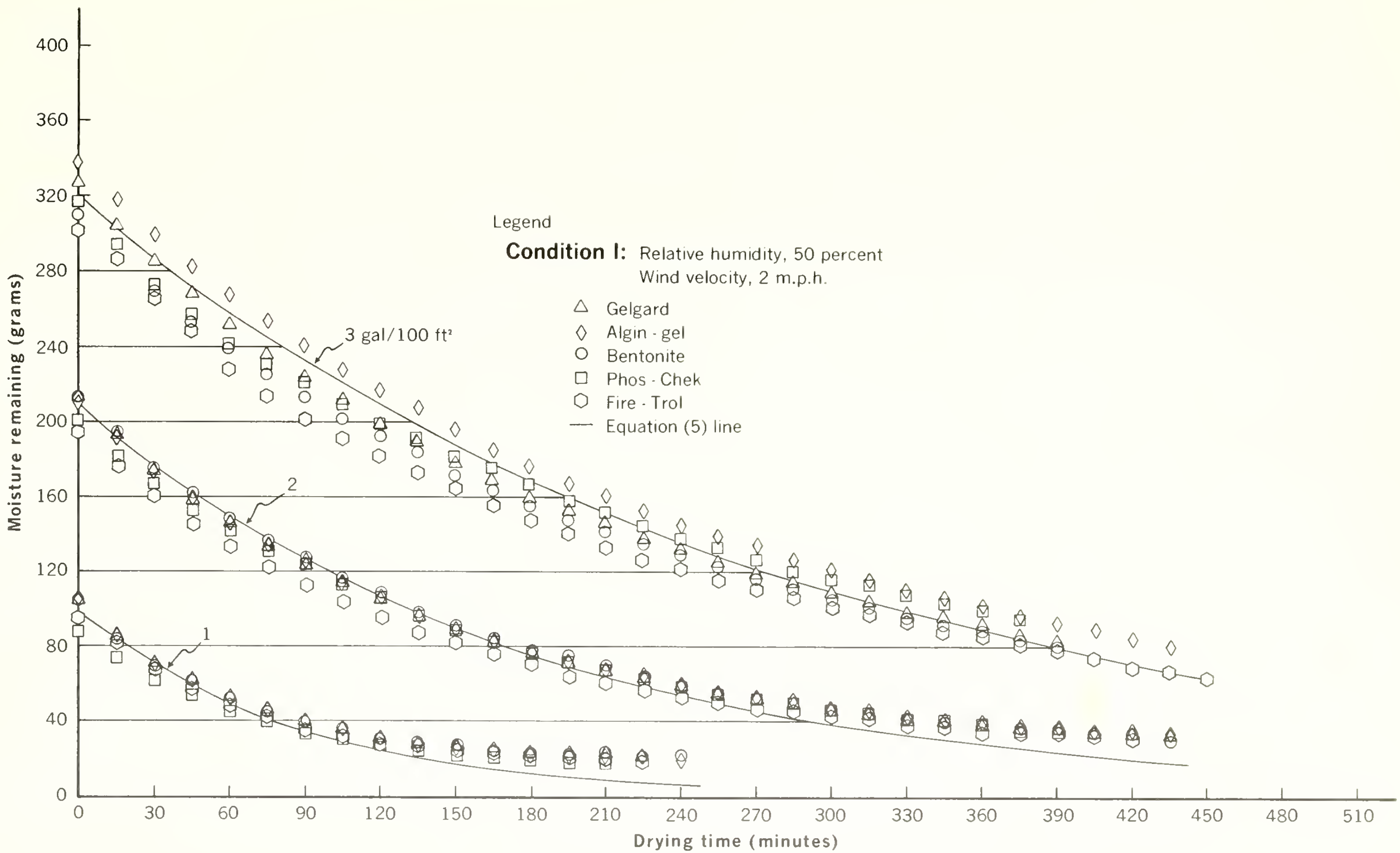


Figure 8a.--Retardant drying rate, Condition I.

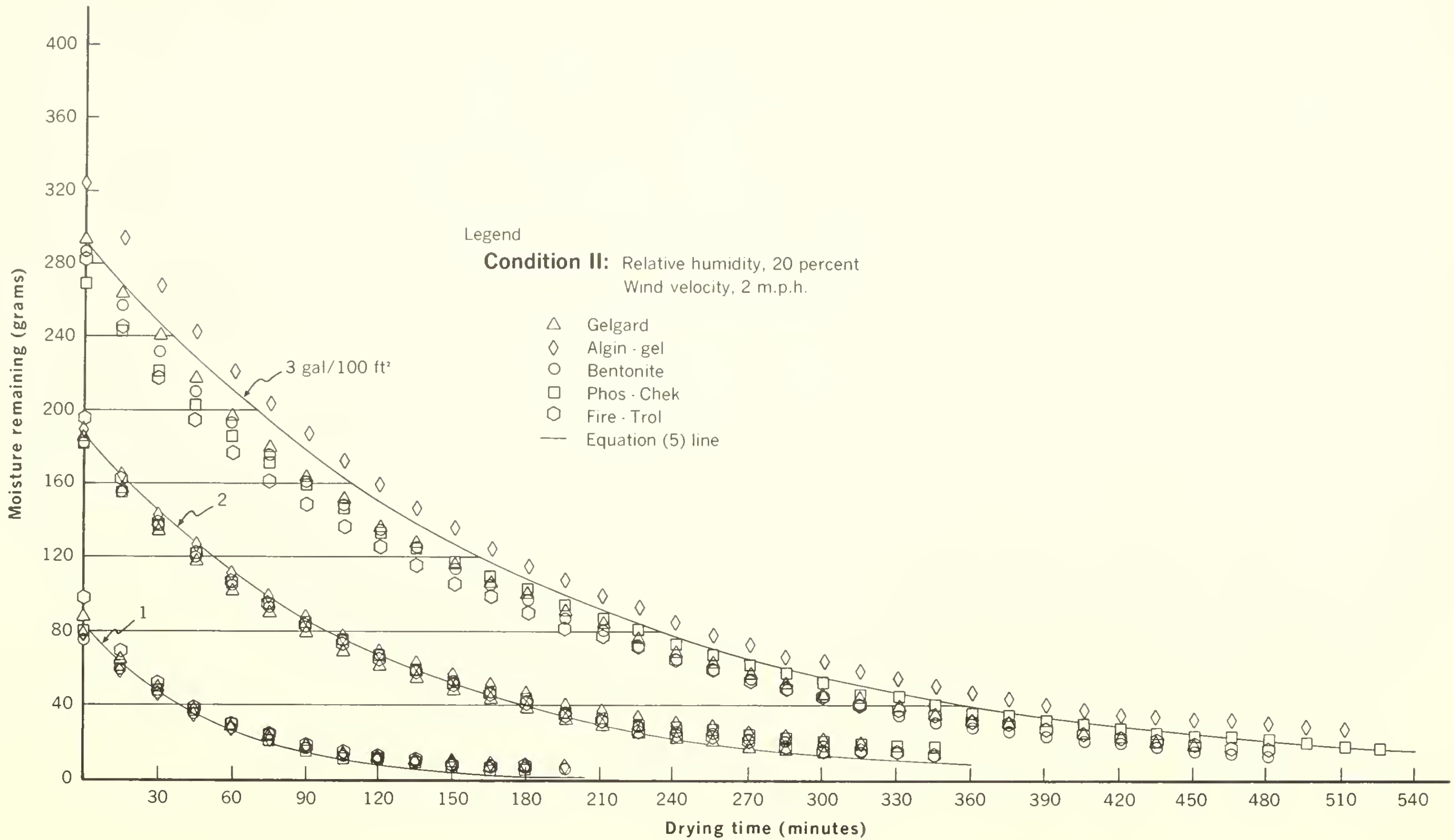


Figure 8b.--Retardant drying rate, Condition II.

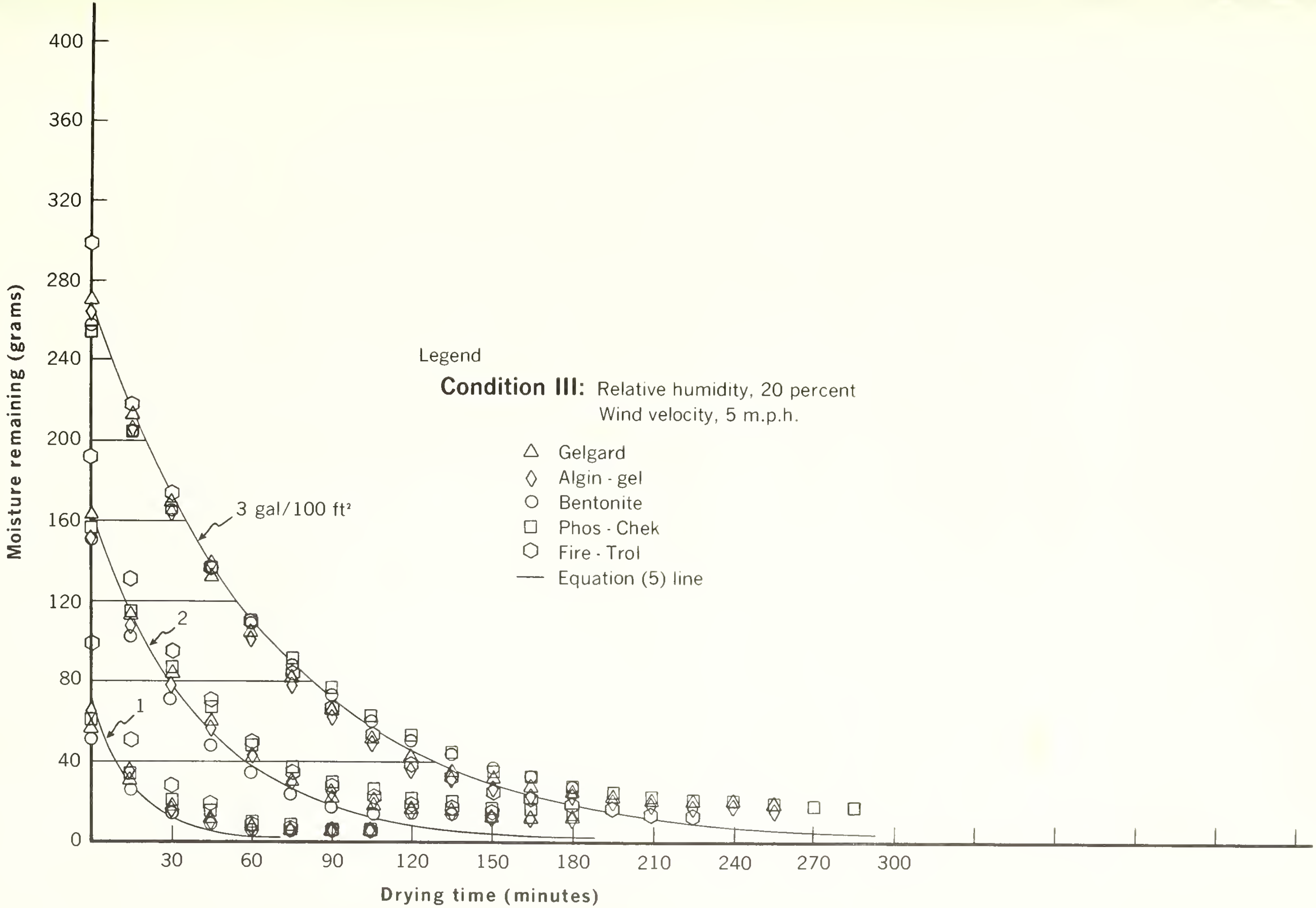


Figure 8c.--Retardant drying rate, Condition III.

Retardants dry by a diffusion process that occurs at the interface between the retardant and the atmosphere. The amount of moisture that leaves the surface and goes into the atmosphere is proportional to the number of water molecules on the surface of the retardant and the environmental conditions that exist at the interface. Thus, M in equation (2) depends upon the number of molecules on the surface of the retardant; and the constant r depends upon the environmental conditions. The drying rate factor r remains constant only for a constant condition.

All of the variables affecting retardant drying and all relations between these variables must be known in order to solve equation (2) from first principles. The experiments conducted in the wind tunnel, however, considered only three variables:

1. Area of retardant surface as controlled by amount of retardant applied to a uniform fuel bed.

2. Difference in vapor pressure between the retardant surface and the atmosphere as governed by relative humidity.

3. Air velocity in close proximity to the fuel bed as governed by wind-tunnel velocity blowing over uniform boundary conditions.

Equation (1) could not be derived from equation (2) and made completely general primarily because the actual value of the initial surface area of the retardant as it clung to the needles and bridged between them could not be determined. However, a satisfactory equation was obtained by considering the three variables tested that affect drying rate, and adjusting r for each variable until a single value resulted.

Surface Area

The surface area of the retardant may be related to the amount of retardant applied uniformly and to the projected area[8] over which it is spread. Consider a unit area of fuel bed (a cross section through the unit area is illustrated in figure 9); if a small amount of retardant is spread uniformly over each needle, it will be thin and will have a relatively large surface area. The maximum surface area possible is equal to that of the needles. As the amount of retardant is increased on the same unit area of fuel bed, liquid bridges form between the needles, and the surface area of the retardant decreases. The limiting value for maximum retardant and minimum surface area equals the projected unit area. This occurs when retardant is applied to fill all the crevices between the needles and only a flat surface of retardant is exposed. The drying rate constant r will therefore be inversely proportional to the amount of retardant applied per unit area.

Vapor Pressure

The correction to the drying rate factor r necessary to account for changes in humidity is provided by considering the difference in vapor pressure. Drying rate is proportional to the coefficient of diffusivity times the difference in vapor pressure between the surface of the retardant and the free stream:

[8] Projected area refers to the flat plane surface area considering the fuel bed to be two-dimensional.

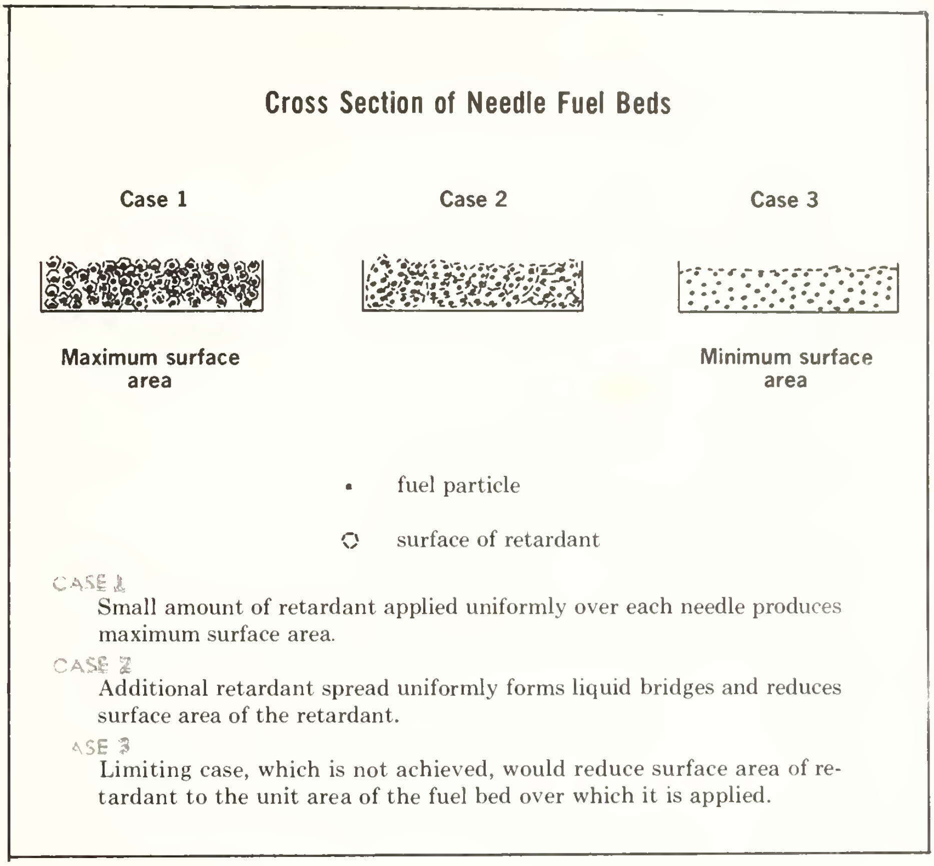


Figure 9.--Relation between surface area of retardant and amount of retardant applied to a unit area of fuel bed.

$$r \approx K\,(pv_o - pv_1) \tag{3}$$

where: K = coefficient of diffusivity

pv_o = saturated vapor pressure at surface of the retardant

pv_1 = partial pressure of the free stream water vapor.

Vapor pressure is determined by the temperature of the gas and the degree of saturation. The vapor pressure at the surface of the retardant may be taken for that of saturated air at the surface temperature T_o. T_o may be obtained in two ways. As an approximation, the wet bulb temperature of the air may be used. For a more exact solution, use the equation

$$T_o - T = \frac{K}{k}\,\frac{L}{c_p}\,\frac{(\rho w - \rho ow)}{\rho} \tag{4}$$

which was developed for estimating the surface temperature of a raindrop[9]

[9] Johnson, John C. Physical meteorology, p. 219, illus. New York: published jointly by Massachusetts Institute of Technology and John Wilson and Sons, Inc. 1954.

where:

T_o = surface temperature of liquid °C.[10]

T = free stream ambient temperature °C.

K = diffusivity of water vapor in air cm.^{2}/sec.

k = thermal diffusivity cm.^{2}/sec.

L = latent heat of vaporization cal./g.

c_p = specific heat at constant pressure cal./g.°C.

ρ_w = ambient vapor density g./cc.

ρ_{ow} = saturated vapor density g./cc. at surface of liquid

ρ = density of air g./cc.

For condition I (90° F., 50-percent RH) equation (4) predicts T_o = 23.8° C. = 75° F. For conditions II and III (90° F., 20-percent RH) equation (4) predicts T_o = 15° C. = 59° F. Having thus determined T_o, the saturated vapor pressure pv_o may be obtained from a steamtable. The free stream partial pressure of water vapor pv_1 may be obtained by multiplying the saturated vapor pressure for the ambient temperature by the relative humidity. For condition I the difference in vapor pressure was 3.94 mm. Hg. For conditions II and III, the difference in vapor pressure = 5.56 mm. Hg.

Air Velocity

Air flowing over the surface of the retardant accelerates the diffusion of water vapor between the retardant surface and the free stream air. Johnson indicates that the correction necessary is proportional to some function of the Reynolds number. The Reynolds number is the product of air density, air velocity, and a significant length of the system divided by the air viscosity. Air velocity was the only one of these variables changed during our tests. The drying rate factor r was therefore assumed to be directly proportional to the air velocity above the fuel.

Figures 8a, 8b, and 8c were first plotted on semilog paper, and a straight line fitted to each of the nine groups of data. The slope of each line gave nine values of the drying rate constant, which we shall designate r_o. Mathematically the modification of r_o assumes the following form:

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[10] Constants for use in equation (4) may be found in table 7.3 of Physical Meteorology, by Johnson (see footnote 9). For a complete solution of the equation, a table of temperature versus vapor density must be used. Such a table is available in handbooks of meteorology. The metric system is used in the retardant drying section of this report because most handbook constants are in this system. The remainder of the report is in the more familiar English units.

let $r' = r_o$ corrected for surface area

$$r' = r_o w_o$$

where w_o = amount of retardant applied per unit area

let $r'' = r_o$ corrected for surface area and vapor pressure

$$r'' = \frac{r_o w_o}{p_{v_o} - p_{v_1}}$$

where p_{v_o} = vapor pressure at surface of retardant

p_{v_1} = vapor pressure in free stream atmosphere

let $r = r_o$ corrected for surface area, vapor pressure and air velocity

$$r = \frac{r_o w_o}{U(p_{v_o} - p_{v_1})}$$

where U = air velocity above fuel bed.

Numerical values for these corrections are shown in table 4. The resulting average value of r is 1.14×10^{-6}. Inserting the corrections for r_o and the new value of r, equation (2) becomes:

$$M = M_o \exp - 1.14\times10^{-6} \frac{U(p_{v_o} - p_{v_1})t}{w_o} \qquad (5)$$

where M = amount at any time, grams[11]

---

[11] M will assume the units of M_o. M_o may be in total values such as pounds or grams or gallons, or it may be in unit values such as grams per square centimeter, pounds per square foot, or gallons per hundred square feet.

Table 4.--Determination of drying rate factor r

Condition	Amount gal./100 sq.ft.	r_o	M_o grams	$\overline{w}_o$ g/cm.^{2}	r'	Ave. r'	$p_{v_o}-p_{v_1}$ mm. Hg.	r''	U cm./sec.	r
I	1	0.010950	97.46	0.03497	3.829×10^{-4}	4.007×10^{-4}	3.94	1.017×10^{-4}	89.4	1.138×10^{-6}
	2	.005513	204.34	.07332	4.042×10^{-4}					
	3	.003633	318.40	.11420	4.149×10^{-4}					
II	1	.018350	84.32	.03027	5.554×10^{-4}	5.800×10^{-4}	5.56	1.043×10^{-4}	89.4	1.167×10^{-6}
	2	.008600	186.72	.06703	5.764×10^{-4}					
	3	.005830	290.94	.10440	6.068×10^{-4}					
III	1	not used	65.52	.02352	--	1.38×10^{-3}	5.56	2.489×10^{-4}	223.5	1.114×10^{-6}
	2	.022270	161.28	.05790	1.289×10^{-3}					
	3	.015360	268.00	.09621	1.478×10^{-3}					
										Ave. r = 1.14×10^{-6}

M_o = initial application amount, grams

U = air velocity at surface of fuel bed, cm./sec.

p_{v_o} = vapor pressure at surface of retardant, mm. Hg

p_{v_1} = partial pressure of moisture in free stream air, mm. Hg

t = time of drying, minutes

w_o = initial application concentration, grams/cm.^{2}.

The lines through the data points (fig. 8) are computed from equation (5). The lines fit the data until the point on the curve where the retardant is nearly dry. As explained, this is believed to result from the depletion of water on the surface of the needles and slower evaporation of moisture from within the needles.

On fine or closely spread fuels such as brush, grass, ground litter, or logging slash, equation (5) provides a good estimate of how much moisture will remain on the treated fuel after drying in a known environment. Logs or other large fuels present a different problem. Equation (5) may also be used to predict effective holding time of short-term retardants by incorporating into the equation an expression for the amount of total moisture required for effective retardation.

Effective Holding Time--Short-Term Retardants

Short-term retardants derive their fire-inhibiting powers from the water they contain. This water, when applied onto a fuel, must evaporate or be driven off by the heat of the fire before the fuel's temperature can be raised to ignition point. Twenty to 22 percent is the generally accepted limit of fuel moisture that will permit combustion in dead fuels without forced convection. Taking the limit of fuel moisture to be at least 22 percent, an expression can be developed for the minimum amount of short-term retardant necessary to be effective against a fire.

Let G = minimum amount of retardant per unit area necessary for effective retardation,

w_f = amount of dead fuel per unit area, and

M_f = fuel moisture content, percent,

then: $$G = w_f\,(.22 - M_f) \qquad (6)$$

G and w_f must be in the same units such as lb./sq.ft., or a conversion constant must be included in the equation.

The equation for retardant drying rate (5) may now be combined with the amount of moisture necessary, equation 6, to estimate the effective time of short-term retardants. The expression for G in equation (6) is substituted for M in equation (5). The initial amount of retardant M_o is changed from total amount to the amount per unit area, and the units are converted to those in general fire control use, resulting in equation (7).

$$w_f\,(.22-M_f) = 1.96\,\exp-\left[\frac{0.0307\,U(p_{v_0}-p_{v_1})t}{G_0}\right] \tag{7}$$

where M_f = fuel moisture content, ratio of moisture to dry weight of fuel

w_f = fuel loading dry weight, tons/acre

G_0 = initial retardant concentration, gal./100 sq.ft.

U = windspeed at 1-foot level, m.p.h.

p_{v_0} = vapor pressure at surface of retardant, in Hg

p_{v_1} = partial pressure of water vapor in air at ambient dry bulb temperature and humidity, p_{v_1} = (relative humidity) $\times$ (saturated vapor pressure), in Hg

t = effective time of retardant, minutes

Equation (7) may be rearranged to solve directly for effective holding time of the retardant.

$$t = \frac{G_0\ \log_e\left[\dfrac{w_f\ (.22-M_f)}{1.96\ G_0}\right]}{-0.0307\ U(p_{v_0}-p_{v_1})} \tag{7.1}$$

where $\log_e$ indicates natural logarithm or logarithm to the base e. Equation (7.1) can now be solved directly for length of holding time if the environmental conditions and fuel conditions are known or can be approximated. As an example, assume:

M_f = 0.05 lb./lb.

w_f = 14.5 tons/acre, dry weight of fuel

G_0 = 3 gal./100 sq.ft., case 1
2 gal./100 sq.ft., case 2

U = 5 m.p.h. at 1-foot level

T_{amb} = 90° F.

RH = 50, 20, 10, and 5 percent

Substitution in equation (7.1) gives effective retardant durations, which are plotted in figure 10.

Limitations of Short-Term Retardant Effective Time Equation

Equation (7) is an empirical equation that was developed for fine dead fuels arranged in a random fuel bed. No consideration has been given for the increased drying rate which would

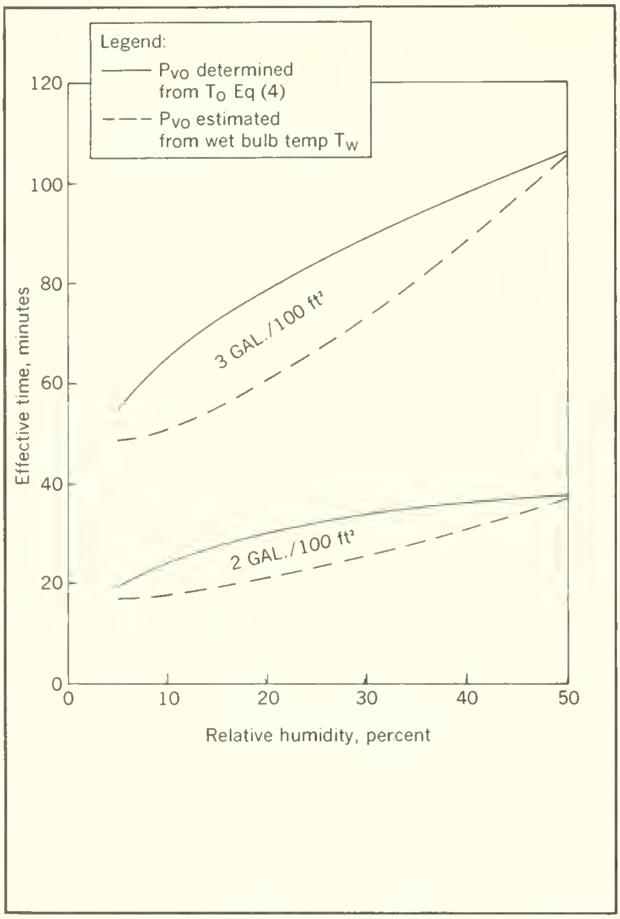

Figure 10.--Short-term retardant an example of effective holdi time. Assume: Windspeed = m.p.h. at 1-ft. level, Temp 90° F., Fuel loading = 14 tons/acre.

result from solar radiation or the close proximity of a fire. Equation (7) will, therefore, pı duce the longest holding time that could be expected, and the effective times shown in figure would be considerably shortened in direct sunlight or near a fire.

Burning Test

Rate of spread, rate of weight loss, and the radiant flux to an overhead radiometer f each fire were measured. Rate of spread, however, was the only variable used in analyzing results of the fires. Rate of weight loss and irradiance supported the rate-of-spread data, tended to be misleading because of the afterburning that often occurred well behind the lead edge of the fire. A "t" test was used to check the significance of changes in environmental c ditions, amount of retardant, and drying time on all of the data. Complete results of the test are given in tables 8-11 (Appendix).

Tables 5 and 6 summarize the rate-of-spread data. Each number cited in the table is average of three or more tests conducted at the stated combination of environmental conditi retardant amount, and degree of dryness. Using this information plus the initial fuel moist and the water content in the retardant mixture, we calculated the total amount of moistu remaining in the fuel bed at the time of ignition.

Table 5.--Short-term retardants--rate of spread

	Environmental condition												
	I					II					III		
Amount of retardant applied (gal./100 sq.ft.)	None	1	2	2	3	None	1	2	2	3	None	1	2
Retardant moisture lost (percent)		33	33	67	67		33	33	67	67		33	33
Forward spread (feet per min.)	1.12	0.435	0.222	0.349	0.160	1.51	0.516	0.264	0.405	0.258	4.38	1.03	0.502
Percent of rate in untreated fuel bed	100	38.8	19.8	31.2	14.3	100	34.2	17.5	26.8	17.1	100	23.6	11.5
Fuel and retardant moisture at time of ignition (percent)	6.0	17.5	29	17.5	23.2	6.0	17.5	29	17.5	23.2	6.0	17.5	29.0

Table 6.--Long-term retardants--rate of spread

	Environmental condition														
	I					II					III				
Amount of retardant applied (gal./100 sq.ft.)	None	1	1	2	2	None	1	1	2	2	None	1	1	2	2
Retardant moisture lost (percent)		67	95	67	95		67	95	67	95		67	95	67	95
Forward spread (feet per min.)	1.12	0.233	0.444	0.169	0.205	1.51	0.418	0.515	0.216	0.231	4.38	1.20	1.71	0.290	0.320
Percent of rate in untreated fuel bed	100	20.8	39.6	15.1	18.3	100	27.7	34.1	14.3	15.3	100	27.6	39.1	6.6	7.3
Fuel and retardant moisture at time of ignition (percent)	6.0	11.0	6.8	15.8	7.5	6.0	11.0	6.8	15.8	7.5	6.0	11.0	6.8	15.8	7.5

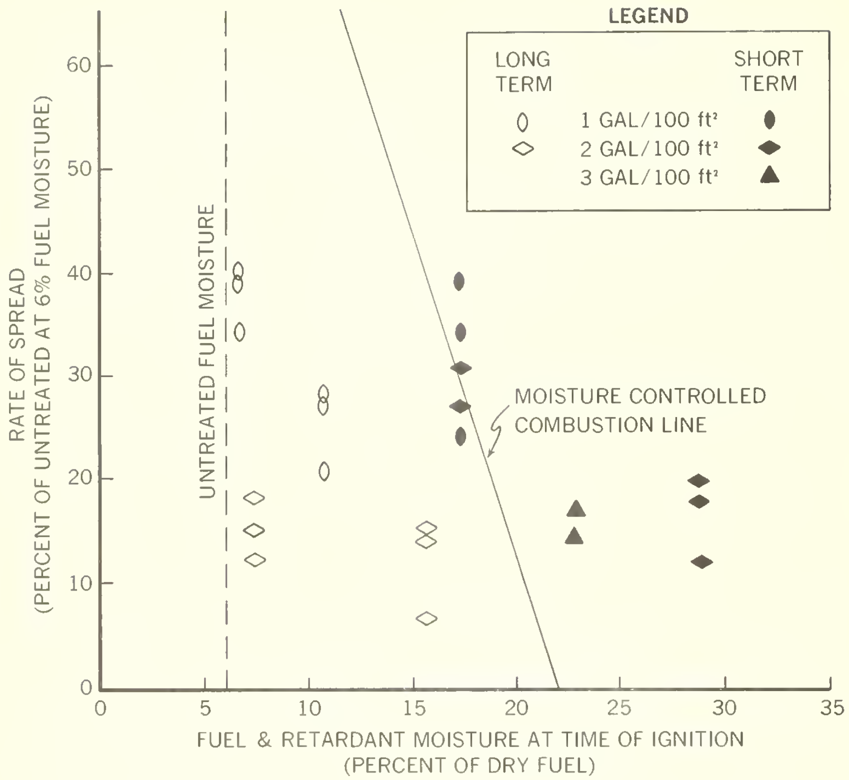

Figure 11.--Effect of total moisture on rate of spread.

The effect of total moisture upon rate of spread is shown in figure 11. Each point is the average of three or more tests. The spread in data is a result of burning in three environmenta conditions. Total moisture is shown as a percent of the dry fuel weight. Rate of spread is shown as a percent of the rate that would occur in an untreated fuel bed at 6-percent moisture content. A line showing the relation between rate of spread and fuel moisture content in untreated fuel beds is shown for comparison with the data points. Data for this line were obtained from previous study of untreated beds.[12] One-hundred-percent rate of spread was taken at 6-percent fuel moisture, and any other rate along the line is based on the 6-percent value. The comparisons of fire retardants were made on this same basis. Note that the line passes througl some of the short-term retardant points and intercepts the fuel moisture coordinate at 22 percent, which was the moisture level used to calculate the effective holding time of short-term retardants in equations 6 and 7.

Refer to figure 11 and note that the short-term retardants are designated by solid symbols and long-term retardants by open symbols. The shape of the symbols designates whether 1, 2, or 3 gal./100 sq.ft. were applied initially. Some interesting conclusions can be drawn from studying figure 11. Data points that fall below 20 percent of the untreated rate of spread were characterized by smoldering combustion; they burned deep in the fuel bed where the retardant had not penetrated. Fuel beds treated with short-term retardant required total fuel moistures greater than the 22-percent fuel moisture limit to suppress the flaming surface fire. When total fuel moisture of the short-term retardant-treated fuel beds was less than 22 percent, the rate of spread began to follow the flaming combustion line of untreated fuel beds at the same

[12] Rothermel and Anderson, op. cit., p. 3.

moisture content. This behavior substantiates the theory that the effective holding time of short-term retardants is limited only by the total amount of moisture on the fuel.

No such limitation exists for the long-term retardant. When the total moisture content was reduced to within 1 or 2 percent of the untreated fuel moisture level (dashed line, fig. 11), the rate of spread was still well below the rate of spread for untreated fuel at the same moisture level. Thus the limitations of solar heating and fire heating mentioned earlier will not shorten the effective holding time of long-term retardants as they would short-term retardants. These facts should be considered seriously in the purchase of retardants, together with relative costs of short-term and long-term retardants.

The effect of initial application amount of long-term retardants is shown in figure 12, where the actual rate of spread is plotted against an approximation of the equivalent National Spread Index. The data now separate and align and best illustrate the effect of initial application amount and retardant drying. Note the marked difference in slope of the lines for initial application amounts of 1 gal./100 sq.ft. and 2 gal./100 sq.ft. For the fuel loading used, an initial concentration of 1 gal./100 sq.ft. was not sufficient to effectively retard the fire. The rate of spread increased sharply with both Spread Index and retardant dryness. However, when the concentration is doubled, it can be seen to be effective even though the Spread Index increases and the retardant loses 95 percent of its moisture. Whatever fire propagation occurred when 2 gal./100 sq.ft. was applied took place near the bottom of the fuel bed, where the retardant did not penetrate.

The "t" tests confirm these observations. Drying time was significantly different when only 1 gal./100 sq.ft. was applied, but was not significant when 2 gal./100 sq.ft. were applied. Where 2 gal./100 sq.ft. were initially applied and the long-term retardant was fully dry (95 percent), the difference due to environment was not significant. In every case, a high significance level was found for differences in initial application amount.

This result should not be entirely unexpected since the long-term retardant contains a fire-inhibiting salt which must contact the fuel if it is to alter the combustion characteristics of the fuel. A certain minimum ratio of retardant to fuel may be expected to exist, and applications below this amount should not be expected to provide sufficient treatment to enough fuel to be effective in suppressing the fire. Our work indicates the ratio for the initial amount of long-term retardant is near 0.4 pound of retardant per pound of dead fuel. This ratio should, of course, be put in terms of the necessary ratio of retardant salt to dry fuel required to hold a fire. Such a ratio would provide a basis of comparison for long-term retardants.

CONCLUSIONS

1. All five of the retardants tested had similar drying rates within each of nine drying combinations.

2. Rates of spread in fuel beds treated with long-term retardants were well below the value which might be expected if moisture alone were causing the effectiveness. In contrast, rate of spread in fuels treated with short-term retardants appears to depend entirely upon total moisture retained.

3. Long-term retardants are effective even after their moisture has evaporated when the initial amount of retardant is sufficient. Short-term retardants remain effective only when the moisture retained around or in the fuel is at least 22 percent of the dry weight of the fuel.

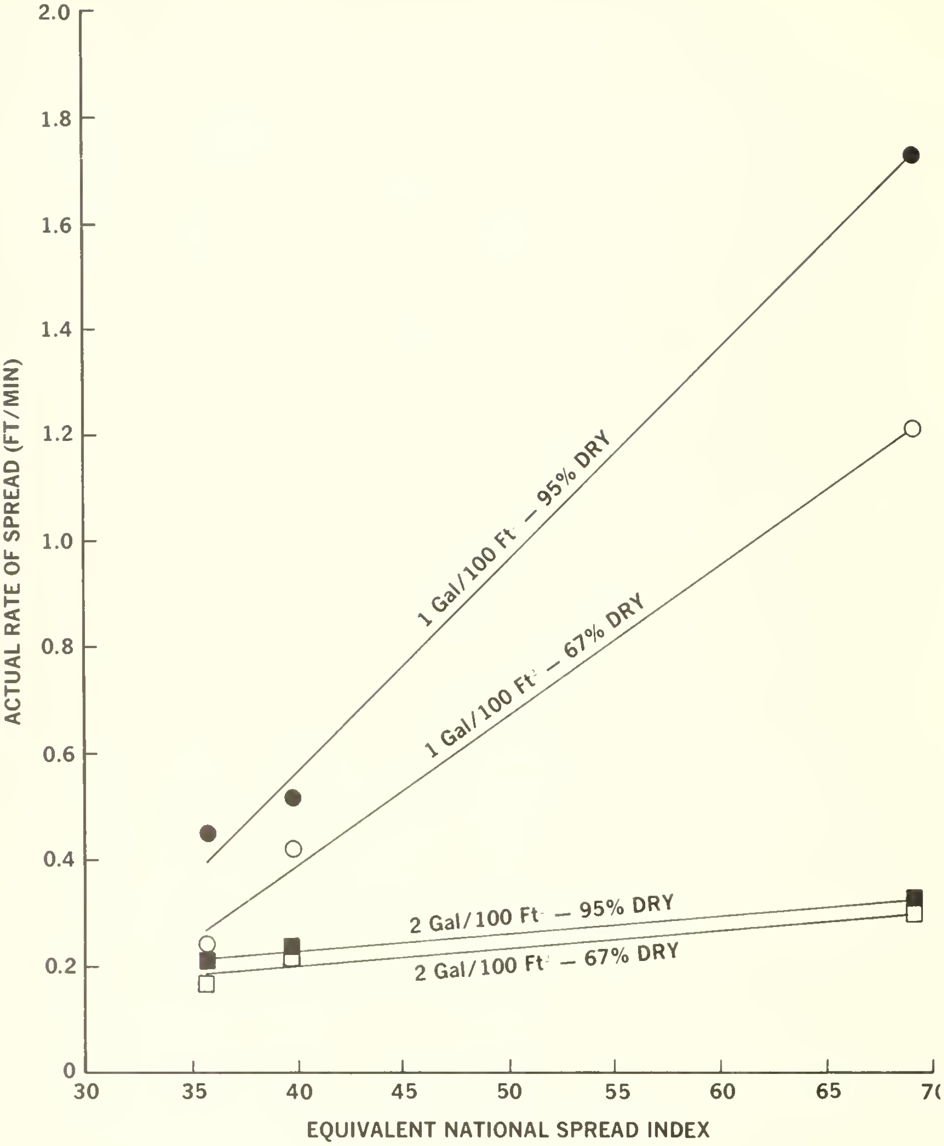

Figure 12.--Influence of concentration and dryness upon rate of spread of long-term retardant.

4. The maximum length of time that a short-term retardant can effectively "hold" a fire can be predicted by equation (7):

$$w_f(.22 - M_f) = 1.96 \exp \frac{-0.0307\, U\, (p_{v_o} - p_{v_1})\, t}{G_o}$$

This holding time may be extremely short when the retardant is subjected to low humidity, moderate airflow, exposure to sunlight, and radiant or convective heating by flames.

5. A certain minimum ratio, by weight, of long-term retardant to fuel appears necessary for best results. Laboratory tests indicate the ratio is near 0.4. Ultimately this ratio will have to be associated with actual weight of salt remaining instead of total weight of solution applied.

BURNING TEST

Treatment and Time Record

Run No. 14 Fire No. ____ Date 4/24/64

Chemical name ____ Symbol ____ ST LT 1/3 2/3 Fully

Condition II Average wind velocity 2.0 m.p.h.

Relative humidity 20.8 percent Average temperature 90.8 °F.

Event	Weight (lbs.) Computed	Actual	Error +	Error −
1. Untreated loaded tare	99.47	99.47		
2. Total weight of application	1.14	1.10		.04
3. Treated loaded tare (1 & 2)	100.61	100.57		
4. Untreated loaded tare	99.47			
5. Chemical	.29			
6. Unavailable water	.08			
7. 1/3 - 2/3 - 95 percent of available water	.26			
8. Total weight at time of burn (4, 5, 6 & 7)	100.10			
9. Amount of water to lose (3-8)	.51	.47		

Event	Time Clock	Elapsed
10. Spray and weigh completed	0955:00	
11. Tray in tunnel	0956:20	0:00:00
12. Weight loss recorder began	0959:30	0:01:10
13. Weight loss recorder stopped	1055:00	
14. Ready to burn	1056:25	
15. Fire reached treated tray	1057:40	1:01:20

Figure 13.--Sample treatment and time record sheet.

Table 7.--Technical mixing data[1] (as used in this study)

Retardant	Manufacturer	Composition	Chemical added to 1 gallon water[2]	
			Grams	Lbs.
Gelgard	Dow Chemical Co.	Proprietary	5.40	0.0120
Algin-gel	Kelco Company	Sodium alginate	18.90	.0416
		$CaCl_2$	1.98	.0044
		Paraformaldehyde	.38 (cc)	.0009
Bentonite	American Colloid Co. and others	High sodium swelling bentonite clay	340.00	[3] .75
			313.20	[4] .72
Phos-Chek 202	Monsanto Co.	Sodium carboxymethyl-cellulose, diammonium phosphate, corrosion inhibitor, preservative	518.00	1.14
Fire-Trol	Arizona Agri-chemical Co.	Attapulgite clay, ammonium sulfate, corrosion inhibitor	1,271.00	2.78

[1] Materials are mixed in amounts generally according to information in "Chemicals for Forest Fire Fighting," NFPA, 1963.

[2] Directions for mixing:

1. Water used is local well water, except for mixing Gelgard, which requires distilled water; water should be 73° F.
2. All mixing reported here was done with the Pacific Southwest Forest and Range Experiment Station's high-shear impeller driven at 2,380 r.p.m.
3. Viscosity should be determined by the following procedure, using Brookfield model LVF viscometer, at spindle speed of 60 r.p.m.:
    a. Mix and let stand at least 18 hours. Record mixture temperature.
    b. Slosh container around for 20 seconds and fill a 1,000-ml. beaker.
    c. Let mixture stand 3 minutes.
    d. Run viscometer 1 minute, then take 3 readings.
    e. Raise spindle out, stir mildly and replace spindle.
    f. Repeat viscometer run as in (d) and (e) above.
    g. Repeat (e) and (f) above: will make 3 runs of 3 readings each.

[3] Drying test.

[4] Burning test.

Table 8.--"t" test for amount of retardant

Runs compared	Dryness condition amount retardant	Rate of spread: Average rate of spread	Rate of spread: Significance of rate of spread	Radiation: Average radiation	Radiation: Significance of radiation	Weight loss: Rate of weight loss	Weight loss: Significance of rate of weight loss
		Ft./min.	Percent	BTU/sq.ft./hr.	Percent	Lbs./min.	Percent
1	1/3 I 2 ST	0.222		6.47		0.16	
2	1/3 I 1 ST	.435	99.5	12.27	99	.25	99.5
3	1/3 II 2 ST	.264		11.42		.21	
4	1/3 II 1 ST	.516	99.5	15.83	95	.34	99
5	1/3 III 2 ST	.502		6.75		.23	
6	1/3 III 1 ST	1.034	99.5	15.38	99.5	.41	95
7	2/3 I 2 ST	.349		10.29		.23	
8	2/3 I 3 ST	.160	99.5	7.78	[1] 70	.12	97.5
9	2/3 II 3 ST	.258		7.94		.22	
10	2/3 II 2 ST	.405	99.5	7.69	[2] N.S.	.27	90
11	2/3 I 2 LT	.169		5.10		.14	
12	2/3 I 1 LT	.233	95	5.62	[3] 60	.15	[3] 70
13	2/3 II 2 LT	.216		6.82		.19	
14	2/3 II 1 LT	.418	97.5	9.31	90	.25	[4] 70
15	2/3 III 2 LT	.290		7.28		.16	
16	2/3 III 1 LT	1.208	99.5	17.21	97.5	.42	99.5
17	F I 2 LT	.205		5.75		.14	
18	F I 1 LT	.444	99.5	9.21	95	.28	99.5
19	F II 2 LT	.231		6.53		.17	
20	F II 1 LT	.515	99	12.33	99.5	.32	99.5
21	F III 2 LT	.320		6.35		.19	
22	F III 1 LT	1.711	99.5	15.33	99.5	.42	99.5

[1] Variation within runs is large and reduces the significance. Sm_7 and Sm_8 = 2.03; S_7 and S_8 = 4.17.

[2] The rate of 3 gal./100 sq. ft. shows greater radiation than the rate of 2 gals./100 sq.ft. Run 10 had no peaks or humps in radiometer, while run 9 had peaks in all fires. Radiation in 10 is probably low, as supported by the fact run 7 had higher radiation and was the same except it was condition I instead of II.

[3] In run 11, all three fires had large peaks, while in run 12 the fires had no peaks, probably making the radiation and weight loss high. Also, in run 12 one fire had a radiation of 3.9, pulling down the average radiation and increasing the sums of squares. S = 2.02 and Sm = 1.17.

[4] The significance is low because the variation within values ranges from .15 to .44 in run 14. S = .15 and Sm = .09. S is greater than the difference between runs 13 and 14.

Table 9.--"t" test for environmental conditions

Runs compared	Dryness condition amount retardant	Rate of spread: Average rate of spread	Rate of spread: Significance of rate of spread	Radiation: Average radiation	Radiation: Significance of radiation	Weight loss: Rate of weight loss	Weight loss: Significance of rate of weight loss
		Ft./min.	Percent	BTU/sq.ft./hr.	Percent	Lbs./min.	Percent
1	1/3 I 2 ST	0.222		6.47		0.16	
3	1/3 II 2 ST	.264	97.5	11.42	99	.21	99.5
2	1/3 I 1 ST	.435		12.27		.25	
4	1/3 II 1 ST	.516	97.5	15.83	90	.34	95
3	1/3 II 2 ST	.264		11.42		.21	
5	1/3 III 2 ST	.502	97.5	6.75	*[1]99	.23	[1]60
4	1/3 II 1 ST	.516		15.83		.34	
6	1/3 III 1 ST	1.034	99.5	15.38	[2]N.S.	.41	[2]N.S.
7	2/3 I 2 ST	.349		10.29		.23	
10	2/3 II 2 ST	.405	80	7.69	*[3]80	.27	80
8	2/3 I 3 ST	.160		7.78		.12	
9	2/3 II 3 ST	.258	99.5	7.94	[4]N.S.	.22	90
11	2/3 I 2 LT	.169		5.10		.14	
13	2/3 II 2 LT	.216	90	6.82	90	.19	90
12	2/3 I 1 LT	.233		5.62		.15	
14	2/3 II 1 LT	.418	95	9.31	90	.25	80
13	2/3 II 2 LT	.216		6.82		.19	
15	2/3 III 2 LT	.290	90	7.28	[5]N.S.	.16	*[5]80
14	2/3 II 1 LT	.418				.25	
16	2/3 III 1 LT	1.208	99.5	17.21	90	.42	90
17	F 1 2 LT	.205		5.75		.14	
19	F II 2 LT	.231	80	6.53	80	.17	80
18	F I 1 LT	.444		9.21		.28	
20	F II 1 LT	.515	90	12.33	95	.32	90
19	F II 2 LT	.231		6.53		.17	
21	F III 2 LT	.320	80	6.35	[6]N.S.	.19	[6]70
20	F II 1 LT	.515		12.33		.32	
22	F III 1 LT	1.711	90	15.33	99.5	.42	99.5

*Significance in the reverse direction.

[1]It appears that data from these two fires are acceptable, the variation being relatively small. It appears the condition of run 5 is critical in that the main agent in the rate of spread is spotting, probably due to the increased wind in condition III. Because of this, the radiation is significantly lower, and the rate of weight loss is not significantly different.

[2]Run 6 again spotted, smoldered, dried out, and then burned more intensively. The radiation charts show a continuous increase in the radiation from 5 to 7 feet in all fires of run 6. In run 4 the radiation is more uniform, not showing the obvious increase from 5 to 7 feet. The averages thus are not significantly different. Because of a large variation in run 6 rate of weight loss, there shows no significant difference between runs 4 and 6 rate of weight loss.

[3]Variation was great, more afterburning occurred in run 7, possibly giving a high average radiation. The fires in run 10 had very little afterburn, thus the probable reason for a lower radiation.

[4]Run 9 fires were very sporadic in their burning pattern. Areas of low radiation and large peaks occurred. Run 8 was much more consistent, variation within also exceeded the variation in between.

[5]Variation is large in both radiation and rate of weight loss. One fire of run 15 with a .10 rate of weight loss is obviously low. Also, since rate of spread was by large fingers, the readings between 3 and 5 feet for rate of weight loss could be low in run 15. (Thus large gains in radiation and weight loss were not shown. The 3- to 5-foot measure does not represent the actual rate of weight loss.)

[6]Variation within fires on these two runs is greater than variation in between. Radiation not uniform as afterburning occurred extensively in run 21.

Table 10.--"t" test for length of drying time

Runs compared	Dryness condition amount retardant	Rate of spread: Average rate of spread	Rate of spread: Significance of rate of spread	Radiation: Average radiation	Radiation: Significance of radiation	Weight loss: Rate of weight loss	Weight loss: Significance of rate of weight loss
		Ft./min.	Percent	BTU/sq.ft./hr.	Percent	Lbs./min.	Percent
1	1/3 I 2 ST	0.222		6.47		0.16	
7	2/3 I 2 ST	.349	97.5	10.29	95	.23	95
3	1/3 II 2 ST	.264		11.42		.21	
10	2/3 II 2 ST	.405	99.5	7.69	*[1] 95	.27	95
11	2/3 I 2 LT	.169		5.10		.14	
17	F I 2 LT	.205	[2] 80	5.75	90	.14	[2] N.S.
12	2/3 I 1 LT	.233		5.62		.15	
18	F I 1 LT	.444	99.5	9.21	90	.28	95
13	2/3 II 2 LT	.216		6.82		.19	
19	F II 2 LT	.231	[2] 70	6.53	*[2] 60	.17	*[2] 70
14	2/3 II 1 LT	.418		9.31		.25	
20	F II 1 LT	.515	90	12.33	90	.32	70
15	2/3 III 2 LT	.290		7.28		.16	
21	F III 2 LT	.320	[2] 60	6.35	*[2] 70	.19	[2] 80
16	2/3 III 1 LT	1.208		17.21		.42	
22	F III 1 LT	1.711	97.5	15.33	*[3] 60	.42	[3] N.S.

* Significance in the reverse direction.

[1] Same as for 3 on conditions--run 10 had very little afterburning. Flame front had not reached the 5- to 7-foot area during the time the rate of spread showed it to be there, thus causing a low radiation measure.

[2] The effect of dryness with this long-term retardant of 2N amount is not significant. The 2/3 dry seems to be as effective as the fully dry, as shown in comparisons of runs 11 and 17, 13 and 19, and 15 and 21.

[3] These low significant differences are probably due to the large amount of variation within run 16.

Table 11.--"t" test for type of retardant--long-term or short-term

Runs compared	Dryness condition amount retardant	Rate of spread: Average rate of spread	Rate of spread: Significance of rate of spread	Radiation: Average radiation	Radiation: Significance of radiation	Weight loss: Rate of weight loss	Weight loss: Significance of rate of weight loss
		Ft./min.	Percent	BTU/sq.ft./hr.	Percent	Lbs./min.	Percent
7	2/3 I 2 ST	0.349		10.29		0.23	
11	2/3 I 2 LT	.169	97.5	5.10	97.5	.14	97.5
10	2/3 II 2 ST	.405		7.69		.27	
13	2/3 II 2 LT	.216	99.5	6.82	60	.19	80

Table 12.--Averages and variations in each run

Run	Dry time	Condition	Amt.	Type retardant	Average rate of spread	± S*	± S_m**	No. of fires	Average radiation	± S*	± S_m**	No. of fires	Rate of weight loss	± S*	± S_m**	No. of fires
			Gal./100 ft.^{2}		Ft./min.				BTU/ft.^{2}/hr.				Lbs./min.			
1	1/3	I	2	ST	0.222	0.017	0.008	4	6.47	2.09	1.04	4	0.16	0.020	0.010	4
2	1/3	I	1	ST	.435	.032	.017	3	12.27	1.87	1.08	3	.25	.028	.016	3
3	1/3	II	2	ST	.264	.014	.008	3	11.42	1.28	.74	3	.21	.012	.007	3
4	1/3	II	1	ST	.516	.022	.013	3	15.83	3.15	1.82	3	.34	.050	.029	3
5	1/3	III	2	ST	.502	.118	.068	3	6.75	1.47	.85	3	.23	.081	.047	3
6	1/3	III	1	ST	1.034	.249	.102	6	15.38	2.52	1.03	6	.41	.090	.052	3
7	2/3	I	2	ST	.349	.099	.044	5	10.29	2.92	1.31	5	.23	.060	.030	5
8	2/3	I	3	ST	.160	.014	.008	3	7.78	1.25	.722	3	.12	.032	.018	3
9	2/3	II	3	ST	.258	.022	.013	3	7.94	.49	.28	3	.22	.029	.017	3
10	2/3	II	2	ST	.405	.037	.021	3	7.69	2.34	1.35	3	.27	.038	.022	3
11	2/3	I	2	LT	.169	.033	.019	3	5.10	.52	.30	3	.14	.020	.012	3
12	2/3	I	1	LT	.233	.032	.018	3	5.62	2.02	1.17	3	.15	.012	.007	3
13	2/3	II	2	LT	.216	.027	.016	3	6.82	1.43	.826	3	.19	.036	.021	3
14	2/3	II	1	LT	.418	.115	.057	4	9.31	2.91	1.45	4	.25	.134	.067	4
15	2/3	III	2	LT	.290	.081	.040	4	7.28	1.26	.63	4	.16	.046	.023	4
16	2/3	III	1	LT	1.208	.276	.159	3	17.21	6.47	3.74	3	.42	.090	.052	3
17	95%	I	2	LT	.205	.029	.017	3	5.75	.038	.022	3	.14	.026	.015	3
18	95%	I	1	LT	.444	.071	.041	3	9.21	2.34	1.35	3	.28	.040	.023	3
19	95%	II	2	LT	.231	.017	.010	3	6.53	1.11	.641	3	.17	.025	.014	3
20	95%	II	1	LT	.515	.022	.013	3	12.33	.354	.204	3	.32	.010	.006	3
21	95%	III	2	LT	.320	.139	.062	5	6.35	2.98	1.33	5	.19	.044	.020	5
22	95%	III	1	LT	1.711	.110	.064	3	15.33	.975	.562	3	.42	.016	.009	3

* S = standard deviation

** S_m = standard error of the mean

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A BIBLIOGRAPHY OF ENGELMANN SPRUCE

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A BIBLIOGRAPHY of ENGELMANN SPRUCE

This bibliography of Engelmann spruce (Picea engelmannii Parry), while generally comprehensive, emphasizes publications on the ecology of the species. It supplements the excellent bibliography by Ronco (1961) on Engelmann spruce and subalpine fir, which emphasized publications about management of these species. The present publication includes references to items published through calendar year 1963 and provides brief annotations describing the nature of information about Engelmann spruce contained in the referenced item. Publications whose titles are descriptive or self-explanatory are not annotated. This bibliography includes references to printed publications and to theses, but it does not refer to typewritten reports.

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FOREST SERVICE CREED

The Forest Service of the U. S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing nation.

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Project headquarters 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)
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- Provo, Utah (in cooperation with Brigham Young University)

U. S. Forest Service
Research Paper INT-20
1965

A TECHNIQUE FOR SAMPLING POPULATIONS OF THE MOUNTAIN PINE BEETLE

by

Robert W. Carlson and Walter E. Cole

INTERMOUNTAIN FOREST & RANGE EXPERIMENT STATION
FOREST SERVICE
U. S. DEPARTMENT OF AGRICULTURE
OGDEN, UTAH

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A TECHNIQUE FOR SAMPLING POPULATIONS OF THE MOUNTAIN PINE BEETLE

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Suitable sampling techniques are basic to the determination of relations between an insect and the host plant. Development of suitable sampling techniques is part of intensive studies on the population dynamics of the mountain pine beetle, Dendroctonus monticolae Hopk., in lodgepole pine, now actively underway in the intermountain area of Utah and Wyoming.

This paper reports results of research designed to develop a procedure for sampling populations of the bark beetle during the mature larval and pupal stages. The experimental design tested for variation between sample sizes and shapes, locations on the tree, and trunk diameters, as well as testing for the nature of the statistical distribution.

The study areas selected, though widely separated geographically, were bioclimatically equivalent as defined by Hopkins' Law. One was on the Wasatch National Forest in Utah and the other on the Teton National Forest in Wyoming. The populations sampled in both areas can be considered as epidemic. The Wasatch population has been epidemic in numbers since 1938. The Teton population has shown cyclic tendencies of recurrent epidemics; the present cycle began about 1958. The affected timber stands differ. The Wasatch stand, in general, consists of smaller diameter trees, as old as those in the Teton stand, or older, but less vigorous. The Wasatch population was characterized by low brood density and a current static trend. The Teton infestation showed a definitely increasing trend.

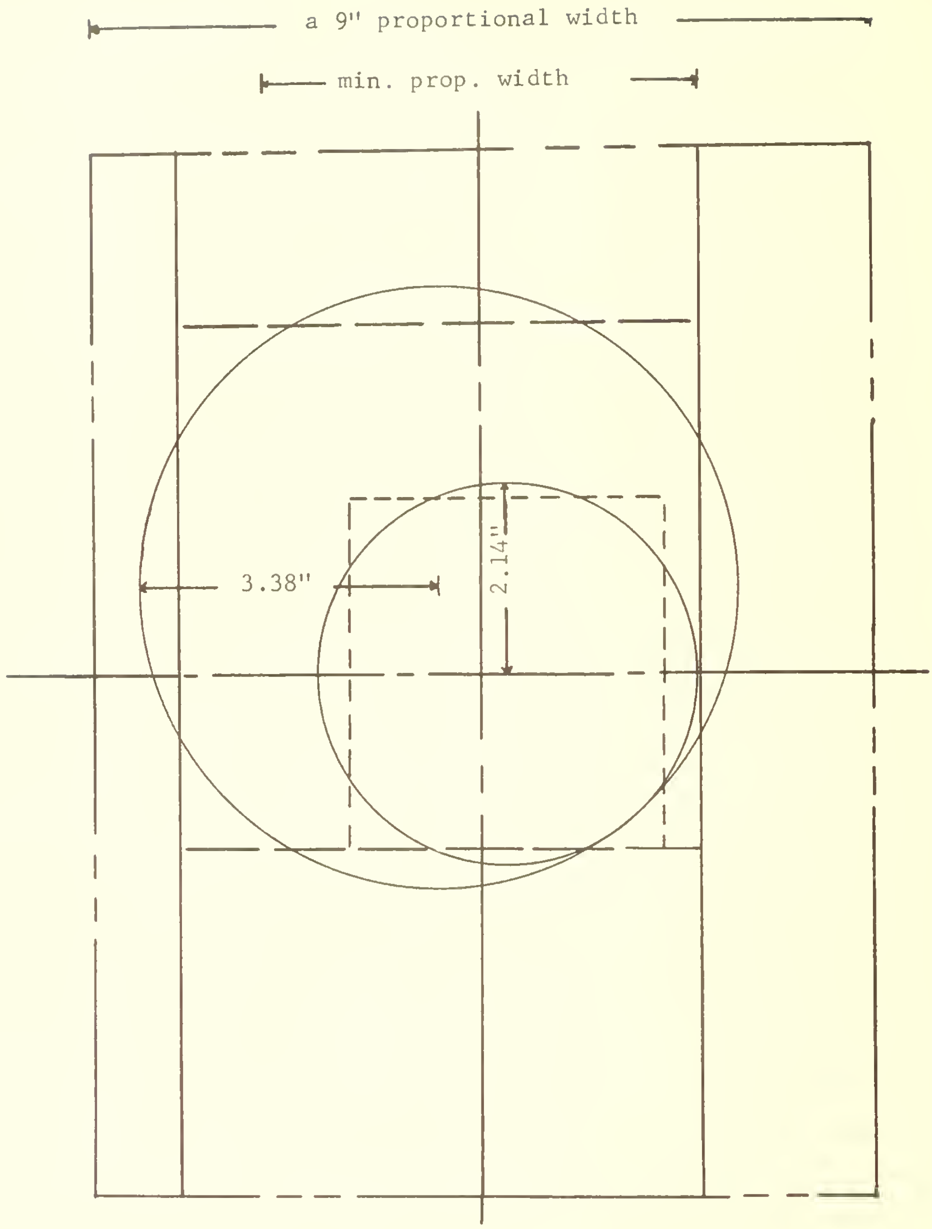
EXPERIMENTAL DESIGN

The experimental work in the two stands was replicated as closely as possible. Three variables were measured (counts): (1) density of attack, (2) length of egg gallery, and (3) density of brood. All existing stages of brood were recorded: mature larvae, pupae, and callow adults. Only successful attacks and consequently successfully constructed egg galleries were recorded.

Sample size: Six sample units were superimposed in a nested fashion at each point sampled (fig. 1). The six units were: four rectangular--1/10, 1/4, and 1/2 sq. ft.--and a sample proportional to tree diameter; and two circular--1/10 and 1/4 sq. ft. Brood counts were made only for the rectangular samples.

Sample location: Each tree was sampled at six points: on the north and south aspects at breast height, 5 feet below the height of infestation, and midway between these two points.

Tree size: Ten trees in each of the following d.b.h. categories per plot were used: 6-9, 9-12, 12-15, and greater than 15 inches. Only 13 trees per plot were sampled for brood, because of the stage of brood development and imminent adult emergence. These trees were selected randomly.



Sample center axis, defining the sample locus
Boundary of 1/2 sq.,ft. rectangular sample
Boundary of 1/4 sq. ft. rectangular sample
Boundary of 1/10 sq. ft. rectangular sample
Boundary of proportional sample.

Figure 1.--The relative placement of the various sample units, showing the method of nesting. Scale: 6" = 1'.

ANALYSIS OF DATA

Statistical distribution: Comparisons of infestations, populations, and other categories can be made on the basis of their statistical distributions. In this study, analysis of distributions was based upon scatter diagrams of variance plotted over means of the three variables measured.

The scatter of variance in relation to mean attack density and gallery length appeared to be random. Comparison of Wasatch and Teton data (figs. 2, 3, 4, and 5) showed no difference in distribution. The brood data, however, typified a contagious distribution--increasing variance with an increase in the mean (figs. 6, 7). There were not enough data to determine the specific contagious distribution involved.

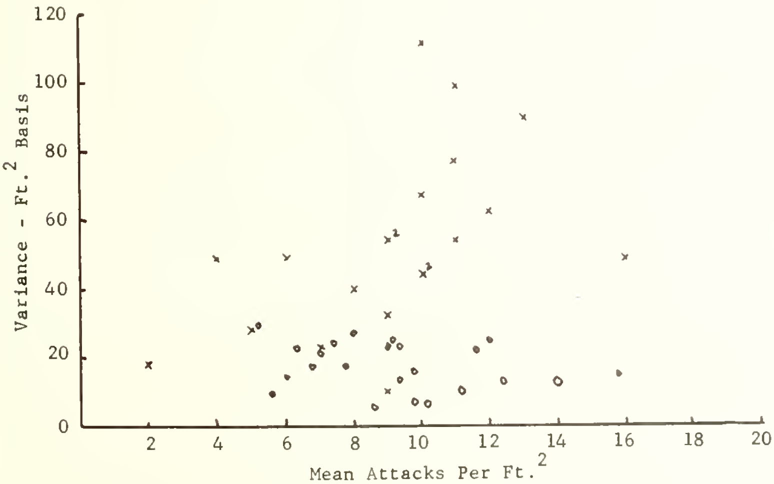


Figure 2.--Teton plot --attack density: x for 1/10 sq. ft. rectangular samples, o for 1/2 sq. ft. samples.

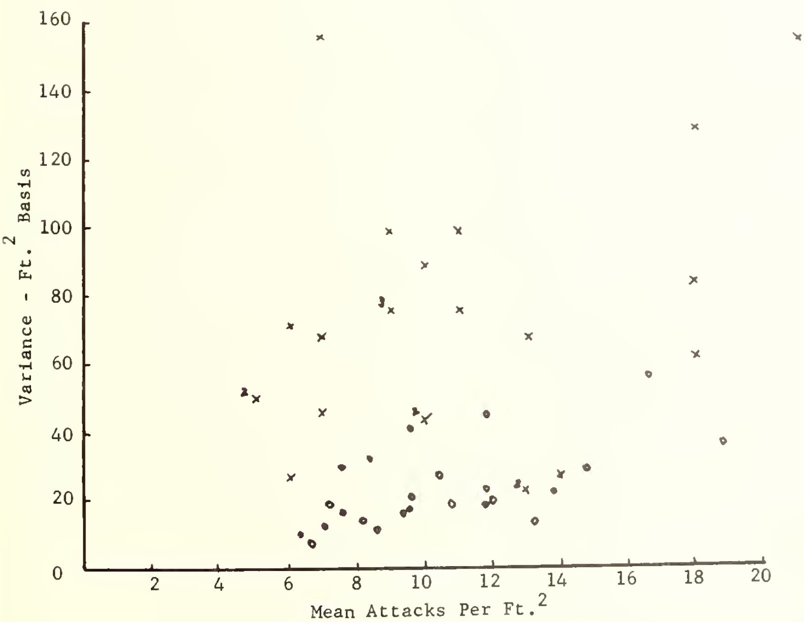


Figure 3.--Wasatch plot--attack density: x for 1/10 sq. ft. rectangular samples, o for 1/2 sq. ft. samples.

Variance analysis of variance: The assumption of normality must also carry the assumption that the variances of the means of the variables are homogeneous before parametric methods can be used. Like means with like variances are considered to be of one population; like means with unlike variances are from different populations.

The data on attack density and brood were converted to a common basis--1 sq. ft.; gallery lengths were converted to a 1/10 sq. ft. basis.

Complete cross-comparisons of variances were made for attack density and gallery length. The 10 trees in each d.b.h. category were considered as replicates (table 1). The cross-comparison of variance for brood density was incomplete because the between-plot difference was not tested. The difference is obvious because the plots were selected on this basis. The basis for replication for brood density was the 13 trees per plot.

Figure 4.--Teton plot --gallery density: x for 1/10 sq. ft. rectangular samples, o for 1/2 sq. ft. samples.

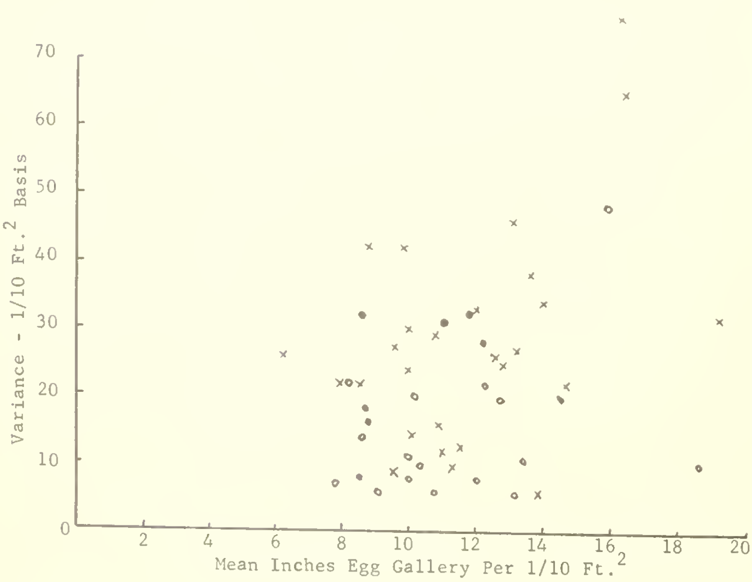


Figure 5.--Wasatch plot--gallery density: x for 1/10 sq. ft. rectangular samples, o for 1/2 sq. ft. samples.

Chi-square analyses: Chi-square comparisons of variance arrangements were used to show the within-tree density trends for d.b.h. categories and plots. These analyses supplemented the variance analysis of variance as a tool in making decisions about proper sampling procedures. Only data for the 1/2 sq. ft. samples were used in the analyses.

Regression analysis: Regression and variance analyses were used to check the relation of each of the following variables to d.b.h.: height of infestation, attack density, and gallery length.

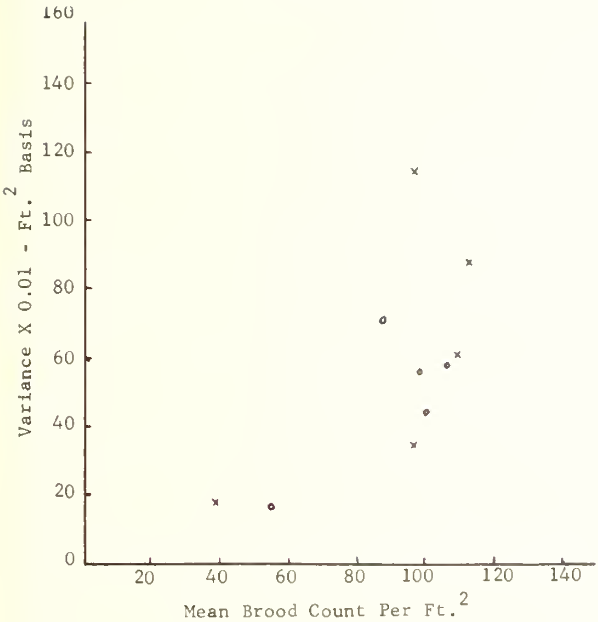


Figure 6.--Teton plot--brood density: x for 1/10 sq. ft. rectangular samples, o for 1/2 sq. ft. samples.

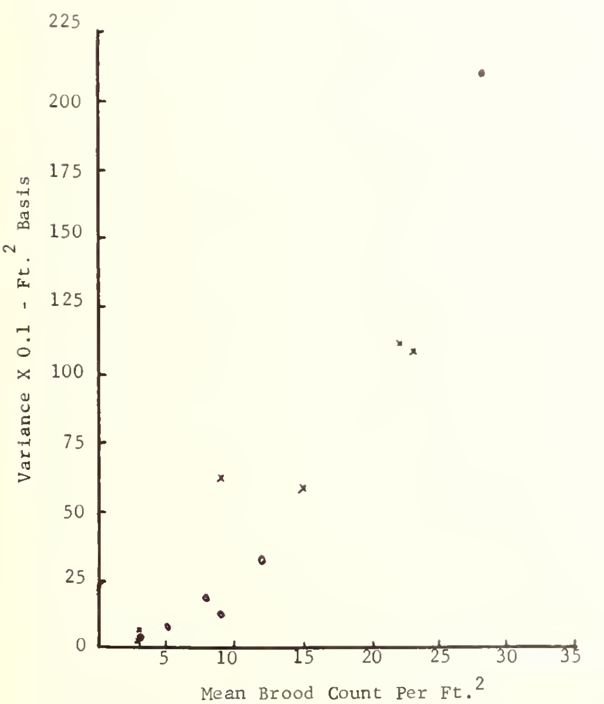


Figure 7.--Wasatch plot--brood density: x for 1/10 sq. ft. rectangular samples, o for 1/2 sq. ft. samples.

Table 1.--Form for computation of sums of squares in variance analysis of variances for attack and for gallery density

Source	Degrees of freedom	Sums of squares
Plots	p-1	$\dfrac{\sum X_P^2 / p}{tsal} - C$
Tree sizes	t-1	$\dfrac{\sum X_T^2 / t}{psal} - C$
Sample sizes	s-1	$\dfrac{\sum X_S^2 / s}{ptal} - C$
PT	(p-1)(t-1)	$\dfrac{\sum X_{PT}^2 / pt}{sal} - C - SS\ (P) - SS\ (T)$
PS	(t-1)(s-1)	$\dfrac{\sum X_{PS}^2 / ps}{tal} - C - SS\ (P) - SS\ (S)$
TS	(t-1)(s-1)	$\dfrac{\sum X_{TS}^2 / ts}{pal} - C - SS\ (T) - SS\ (S)$
Error, PTS	(p-1)(t-1)(s-1)	$\dfrac{\sum X_{PTS}^2 / pts}{al} - C - SS\ (P) - SS\ (T) - SS\ (S)$
Subtotal	pts-1	$\dfrac{\sum X_{PTS}^2 / pts}{al} - C$

(Continued)

Table 1.--(con.)

Source	Degrees of freedom	Sums of squares
Aspects	a-1	$\frac{\sum X_A^2}{\frac{a}{ptsl}} - C$
Levels	l-1	$\frac{\sum X_L^2}{\frac{l}{ptsa}} - C$
AL	(a-1)(l-1)	$\frac{\sum X_{AL}^2}{\frac{al}{pts}} - C - SS\ (A) - SS\ (L)$
AP	(a-1)(p-1)	$\frac{\sum X_{AP}^2}{\frac{ap}{tsl}} - C - SS\ (A) - SS\ (P)$
AT	(a-1)(p-1)	$\frac{\sum X_{AT}^2}{\frac{at}{psl}} - C - SS\ (A) - SS\ (T)$
AS	(a-1)(s-1)	$\frac{\sum X_{AS}^2}{\frac{as}{ptl}} - C - SS\ (A) - SS\ (S)$
LP	(l-1)(p-1)	$\frac{\sum X_{LP}^2}{\frac{lp}{tsa}} - C - SS\ (L) - SS\ (P)$
LT	(l-1)(t-1)	$\frac{\sum X_{LT}^2}{\frac{lt}{psa}} - C - SS\ (L) - SS\ (T)$
LS	(l-1)(s-1)	$\frac{\sum X_{LS}^2}{\frac{ls}{pta}} - C - SS\ (L) - SS\ (S)$
Error, PTSAL	(p-1)(t-1)(s-1) x(a-1)(l-1)	$\frac{\sum X_{PTSAL}^2}{ptsal} - C -$ Subtotal SS - SS (A)- SS (L) - SS (AL) - SS (AP) - SS (AT - SS (AS) - SS (LP) - SS (LT) - SS (LS)
Total	ptsal-1	$\frac{\sum X_{PTSAL}^2}{ptsal} - C$

$$C = \text{correction term} = \frac{(\sum X_{PTSAL})^2}{ptsal}$$

RESULTS

Sample size: The variance analysis of variances showed significant differences between sample sizes, diameters, and plots for the attack density and gallery length variables, but showed no significant differences between sample sizes for brood. The Student-Newman-Keul's Multiple Range Test (Steel and Torrie 1960)[1] showed that all sample sizes differed significantly from each other for gallery length, and the 1/10 sq. ft. sample differed significantly from all others for attack density. The variance between diameter for both attack density and gallery length did not show like patterns of occurrence. The test failed to reveal differences between sample heights for attack density, and only top and mid-sample heights differed significantly for brood density.

The brood density variation was greater than either the attack density or gallery length variation. Thus, inferences drawn from the brood density variable will be used to determine sample size for the sampling plan.

The Teton data showed downward trend of the coefficient of variation with increase of sample size, but the Wasatch data did not. This distribution of the coefficient of variation is probably due to the effect of zero counts--the larger the sample size the fewer zero counts, and the greater likelihood of reducing variance.

Sample location: The variances of all three variables were generally greater at breast height and mid-height than at the top sampling height. The only significant difference was between mid- and top heights for the brood density variable. On a percentile basis, the three variables were also more consistent. Variance tends to be greatest at breast height, but since the mean values also tend to be larger at this position, the coefficients of variation are not correspondingly high.

Aspect: A significant interaction between aspects by plots indicated that there was never complete consistency. In some interactions, as with aspects, the data cannot be treated as if they fit the same distribution. Random placement of samples, by aspect, can eliminate this effect.

Tables 2, 3, and 4 show the results of the variance analysis of variances.

Tree diameter: Not enough trees were sampled to permit any analysis of brood density in relation to d.b.h.

Regression analysis showed that both attack density and gallery length were significantly related to tree size. Attack density and gallery length increased with tree diameter (tables 5, 6, and 7).

Size of sample needed: The number of samples (trees) needed for a 20-percent SME at the 2/3 probability level was computed for each sample size and all three variables at d.b.h. The north and south samples were combined because they were not random with respect to each other and in effect constituted a single sample.

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[1] Steel, G. D., and J. H. Torrie. Principles and procedures of statistics. New York: McGraw-Hill Book Co., Inc. 481 pp. 1960.

Table 2.--Variance analysis of variances for attack density per square foot[1]

Source	Sum of squares	Degrees of freedom	Mean square	F
Plots	10668.95	1	10668.95	26.56**
Tree sizes	12887.36	3	4295.79	10.70**
Sample sizes	107007.54	5	21401.51	53.29**
PT	1776.20	3	592.07	1.47
PS	2491.72	5	498.34	1.24
TS	7241.00	15	482.73	1.20
Error, PTS	6020.75	15	401.38	
Subtotal	148093.52	47		
Aspects	0.49	1	0.49	0.00
Levels	2264.04	2	1132.02	3.26*
AL	411.86	2	205.93	0.59
AP	1530.43	1	1530.43	4.41*
AT	2087.41	3	695.80	2.00
AS	1066.13	5	213.23	0.61
LP	3727.52	2	1863.76	5.37*
LT	2949.48	6	491.58	1.42
LS	2327.64	10	232.76	0.67
Error, PTSAL	72296.93	208	347.58	
Total	236755.45	287		

[1]Variances computed on a 1 square foot basis.

Table 3.--Variance analysis of variances for gallery density per 1/10 square foot[1]

Source	Sum of squares	Degrees of freedom	Mean square	F
Plots	180.8485	1	180.8485	4.86*
Tree sizes	8774.8823	3	2924.9608	78.68**
Sample sizes	5750.9965	5	1150.1993	30.94**
PT	4140.8553	3	1380.2851	37.13**
PS	84.0797	5	16.8159	0.45
TS	423.1305	15	28.2087	0.76
Error, PTS	556.8869	15	37.1258	
Subtotal	19911.6797	47		

(Continued)

Table 3.--(con.)

Source	Sum of squares	Degrees of freedom	Mean square	F
Aspects	1.4056	1	1.4056	0.00
Levels	1800.3353	2	900.1676	1.71
AL	243.1305	2	121.5518	0.23
AP	2786.9334	1	2786.9334	5.30*
AT	194.6111	3	64.8704	0.12
AS	40.5396	5	8.1079	0.02
LP	119.1520	2	59.5760	0.11
LT	4236.7795	6	706.1299	1.34
LS	668.6304	10	66.8630	0.13
Error, PTSAL	109753.6130	208	527.6616	
Total	139756.7831	287		

[1]Variances computed on a 1/10 square foot basis.

Table 4.--Variance analysis of variances for brood density per square foot

Source	Sum of squares	Degrees of freedom	Mean square	F
Plots (Blocks)	370909825.92	1		
Sample sizes	12845676.64	3	4281892.21	1.16
Error, PS	11038342.64	3	3679447.55	
Subtotal	394793845.20	7		
Aspects	17908167.36	1	17908167.36	5.32*
Levels	35517526.09	2	17758763.04	5.27*
AP	44466345.09	1	44466345.03	13.20**
AS	1774537.12	3	591512.37	0.18
AL	33448518.07	2	16724259.04	4.96*
LP	19075248.37	2	9537624.51	2.83
LS	1364835.05	6	227472.51	0.07
Error, PSAL	77471934.61	23	363344.98	
Total	625820956.90	47		

Table 5.--Regression and variance analysis for height of infestation X d.b.h.

Regression matrix

	N	X	Y	D.F.
N	80	974.10	2052.00	
X		12799.57	26485.66	
Y			58716.50	80
X		938.68	1500.00	
Y			6082.70	79
Y			3685.72	78

Analysis of variance

Source	SS	D.F.	MS	F
B_o	52633.80	1		
B_1	2396.98	1	2396.98	49.42**
Res.	3685.72	76	48.50	
Total	58716.50			

X = D.b.h.
Y = Height of infestation

Table 6.--Regression and variance analysis for attack density X d.b.h.

WASATCH PLOT

Regression matrix

	N	X	Y	D.F.
N	40	487.50	398.00	
X		6414.29	5160.90	
Y			4454.00	40
X		472.88	310.28	
Y			493.90	39
Y			290.31	38

Analysis of variance

Source	D.F.	SS	MS	F
B_o	1	3960.10		
B_1	1	203.59	203.59	27.96**
Res.	38	290.31	7.64	
Total		4454.00		

TETON PLOT

Regression matrix

	N	X	Y	D.F.
N	40	486.60	530.00	
X		6385.28	6792.40	
Y			8016.00	40
X		465.79	344.95	
Y			993.50	39
Y			738.04	38

Analysis of variance

Source	D.F.	SS	MS	F
B_o	1	7022.50		
B_1	1	255.46	255.46	13.15**
Res.	38	738.04	19.42	
Total		8016.00		

X = D.b.h.
Y = Density of attack

FOREST SERVICE CREED

The Forest Service of the U. S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing nation.

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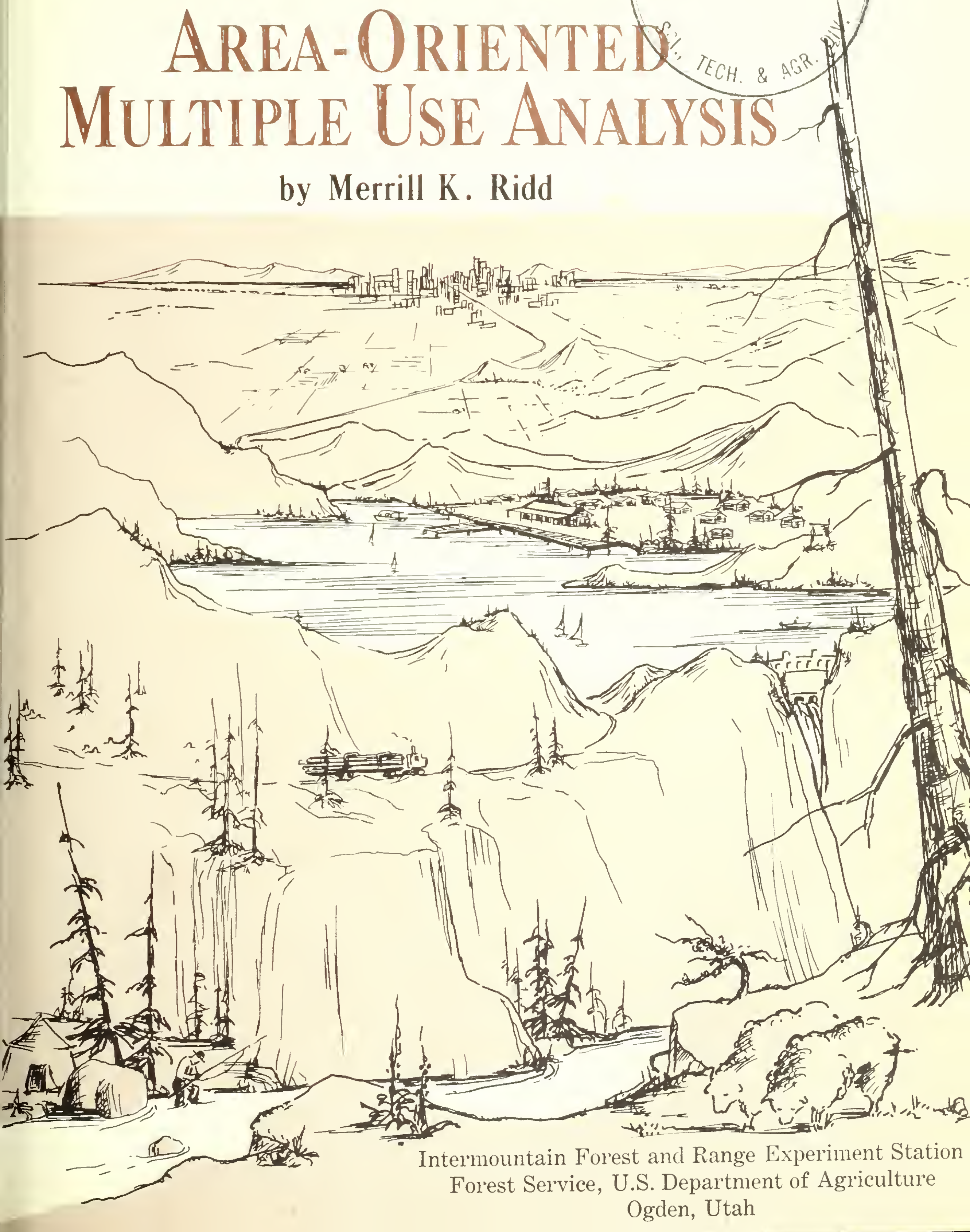
AREA-ORIENTED MULTIPLE USE ANALYSIS

by Merrill K. Ridd



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AREA-ORIENTED MULTIPLE USE ANALYSIS

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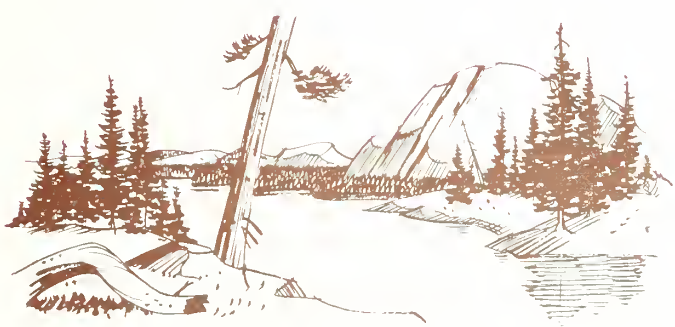

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INTRODUCTION

Since the introduction of "conservation" as a resource management slogan, few expressions concerning resources have awakened such interest as "multiple use." And few have raised more questions. Perhaps because of the complexity of multiple use management in action, research has not yet come to grips with some of the vital aspects of the public land manager's problem.

The purposes of this paper are: first, to clarify the purpose of multiple use management; second, to discuss approaches to multiple use analysis; and finally, to illustrate the need for area-oriented multiple use analysis and to suggest the issues that need to be considered.

Meaning and Objective of Multiple Use

The term "multiple use" may be applied either to areas of land or to particular resources. When applied to land areas, it refers to varied uses; that is, the production and management of various resources or resource combinations on a given land unit (left-hand side of figure 1). The relation of the several resources in the area to one another may be competitive or complementary.

When applied to individual resources, "multiple use" refers to utilization of a particular resource for various purposes. For example, water may be used for irrigation, municipal and industrial water supply, recreation of various types, and other varied functions. Here again, uses may be competitive or complementary. Timber, in the same sense, may be used for lumber, pulpwood, Christmas trees, or scenery. Forage may be used as feed for cattle or for wildlife, for scenery, watershed stabilization, and so forth. Multiple use land management actually involves both multiple use of individual resources and of land areas. Demands on particular resources for specific uses, in turn, place demands on land areas where resources are produced.

The object of multiple use management is very simple. It is to manage the resource complex for the most beneficial combination of both present and future uses. The idea of deriving maximum benefit from a given resource base is not new, but it becomes more important as competition increases for limited and interrelated resources. It was not until 1960 that Congress enacted legislation to establish "multiple use" as policy on any of the public lands. For the National Forests, the policy was laid down by Public Law 86-517 of June 12, 1960. The law states in part:

> The Secretary of Agriculture is authorized and directed to develop and administer the renewable surface resources of the national forests for multiple use and sustained yield of the several products and services obtained therefrom.

The principle of sustained yield is corollary to multiple use. It is, in fact, implied in the definition of multiple use given in Public Law 88-607 of September 19, 1964, outlining authority for multiple use management of land in the custody of the Bureau of Land Management. This law indicates that:

> "Multiple use" means the management of the various surface and subsurface resources so that they are utilized in the combination that will best meet the present *and future* needs of the American people . . . .

While the doctrine of multiple use is widely accepted, there is still some misunderstanding of how it should be accomplished. The multiple use concept does not demand that every acre in question be utilized for

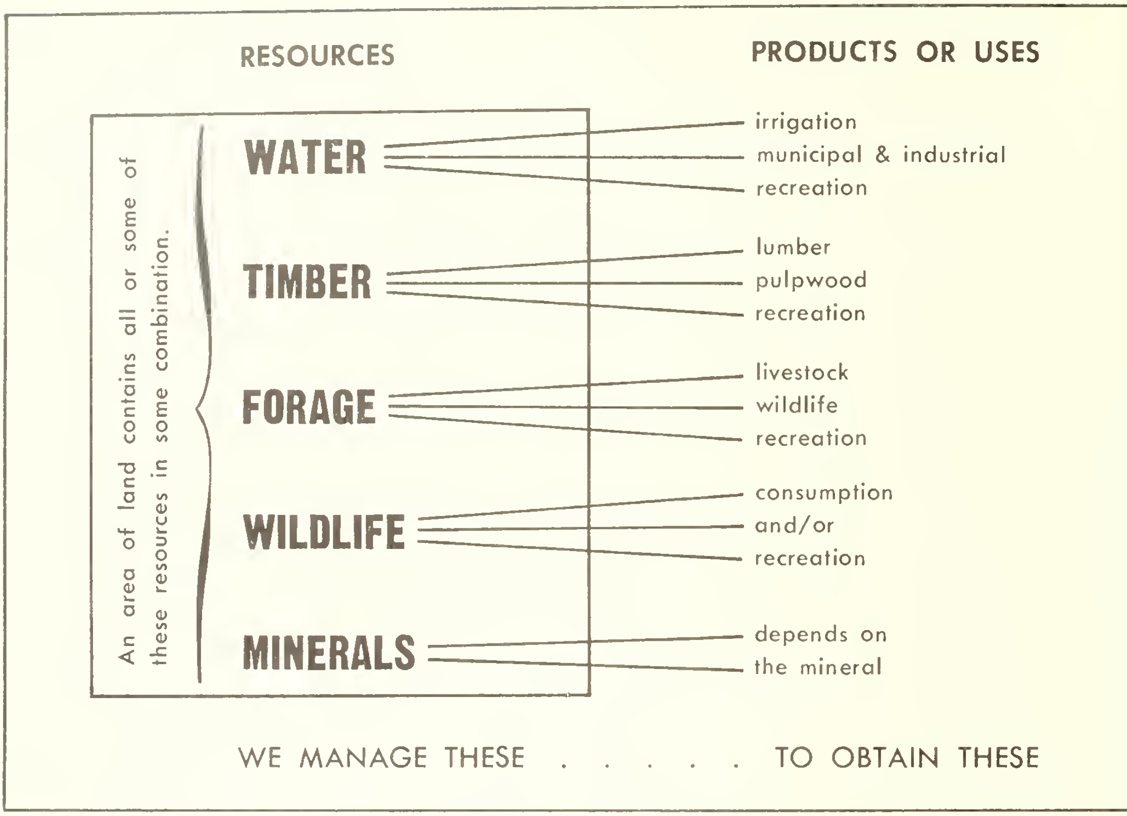

Figure 1.—Resources and resource uses

RESOURCES

A discussion of multiple use often relates primarily to the first four resources listed above — the renewable surface resources of water, timber, forage, and wildlife — along with recreation, meaning the recreation opportunity. Actually, of course, recreation is a kind of use (see footnote 2). Minerals, because of their different character, are not always listed. They are not renewable in the usual sense, their distribution is generally erratic, and they are often under the surface. Nevertheless, where they do occur and are exploited, their extraction often has real effects on the surface resources, and thus becomes an important part of multiple use management. In a very real way we manage the method of their exploitation to protect other resource values. Soil is not listed because we do not manage it per se for use but as the basic constituent of the watershed and a foundation for the surface renewable resources and crops.

PRODUCTS OR USES

Many other products and uses could be listed. Use may take place on site or at some distant point. It may be consumptive or nonconsumptive.

In the case of recreation, use may be centered primarily on one resource; however, the "quality" of the recreation experience is generally influenced by an assemblage of resources — the environmental complex. Wilderness is a primitive or near primitive condition of the environmental complex.

all possible uses and resources simultaneously. Both Acts cited above point out that some land will be used for "less than all of the resources." Designation of a wilderness area, for example, does not necessarily violate the multiple use philosophy. Such use may not provide the greatest dollar return, but when the whole scale of values is considered it is presumed to provide the greatest overall benefit for that particular site. However, highly restrictive use areas will occupy a small percentage of the total acreage of public wildlands. Most of the public land will be utilized, to varying degrees, for a wide array of uses, as dictated by capacity, demand, and prudence.

Multiple use management of the land may be accomplished by any one of the following three options, or by any combination of the three: (1) concurrent and continuous use of the several resources obtainable on a given land unit; (2) alternating or rotational use of the various resources or resource combinations on the unit, so that multiple use is achieved on a time basis; or (3) geographical separation of uses or use combinations so that multiple use is accomplished across a mosaic of units. All of these are legitimate multiple use practices and should be applied in the most suitable combination on lands under public administration. It is significant that in all three options noted above we are dealing with areas of land. Public Law 86-517 states:

> In the administration of the national forests due consideration shall be given to the relative values of the various resources in *particular areas.* (italics added)

A similar statement appears in P.L. 88-607. Delineation of relatively homogeneous units of land with respect to physical characteristics and use potential is helpful both in inventorying and in managing the land resources. Units vary in size, and combinations and degrees of use vary between units. Size of the units depends primarily on the degree of heterogeneity of the landscape.

From the public's point of view, regardless of the area in question, multiple use management must become involved in a somewhat broader set of parameters than the private investor is usually concerned with. Whereas the private investor makes decisions based upon the profit motive, a nation interested in preserving benefits for future generations may have to make investments and provide safeguards beyond the dictates of limited business economics. The western range industry illustrates the point. Early stockmen maximized direct, short-run returns, and, as a result, contributed to the eventual deterioration of other resource values as well as to the decline of the range industry itself. Multiple use is the antithesis of this. It provides a plan with vision, a plan that accommodates the full spectrum of today's needs and at the same time provides for tomorrow's requirements, a plan which will keep short-range objectives and short-sighted evaluations from sweeping away opportunities for the future.

Both P.L. 86-517 and P.L. 88-607 make it clear that the application of multiple use principles requires "harmonious and coordinated management of the various resources, each with the other, without impairment of the productivity of the land . . . ."

The multiple use philosophy is deeply rooted in two axioms. One is that renewable resources belong to all the people (not to selected groups of users) and to all generations. The other is that resources represent capital — just as real as the capital invested in man-made structures. Wise use of this capital generates economic growth and social benefits; unwise use will result at the same time in some drain on the social economy. Consequently, we must be careful to avoid excessive use or mismanagement for current gain, which would lower the productive capacity of the resource base and unduly handicap future generations. Ciriacy-Wantrup[1] urges maintaining a "safe minimum standard of conservation," by refraining from using the resources to the point that would make it "uneconomical to halt and reverse depletion." While the problem of defining what is economical is still open, the

[1] *Ciriacy-Wantrup, S. V. Resource conservation: economics and policies. p. 253. 395 pp., Rev. Ed. Berkeley: Univ. Calif. Press. 1963.*

principle is sound. Ruskin summed it up this way:

> God has given us the Earth for our life. It is a great entail. It belongs as much to those who follow us as it does to us, and we have no right by anything we may do or neglect to do to involve them in unnecessary penalties or deprive them of benefits which are theirs by right.

Thus, we must endeavor to provide the combination of products required by the present generation, and at the same time secure production alternatives for the future. The challenge for multiple use research is to help provide not only the data but also the framework on which this type of program must be based.

Multiple Use Analysis

From a practical standpoint there are two fundamental types of multiple use research: resource-oriented and area-oriented.[2] To draw such a distinction may be a little hazardous because the separation is not always clear-cut. Yet there is a sharp difference in method and objectives. Both, however, are essential and nothing in this discussion should be construed as an effort to rank them in order of importance.

The resource-oriented approach seeks to discover interrelations among the several resources; e.g., how the management of one resource affects production in others or how one use of a particular resource affects other uses of the same resource. Thus, physical rates of substitution between resources or resource uses, and even cost and benefit comparisons of alternative production combinations may be taken into account. Resource-oriented studies may deal with a single resource in alternative uses, with two resources, or with several. They may range from highly abstract to primarily empirical methods.

Typical of an abstract approach is the effort by Gregory[3] to fit multiple use into joint production theory. Another example is Hopkin's[4] hypothetical transformation curve showing the different numbers of cattle and deer that could be produced simultaneously on a land unit. After the curve is constructed, Hopkin assumes a price ratio or value relation between deer and cattle and illustrates the optimum production level of each. To the manager of public lands, the real problem in applying such a theory lies in establishing a meaningful value relation between a cow and a deer. In spite of this problem, theoretical models help to sharpen our conceptual framework, provided we recognize the critical limitations that result from taking the problem out of context.

A good example of an empirical study in resource-oriented multiple use analysis is the so-called Beaver Creek Project in central Arizona. In the Salt and Verde River basins northeast of Phoenix, the Rocky Mountain Forest and Range Experiment Station in cooperation with several other agencies has set up a carefully designed study to determine the response of water yield to various treatments of the watershed.[5] Initially a water problem, the project has broadened into a sound multiple use research program. Its purpose is to determine the effect of various watershed management practices not only on water yield, but also on livestock, forage, timber production, wildlife habitat, and recreation potential. In addition to gathering much needed data on physical interrelations and production rates, the plan calls for an evaluation of costs and benefits involved in the various land treatment measures.

The information being developed by resource-oriented studies is basic to an under-

[2] *In this connection, "area" connotes more than space or location; for purposes of this discussion an area is a segment of the natural environment and human culture, which we may call a human ecological community.*

There may be "people-oriented" multiple use analysis, which would look at resource relationships from a standpoint of the needs of society. It will be seen that, for specific areas at least, this aspect is encompassed in area-oriented analysis.

[3] *Gregory, G. Robinson. An economic approach to multiple use. Forest Sci. 1:6-13. 1955.*

[4] *Hopkin, John A. Use of economics in making decisions relating to range use. Jour. Farm Econ. 38: 1594-1603. 1956.*

[5] *U.S. Forest Service. Rocky Mountain Forest and Range Expt. Station Annual Report(s), 1961-63.*

standing of resource capacities. Yet from the viewpoint of the public land manager something more needs to be considered — community and regional dynamics. To accomplish sound management, resources must be related not only to each other but to settlement patterns, markets, access, and to the changing nature of these factors. These things are not constants, and cannot be ignored. The public land manager's job is not just to maximize product output. He must find a balance between resource capacities and community demands. He needs some guidelines for doing this. Area-oriented multiple use analysis can provide these guidelines.

In multiple use land management, there are resource capabilities on the one hand, needs and wants of the people on the other, and the interaction between them (fig. 2). Until research likewise encompasses all three, it cannot satisfy the requirements of the land manager. Only by examining specific situations on the ground is it possible to effectively analyze these relations and thereby identify the land use issues — hence, the necessity for area-oriented, or areal analysis.

Resource-oriented and area-oriented studies in multiple use may be indistinguishable in some respects inasmuch as a large body of material is common to both fields. Both are concerned with the interrelations among resources. However, their viewpoints are quite different. The major objective of resource-oriented studies is the discovering of relationships among the resources and their uses. Areal studies have as their core objective the analysis of specific resource situations in particular areas. They deal not only with the supply of resources, but also with demand in a rather comprehensive way. Areal analysis draws from resource studies that information needed to describe resource potentials of the area in question, and relates this to the changing local and regional demand for those resources. A fuller explanation of this follows.

Both kinds of multiple use analysis are essential and should be encouraged. They are complementary. Some fine progress is being made in resource-oriented studies, but the field of areal multiple use analysis has been little cultivated. The remainder of this paper discusses the methods and issues involved in areal analysis.

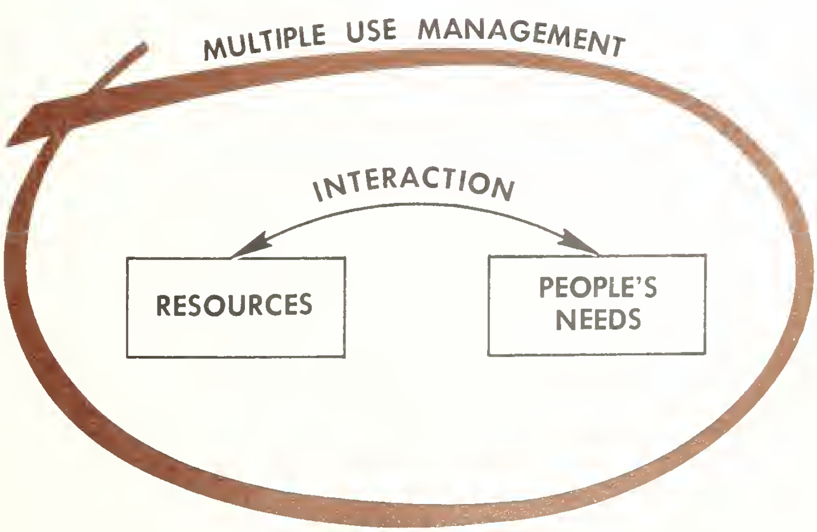

Figure 2.—Schematic diagram of multiple use management of the land.

AREA-ORIENTED MULTIPLE USE ANALYSIS

Fundamentals

The purpose of areal multiple use analysis is to provide an analytical framework for evaluating the pertinent physical, biological, economic, and social factors relating to resource development in a particular place as a basis for making sound land management decisions. As indicated earlier, the basic frame of reference in which the many factors may be analyzed is a specified area of land.

Delineating the area of study.—For this discussion, an area is a portion of the landscape where man and his activities provide a meaningful unit for analysis. The area is outlined on the basis of land use considerations rather than by political or ownership lines, except where the latter are fairly well aligned with patterns of land use.

The area is a sort of functional unit with a high degree of internal cohesion and interdependence with respect to land use and resource considerations. Such an area may be regarded as a human ecological community. Like any biotic community it is at the same time related in important functions to the outside world.

These questions naturally arise: Isn't each area unique, thus requiring separate analysis? How is it possible to extend findings beyond the area analyzed? Of course each area is unique. Usually, however, there are some broad characteristics that permit some generalizing.

In order to identify some of these broad patterns one might begin at a statewide level to get a picture of the distribution and flow of resources and resource uses. The State can then be divided into provinces with respect to characteristics of land use. In Utah, for example, five land use provinces may be identified (fig. 3). Each has its distinguishing and unifying characteristics.

Within a province an area may then be selected for detailed analysis. If carefully chosen and delineated, the area may satisfactorily represent the land use problems and opportunities of the province as a whole. Analysis made within the area will then provide broad guidelines for the province, as well as more specific guides for the area itself.

In our multiple use study, the Paunsaugunt Plateau Area was selected and outlined to represent south-central Utah (fig. 3). The area consists of about 1,000 square miles, with the Paunsaugunt Plateau and the clusters of communities about its base functioning as a node. The area consists of part of

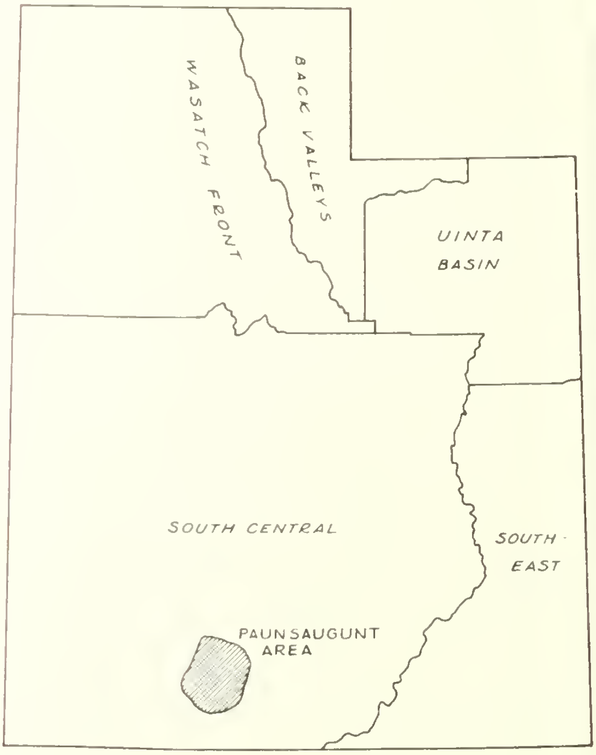

Figure 3.—Land use provinces of Utah, a tentative delineation.

one National Forest Ranger District on the plateau, Bryce Canyon National Park on the eastern rim, a scattering of private land around the foot of the plateau, and a large stretch of Bureau of Land Management land reaching out to the south and east.

Defining the issues.—No area is an island. It is but a part of a region and a nation. Hardly a thing can be done in the management of the resources in an area that does not affect material, money, and people far beyond the confines of that place and far into the future.

The study area serves as a stage on which the elements of resource utilization can be examined. As indicated earlier, the multiple use decision-making process must consider more than resource interrelations. Many other factors enter in. For purposes of this discussion, the factors which should play a role in multiple land use decisions, and therefore enter into analysis, are assembled into four groups:

1. The condition and capacity of the resources, and costs of production.

2. The flow of benefits from the resources and their distribution to the social economy within and beyond the area.

3. Trends in use of the resources, anticipated influences from inside and outside the area, and projected demands, and

4. The institutional structure through which the resources are utilized.

The first group involves an analysis of the condition, trend, and interdependence of the resources, and an estimate of potential production under varying management practices and costs. The second involves an evaluation and comparison of the existing and potential economic and social benefits generated by each of the resources of the area, and the distribution of those values in space and time. It involves an examination of the local economy and culture, its dependence on the resources of the area, and the dependence of outside communities on the same resources. The third group is concerned with trends in resource use in the area; developments taking shape in the community, region, and nation, which may influence the local economy and resource use; and finally, projected demands on the local resources. The fourth group calls for an evaluation of the political and social structure through which resources are utilized, and the possible effects on resource development.

All of these factors must be considered in a context of space and time. Values stemming from local resources extend beyond the local scene to state, regional, and national levels. They may be enjoyed today or they may accrue to future generations as a result of wise planning and investment. Conversely, future generations may suffer because of inaction or poor management today.

Selected Examples From the Paunsaugunt Area

To illustrate some aspects of the four groups of factors, a few examples from the Paunsaugunt Area are selected. Many other

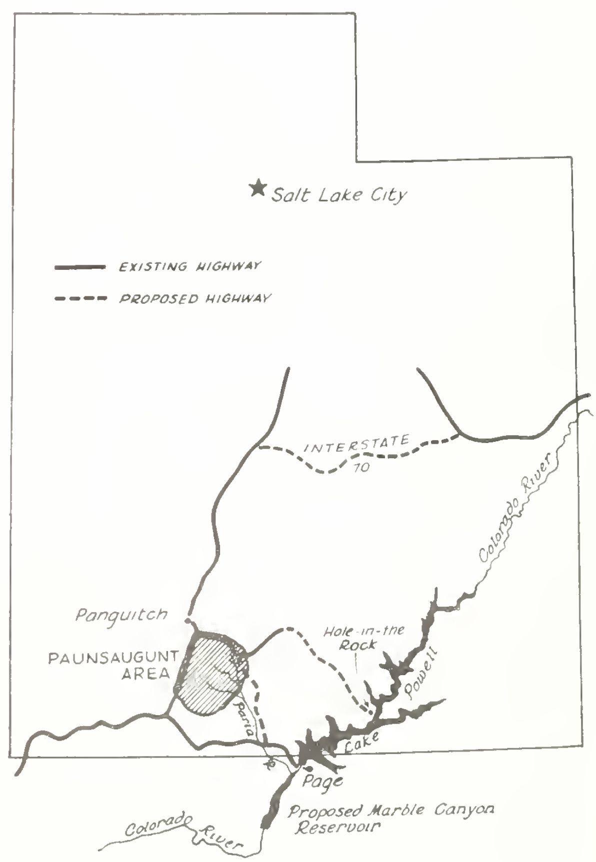

Figure 4. **The Paunsaugunt Area and some related features.**

Figure 5.—Generally we speak of resources in terms of what they contribute to the economy. But some resources may become a liability. This once-productive rangeland was converted to sagebrush and pinyon-juniper cover; now it is being riddled by erosion. Sediment leaving the area is not only a loss of capital here, but a liability downstream.

examples could have been chosen. Those described here merely illustrate the nature of the problem.

Condition and capacity of the resources.— Land in a declining condition presents a problem quite different from that of healthy land. Thousands of acres of public rangeland below the plateau in the Paunsaugunt Area are seriously depleted and virtually unproductive. Much of this land is laced by active channel and sheet erosion. One might conclude from the viewpoint of private investment that range rehabilitation there is out of the question because grazing values cannot justify such expenditure — that the land is unproductive and useless. But the loss of soil from the watershed is only part of the cost to society. Every acre-foot of soil swept away contributes to the eventual demise of Lake Mead or to the impairment of other facilities. Much of the land under erosion in the Paunsaugunt Area drains into the Paria River and, in turn, into the Colorado, a major lifeline in the Southwest (fig. 4). This fact changes the whole complexion of range management problems in this part of the Paunsaugunt Area. The Paria River, carrying one-sixth of its volume in sediment, is one of the most heavily silt-laden streams in America.

Unless it is checked, sedimentation from the Paria is a direct threat to two important structures: (1) It could significantly reduce the usable storage of the proposed Marble Canyon Reservoir in 40 to 50 years, and (2) it could adversely affect the tail water from Glen Canyon Dam and reduce its powerhead. It is quite clear from this example that the responsibility of the land manager extends far beyond the confines of his management unit and far into the future.

The long-range implications to the Southwest are inestimable. This close association of range and watershed problems is but one example of the many interrelations among resource uses that are a part of areal multiple use analysis. Management necessary to achieve maximum production of a given resource in an area may increase or decrease production in other resources. For each resource, the amount of these effects on the others should be estimated. Once these relative potentialities have been determined, they can be weighed against projected demands, costs of production, and the flow of benefits, to help the manager determine a course of action.

The flow of benefits.—Benefits may flow from the resources in terms of dollar values or in some intangible form. To recognize and weigh only dollar values is quite misleading. Dollar and other values are, in fact, inseparable. Intangible values contribute to economic growth by stimulating human energies, which are thus released into the social economy. This comes in addition to the intrinsic value to the individual involved.

The importance of considering values other than those expressed in dollars is recognized in the two multiple use Acts cited early in this paper. Those documents require that consideration be given to the "relative values of the various resources, and not necessarily the combination of uses that will give the greatest dollar return or the greatest unit output."

One of the virtues of the area-oriented approach is that intangibles, despite our inability to measure them adequately, take on a dimension of reality. The mention of intangible value often brings to mind such uses as fishing, hunting, camping, and other outdoor recreation. But some degree of intangible value is associated with all resource activities. For example, cattle raising is commonly considered to have a definable market value. However, a critical audit of the books of many stockmen in the Paunsaugunt Area probably would reveal that in terms of dollars alone these men are fighting a losing battle, partly because of forced livestock reductions resulting from poor range conditions. To most of them, raising cattle is only a secondary source of income. Yet, they justify continuation of their marginal operation on the basis of enjoyment, or of the security of having a few cows on the range. Being a cowboy may not always bring in much money, but it apparently buys a lot of satisfaction.

In appraising the growth opportunity of an area, the public land manager must consider not only the value of resources at the point of production, but how much and where these values expand through the economy. To appreciate the influence of the various resources on the economy, the resource planner should have some information on (1) the multiplier effect on income through the use of each resource, or on the product value and value added by processing of each resource, and (2) the distribution of wealth generated.

Figure 7 shows the estimated relative dollar value of the five wildland resources

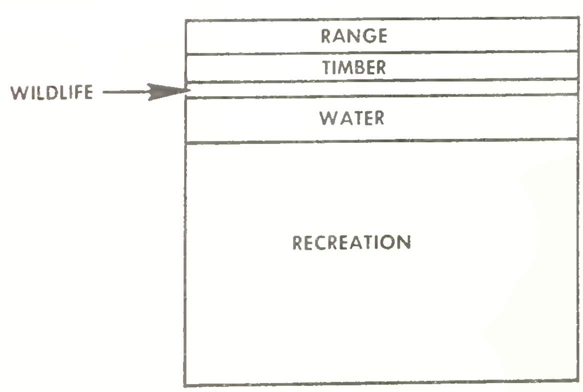

Figure 7.—Relative dollar values of Paunsaugunt Area resources at point of harvest, 1962. These are tentative estimates and are introduced here only for illustration.

Figure 6.—Many cattlemen run fewer than 50 head, and nearly all operators work off the ranch for their main source of income. The roundup often becomes a family activity.

taken at the point of "harvest" from public land in the Paunsaugunt Area for 1962.[6] To compare benefits only at this point would be misleading.

As the resources move into the economy, some interesting patterns emerge (fig. 8). Timber values, and especially water values, expand many times. Only a small part of the value generated by water is realized inside the Paunsaugunt Area. Most of it is realized outside the State. Timber also generates the larger part of its value outside the area. Most of the wildlife values benefit people living outside the area, while a large part of the livestock money stays to support the local economy. All of the dollar value shown for recreation is realized in the immediate area. The wealth generated by Bryce Canyon beyond the Paunsaugunt Area was not estimated.

The purpose of the foregoing summary of dollar values is twofold. First, it suggests the importance of considering values of the various resources beyond the point of har-

[6] *Dollar value realized from timber delivered to the mill, the sale of cattle from the range, and local expenditures by hunters and by tourists. The estimate for water at this point is indicated by imputed values for irrigation and domestic use.*

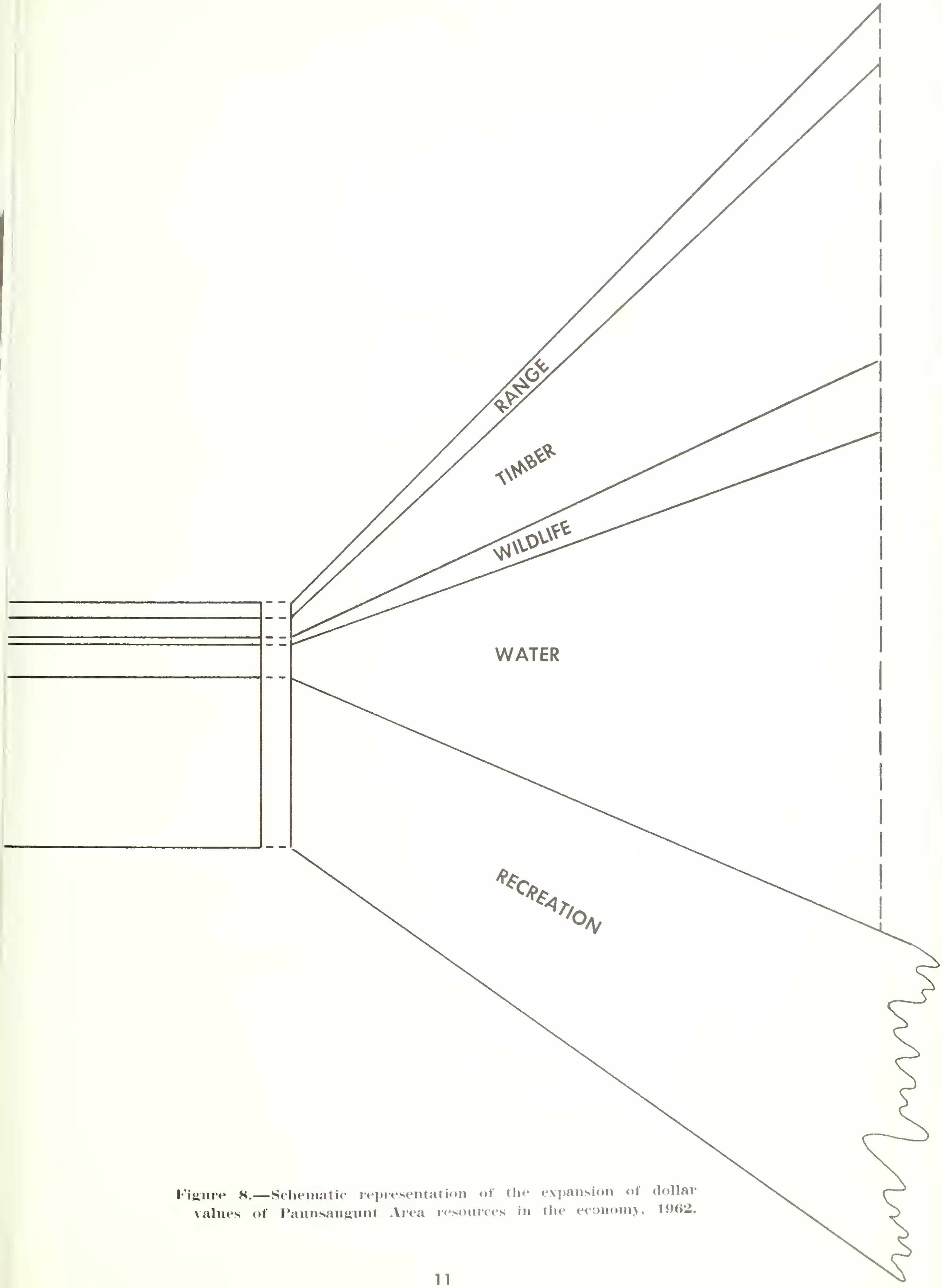

Figure 8.—Schematic representation of the expansion of dollar values of Paunsaugunt Area resources in the economy, 1962.

vest. Here we see timber and water values expand many times from the point of harvest, while wildlife and range forage expand at a much lower rate. In other words, a dollar's worth of harvested timber or water may contribute more to the national economy than a comparable unit of other resources. We also see the tremendous influence of an important recreation industry; the dollar-generating power of Bryce Canyon indicates the potential of much of the canyon country in southern Utah. Second, it indicates the need for considering *where* dollar values are generated. The value added to the local economy by some resources may be much greater than that added by others. For example, in the competitive situation between cattle and deer, so common in this region, it is well to note that even though deerhunting may generate more wealth, it may be of relatively little value to the local community compared to the livestock industry, which has great local significance.

If we compare the total wealth-generating capacity of water with that of other resources, it might seem that any decision between water production and production of range forage or timber, for example, should automatically favor water. However, such a conclusion is not so easily drawn when one considers the social economy of the Paunsaugunt Area, which is heavily dependent on the livestock and timber industries.

It should be emphasized that these figures do not pose as a final tally on dollar values of resources from the Paunsaugunt Area. They are used merely to indicate the need to evaluate the influence of various resource uses in a broad spectrum of wealth generation and distribution.

Trends, potential influences, and demands.—To simplify analytical procedures there may be a temptation to pickle time — that is, to ignore the element of change. In a constantly evolving world, resource planners cannot afford this luxury. To provide for future needs they must evaluate trends and shifting patterns in resource use, and the possible impacts on the area of developments that are taking place both inside and outside. Then the difficult question of projected demands may be tackled.

For example, the growing importance of southern Utah to the Southwest and particularly to southern California is a key factor to be considered in the Paunsaugunt Area, not only in connection with the water resources, but in regard to tourism and recreation, fishing and hunting, and even timber production. Nonresident deerhunters, mainly from California, have increased fivefold since 1957 and now exert more than half the hunter pressure in this area. Utah now ranks fourth among the 50 States in the number of nonresident hunting licenses sold (1962).

Several outside developments now underway will have a tremendous effect on the economic activity of southern Utah in the years ahead. Perhaps the most important of these to the Paunsaugunt Area is Glen Canyon National Recreation Area encompassing Lake Powell. One of its large recreation sites (Hole-in-the-Rock) will be accessible by paved road only through the Paunsaugunt Area (fig. 4). Construction of a surfaced highway through Cottonwood Wash near the Paria River, linking Page and Panguitch, and cutting 40 miles from the distance between Salt Lake City and Page, could have a remarkable effect on the Paunsaugunt. Completion of Interstate 70 across a remote desert in east-central Utah will shorten the distance between Denver and Los Angeles and direct more traffic to the southern end of Utah. These and other projects will increase the flow of new money into the area and create new demands on the land.

Estimation of future demands for an area is not an easy task. It could be aided, however, for some resource uses if national demands could be suggested and then divided up by regions. The objective for a State, province, or area could thus be approached with more confidence.

Institutional structure.—Finally, relative to the fourth group of factors, a realistic management plan must work within the existing institutional framework or seek to modify

Figure 9.—Southern Utah has become a popular hunting ground for increasing numbers of Californians. Rapid population growth, new interstate highways, and other factors suggest a continuation and perhaps even an acceleration of recreational use.

it in order to be effective. For example, federal agencies "manage" the wildlife habitat while the State controls harvest of the game. There are several land ownership problems, one of which is that the Forest Service operates summer range while the Bureau of Land Management operates winter and spring-fall range. Use of National Forest and BLM range is closely related, yet coordination is slight. Another problem arises from fragmented patterns of land ownership. Even within agencies the necessary division of functional responsibilities presents certain problems. These and many other constraints point up the need for greater cooperation in planning and action between and within the various land management agencies and private interests. Hopefully, as more information is gathered and the interdependence of various groups and resources is more clearly demonstrated, some of the difficulties can be lessened.

SUMMARY AND CONCLUSIONS

The primary intent of this paper has been to demonstrate the need for an areal analysis and to broadly categorize and discuss the factors involved in the multiple use management of public lands. An outline for organizing these factors into report form for a specific study area, such as the Paunsaugunt, will appear in subsequent papers. The few examples selected above are only for illustration. Recognition of both intangible and tangible facets of value and the effects of space and time have been stressed.

The aim of areal multiple use analysis as suggested herein is to provide a framework in which available information of importance in the management of a given unit of wildland can be arranged, analyzed, and evaluated for the making of sound decisions. Presently, there is a great deal of useful information which is not easily accessible to the land manager or is not readily applied to his particular area of responsibility. Use of this method should help to close this gap between resource research and problems on the ground. There is a growing need for closer correlation between lands of different ownership and management, in analysis and planning, funding, and action.

Areal analysis is not intended to replace any other form of research, but rather to complement it. Indeed, it relies on other types of multiple use analysis and studies in other fields — physical, biological, economic, and social — for basic data and relationships. However, it is felt there is a need to pull these things together as they apply to particular communities. Only by delineating an area of study can resources be inventoried and analyzed for the purpose of planning and management. Only in an areal context can the dynamic interdependence between the local community and resources and the broader setting be understood. Only in this way can the distribution of values and the reality of intangible values be appreciated. And in an areal context the findings of resource-oriented studies can be made effective.

If well chosen and defined, a study area may fairly well represent the conditions of the province and allow the extension of general findings and recommendations across other areas of the same province. In places where use patterns are complex, the opportunity to extend results from one area to another may be more limited.

A study based on considerations suggested in this paper should help the public land manager identify his responsibility through broader understanding of the issues involved and how to resolve them.

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Project headquarters 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)

FOREST SERVICE CREED

The Forest Service of the U. S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing nation.

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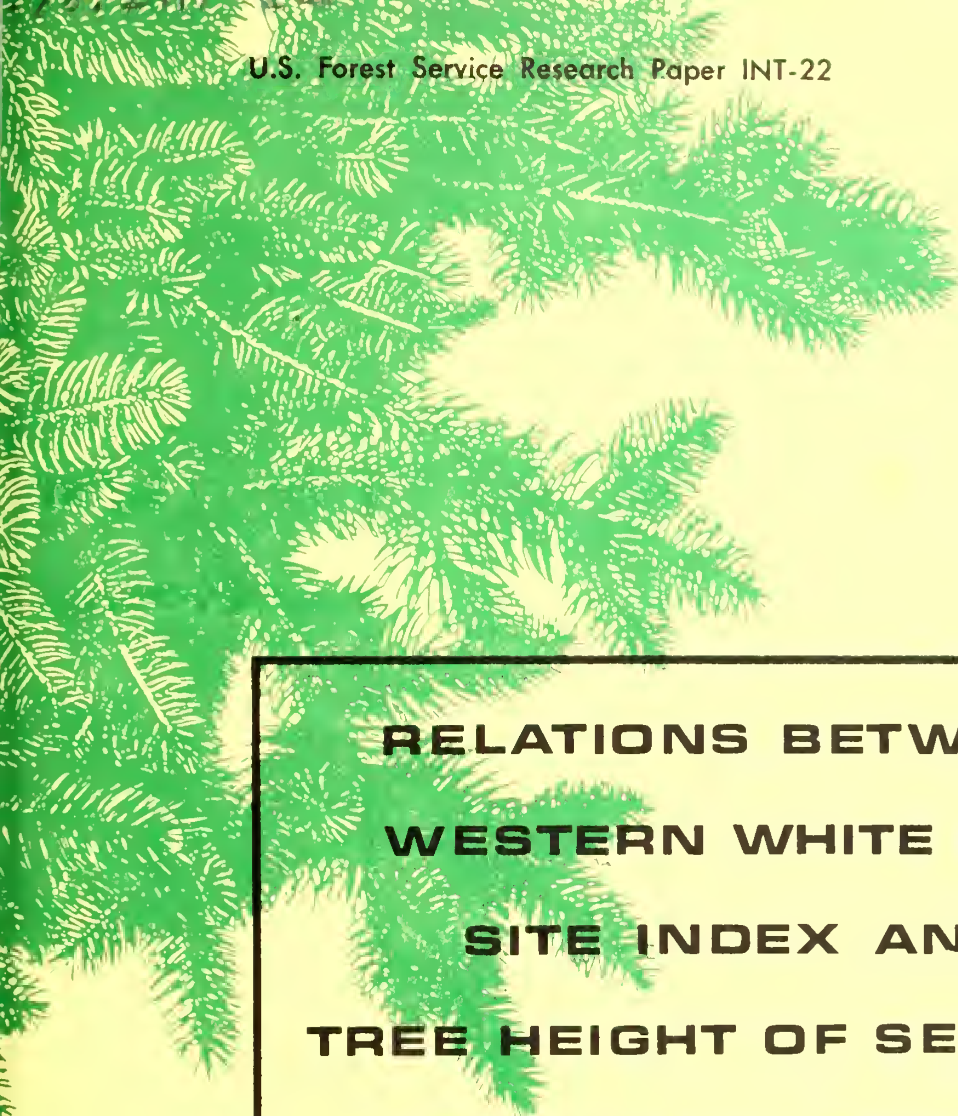

RELATIONS BETWEEN WESTERN WHITE PINE SITE INDEX AND TREE HEIGHT OF SEVERAL ASSOCIATED SPECIES

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THE PROBLEM

The western white pine (*Pinus monticola* Dougl.) forest type occupies about 2.4 million acres of commercial forest land in the northern Rocky Mountain region. Another 2 million acres or more could grow white pine, but the species is not present in quantity because of past cutting practices or quirks of nature.

Management on these areas is difficult for several reasons. White pine silvicultural practices have been especially complicated by blister rust disease. Sites now occupied by white pine, or that could grow it, generally rank quite high in terms of production potential, but the characteristic steep slopes and rough topography cause frequent and abrupt changes in site quality. Also, species composition on land capable of growing white pine is typically complex: as many as 10 species occur on some sites. Common associates of white pine are Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco), western larch (*Larix occidentalis* Nutt.), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), grand fir (*Abies grandis* (Dougl.) Lindl.), western redcedar (*Thuja plicata* Donn), lodgepole pine (*P. contorta* Dougl.), Engelmann spruce (*Picea engelmannii* Parry), and subalpine fir (*Abies lasiocarpa* (Hook) Nutt.).

The wide representation of species offers the forest manager considerable latitude in choosing a particular species or combination of species to favor in future stand management. Sound economic decision in management planning requires knowledge of how the performance of available alternative species compares on specific sites. It is therefore important to know the comparative height-growth capabilities because height is presently the best single indicator of site or yield capacity.

Methods for estimating comparative heights have been developed for some of the species capable of growing on white pine land. From these, two important kinds of information can be obtained. First, a prediction of height growth of alternate species can be made from information on white pine performance; second, on lands where white pine is scarce or absent, the capacity of the land to grow it can be estimated from known heights of alternate species. This information should be useful in establishing preferential guides for planting and thinning operations.

METHODS

PLOT DESCRIPTIONS

One hundred and eight permanent plots in northern Idaho western white pine stands extending from the Kaniksu National Forest to the Clearwater National Forest were selected for analysis. These plots provided sufficient height data on white pine and other species to be considered usable for this study. The plots ranged in size from 0.1 acre to 2.0 acres and had been measured at 5- or 10-year intervals over varying lengths of time — some for as long as 40 years. Most of the plots were at elevations between 2,000 and 4,000 feet above sea level, but 13 were at higher elevations, some approaching 5,000 feet. Nearly 90 percent occupied topographic positions classified as upper, middle, and lower slope; the remainder were classified as ridge and flat (or bench) locations.

By the ecological classification developed by Daubenmire,[1] the majority of plots fell into the *Thuja-Tsuga/Pachistima* habitat type. The only other types represented were *Abies grandis/Pachistima* and *Thuja/Pachistima*, each with about 10 percent of the plots.

From the 108 plots, we had a total of 483 recorded observations of height of western white pine and trees of associated species. These records include some remeasurements of several trees at different ages. Adequate data for analysis were found for five of white pine's common associates — western larch, lodgepole pine, Douglas-fir, grand fir, and western hemlock. Western hemlock and lodgepole pine had fewer than half as many measured height comparisons as the others, but the important age-class range between 20 and 80 years was quite well represented (table 1).

[1]*Daubenmire, R. Forest vegetation of northern Idaho and adjacent Washington, and its bearing on concepts of vegetation classification. Ecol. Monog. 22:301-330. 1952.*

Table 1. — **Number of observations of comparative height between western white pine and other species, by age class**

Age class (years)	Western larch	Lodgepole pine	Douglas-fir	Grand fir	Western hemlock
21-40	28	14	34	38	26
41-60	82	61	80	79	30
61-80	116	41	106	77	29
81-100	39	2	27	35	23
101-120	2	0	12	16	8
121-140	3	0	9	11	0
Total	270	118	268	256	116

STATISTICAL METHODS

Multiple linear regression analysis was used to develop equations for (1) estimating the height of five alternative species from site data that included western white pine height or site index, and (2) estimating western white pine site index from known heights of the alternate species. The variables entering into the analyses are noted below.

Estimating Height of Alternative Species

The dependent variable was the average height of dominant and codominant trees at given stand age for any single species other than white pine. Thirteen independent variables were included in the gross analyses for each species:

1. **Western white pine site index (WPSI[2]):** Determined from stand measurements and reference to published site index curves.[3] Watt[4] had already verified validity of these curves for general application.

2. **Stand age (A):** As defined by Haig,[5] the age of the oldest tree, providing it does not differ by more than 3 years from the age of the next oldest tree.

[2]*Abbreviated variable designation as used in subsequent equations.*

[3]*Haig, Irvine T. Second-growth yield, stand, and volume tables for the western white pine type. U.S. Dept. Agr. Tech. Bul. 323, 67 pp. 1932.*

[4]*Watt, Richard F. Second-growth western white pine stands: site index and species changes; normality percentage trends; mortality. U.S. Dept. Agr. Tech. Bul. 1226, 60 pp. 1960.*

[5]*Haig, op. cit.*

3. **Reciprocal of stand age (1/A).**

4. **Reciprocal of western white pine site index (1/WPSI)**

5. **Product of western white pine site index and stand age (WPSI·A)**

6. **Ratio of western white pine site index to stand age (WPSI/A)**

7. **Elevation above sea level (E)**

8. **Reciprocal of elevation (1/E)**

9. **Aspect:** Expressed as the sine (SinAz) or cosine (CosAz) of the average azimuth reading.

10. **Habitat type (HT):** A discrete variable limited to only three habitat-type conditions: *Abies/Pachistima*, *Thuja/Pachistima*, and *Thuja-Tsuga/Pachistima*.

11. **Topographic position (TP):** A discrete variable having five categories: ridge, upper slope, middle slope, lower slope, and flat or bench.

12. **Western white pine height (WPht):** Average height of measured dominant and codominant white pine.

13. **Ratio of western white pine height to stand age (WPht/A)**

Estimating Western White Pine Site Index

Seven of the nine independent variables used in this second series of analyses were the same as in the first; i.e., stand age and its reciprocal, elevation and its reciprocal, aspect, habitat type, and topographic position. The other variables were:

1. **Height of other species:** Average height of measured dominant and codominant trees of given species — western larch (WLht), lodgepole pine (LPht), Douglas-fir (DFht), grand fir (GFht), or western hemlock (WHht).

2. **Ratio of other-species height to stand age (WHht/A, etc.)**

Values for the two nonquantifiable variables, habitat type and topographic position, were calculated by assigning orthogonal coefficients to each habitat type and topographic position. The partial regression coefficient obtained from the regression for habitat type and topographic position multiplied by the orthogonal coefficient assigned each habitat type and topographic position gives the value of each.

RESULTS

PREDICTING HEIGHTS OF ASSOCIATED SPECIES

Two equations are presented below for each of the five alternative species. Equation I, based only on stand age and white pine site index, or white pine height alone, provides a simplified means of estimating heights of other species without serious lack of accuracy. Graphs for making specific predictions and a table showing general height comparisons among species are in Appendix A. These can**not be used in a reverse order; that is, white pine site index cannot be predicted from other species' height and stand age.** The series of equations in the next section are for that purpose.

Equation II includes all significantly related variables that give increases in accuracy of estimates worthy of consideration. Because of the more lengthy computations and more specific site measurements needed, use of Equation II will generally be limited to situations requiring the best possible estimate for small and quite homogeneous areas. Condensed tabular values given in Appendix B will facilitate calculations.

Western Larch Equation I:

$$\text{WLht} = +\ 22.6 + 0.79(\text{WPSI}) + 0.74(\text{A}) - 1{,}200(1/\text{WPSI}) - 17(\text{WPSI/A})$$

For this equation, $R^2 = 0.87$; $S\bar{y} = \pm 8.2$ feet.

Western Larch Equation II:

$$WLht = -148.4 + 1(WPSI) + 0.80\ (A) + 1{,}400(1/A) - 1{,}200(1/WPSI) - 38(WPSI/A) + 0.019(E) + 260{,}000(1/E) + 3.1(CosAz) + \text{HT value}^{6} + \text{TP value}^{6}$$

Abies/Pachistima	−9	Ridge	+12
Thuja/Pachistima	+6	Upper slope	+1
Thuja-Tsuga/Pachistima	+3	Middle slope	0
		Lower slope	−1
		Flat or bench	−12

$R^2 = 0.91$; $S\bar{y} = 7.1$ feet.[7]

Lodgepole Pine Equation I:

$$LPht = +15.8 + 0.81(WPht)$$

$R^2 = 0.87$; $S\bar{y} = \pm 6.5$ feet.

Lodgepole Pine Equation II:

$$LPht = -65.3 - 800(1/A) - 210(1/WPSI) + 0.016(E) + 170{,}000(1/E) + 6(CosAz) + 0.66(WPht) + \text{HT value} + \text{TP value}$$

Abies/Pachistima	+6	Ridge	−1
Thuja/Pachistima	0	Upper slope	−3
Thuja-Tsuga/Pachistima	−6	Middle slope	+5
		Lower slope	+4
		Flat or bench	−5

$R^2 = 0.93$; $S\bar{y} = \pm 5.2$ feet.

Douglas-Fir Equation I:

$$DFht = +69.3 - 500(1/A) - 1{,}200(1/WPSI) + 0.0108(WPSI \cdot A) - 11(WPSI/A)$$

$R^2 = 0.92$; $S\bar{y} = \pm 7.6$ feet.

---

[6] *Insert the appropriate value for habitat type and topographic position as listed below each equation in which they occur.*

[7] *R^2, the coefficient of determination, multiplied by 100 gives the percent of the variation in tree height that is explained by the independent variables used. $S\bar{y}$ is the standard deviation from regression.*

Douglas-Fir Equation II:

$$\text{DFht} = +\,58.5 - 1{,}300(1/\text{WPSI}) + 0.0121(\text{WPSI}\cdot\text{A}) - 16(\text{WPSI}/\text{A}) + \text{HT value} + \text{TP value}$$

Abies/Pachistima	0	Ridge	+4
Thuja/Pachistima	−1	Upper slope	−1
Thuja-Tsuga/Pachistima	0	Middle slope	0
		Lower slope	+1
		Flat or bench	−4

$R^2 = 0.93$; $S\bar{y} = \pm\,7.2$ feet.

Grand Fir Equation I:

$$\text{GFht} = +\,13.6 + 0.75(\text{WPSI}) + 0.80(\text{A}) - 1{,}260(1/\text{WPSI}) - 15(\text{WPSI}/\text{A})$$

$R^2 = 0.94$; $S\bar{y} = \pm 7.6$ feet.

Grand Fir Equation II:

$$\text{GFht} = +\,54.1 + 1.8(\text{WPSI}) - 1{,}100(1/\text{WPSI}) - 0.014(\text{WPSI}\cdot\text{A}) - 25(\text{WPSI}/\text{A}) - 0.0022(\text{E}) + 1.8(\text{CosAz}) + 1.35(\text{WPht}) - 77(\text{WPht}/\text{A}) + \text{HT value} + \text{TP value}$$

Abies/Pachistima	−1	Ridge	+1
Thuja/Pachistima	0	Upper slope	−2
Thuja-Tsuga/Pachistima	+1	Middle slope	+3
		Lower slope	−2
		Flat or bench	+1

$R^2 = 0.96$; $S\bar{y} = \pm 6.3$ feet.

Western Hemlock Equation I:

$$\text{WHht} = +\,0.7 + 0.91(\text{WPht})$$

$R^2 = 0.98$; $S\bar{y} = \pm 4.1$ feet.

Western Hemlock Equation II:

$$\text{WHht} = -\,16 + 0.33(\text{A}) + 45{,}000(1/\text{E}) + 0.65(\text{WPht}) + \text{TP value}$$

Ridge	−1
Upper slope	+3
Middle slope	0
Lower slope	−3
Flat or bench	+1

$R^2 = 0.99$; $S\bar{y} = \pm 3.4$ feet.

ESTIMATING WHITE PINE SITE INDEX

A second objective of this study was to provide a means for estimating white pine site index when white pine is absent, but when height and age of a common associate species can be measured. The equations that follow have a lower coefficient of determination and consequently a somewhat higher standard deviation from regression than the prediction equations for estimating tree height. They are shown graphically in Appendix C. Variables other than tree height and age contributed little increased accuracy to estimates; so more complex equations are omitted.

From Western Larch Height:

$$WPSI = -7.3 + 0.8(WLht) + 1{,}800(1/A) - 600(1/WLht) - 0.003(WLht \cdot A)$$

$$R^2 = 0.37;\ S\bar{y} = \pm 11.0 \text{ feet.}$$

From Lodgepole Pine Height:

$$WPSI = +\ 33.8 + 1.1(LPht) - 1.2(A) + 600(1/A)$$

$$R^2 = 0.51;\ S\bar{y} = \pm 12.0 \text{ feet.}$$

From Douglas-Fir Height:

$$WPSI = -\ 51.5 + 0.8(DFht) + 0.6(A) + 3{,}400(1/A) - 1{,}100(1/DFht) - 0.005(DFht \cdot A)$$

$$R^2 = 0.50;\ S\bar{y} = \pm 9.7 \text{ feet.}$$

From Grand Fir Height:

$$WPSI = -\ 28.8 + 0.28(A) + 1{,}200(1/A) + 43(GFht/A) + \text{HT value}$$

Abies/Pachistima	+3
Thuja/Pachistima	0
Thuja-Tsuga/Pachistima	−3

$$R^2 = 0.51;\ S\bar{y} = \pm 10.7 \text{ feet.}$$

From Western Hemlock Height:

$$WPSI = +\ 37.9 + 1.1(WHht) - 1.0(A) + 500(1/A)$$

$$R^2 = 0.50;\ S\bar{y} = \pm 11.3 \text{ feet.}$$

DISCUSSION AND CONCLUSIONS

Estimating height of one species simply from measurements of another species has definite limitations. Different species are not equally sensitive to differences in various site factors; consequently, the relations between species-growth characteristics must become more complex as site variation increases. While several different physical environments may give a similar numerical site index for white pine, the relative height response of another species may differ at each location, depending on its reaction to the particular combinations of environmental conditions. For this reason, the use of the longer formula may be warranted on specific areas that are important.

Site indexes were not compared directly at this time because good site curves were not available for all of the species associated with western white pine. Also, results elsewhere[8, 9, 10] point out that comparisons of site indexes are most successfully applied within areas of fairly uniform environment. Since the environments within the western white pine type are characterized by extreme variation (even locally), future studies of comparative site index must identify and measure the important site variables that affect relations among the type-species.

While the prediction equations given in this paper can be useful in making management decisions, the user should be aware of their limitations. Many of the source data have been taken from plots in unmanaged second-growth stands. Conditions of density and species composition have no doubt affected height-growth relations differently than they would on intensively managed plots. These equations should be used with these limitations in mind.

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[8] *Hodgkins, Earl J. Testing soil-site index tables in southwest Alabama. Jour. Forestry 54: 261-266. 1956.*

[9] *Foster, Ralph W. Relation between site indexes of eastern white pine and red maple. Forest Sci. 5:279-291. 1959.*

[10] *Della-Bianca, Tino, and David F. Olson, Jr. Soil-site studies in Piedmont hardwood and pine-hardwood upland forests. Forest Sci. 7:320-329. 1961.*

APPENDIX A

Graphs and a summary table predict the average dominant-codominant height of five species other than western white pine from white pine site index and stand age (Equation I series). Arrows show the direction in which graphs are to be read. The dashed portions of curves are extrapolations beyond actual data.

THESE GRAPHS AND THE SUMMARY TABLE ARE NOT TO BE USED FOR ESTIMATING WHITE PINE SITE INDEX.

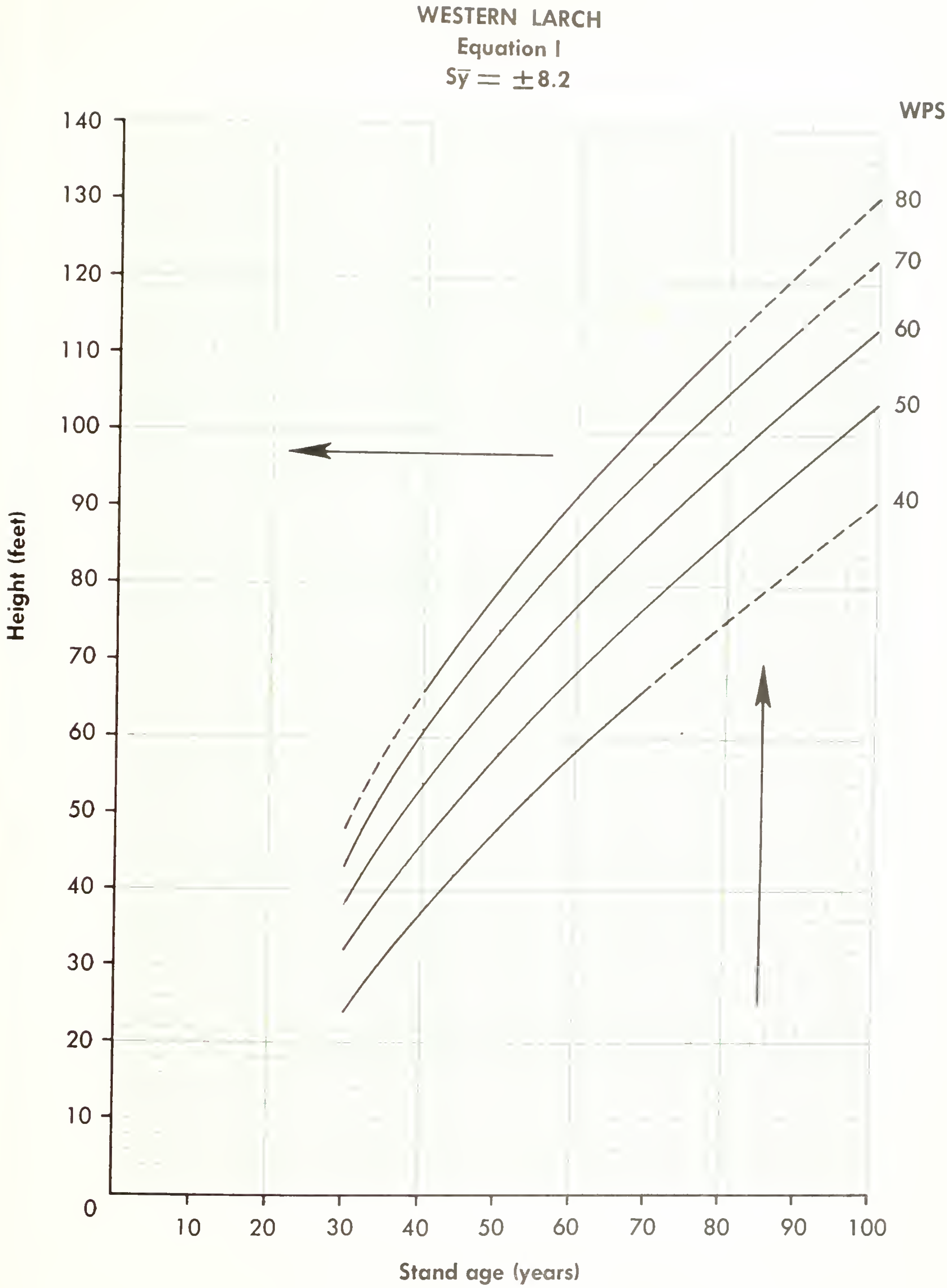

Figure 1. — Predicted average height of dominant and codominant trees by white pine site index and stand age.

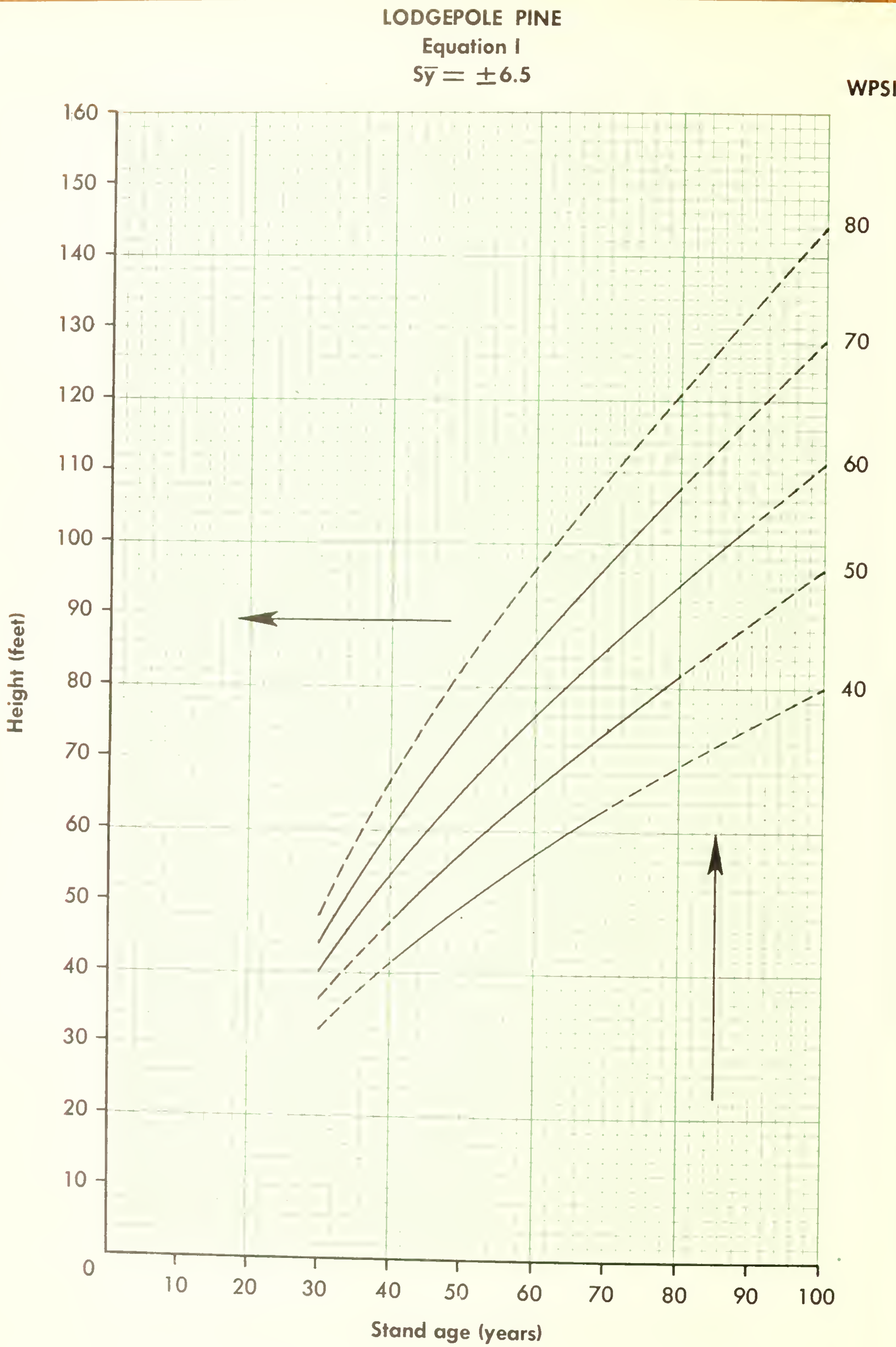

Figure 2. — Predicted average height of dominant and codominant trees by white pine site index and stand age.

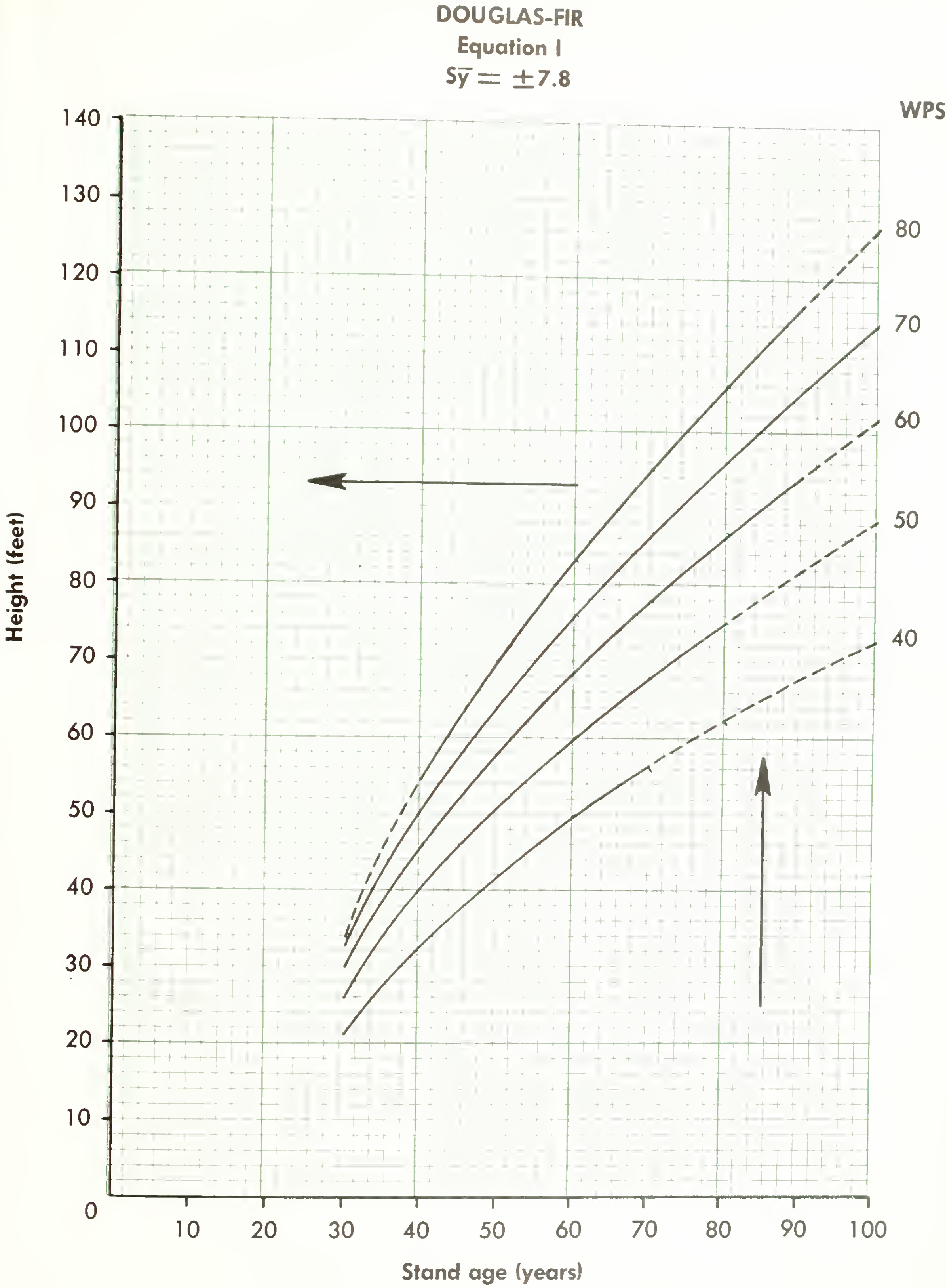

Figure 3. — Predicted average height of dominant and codominant trees by white pine site index and stand age.

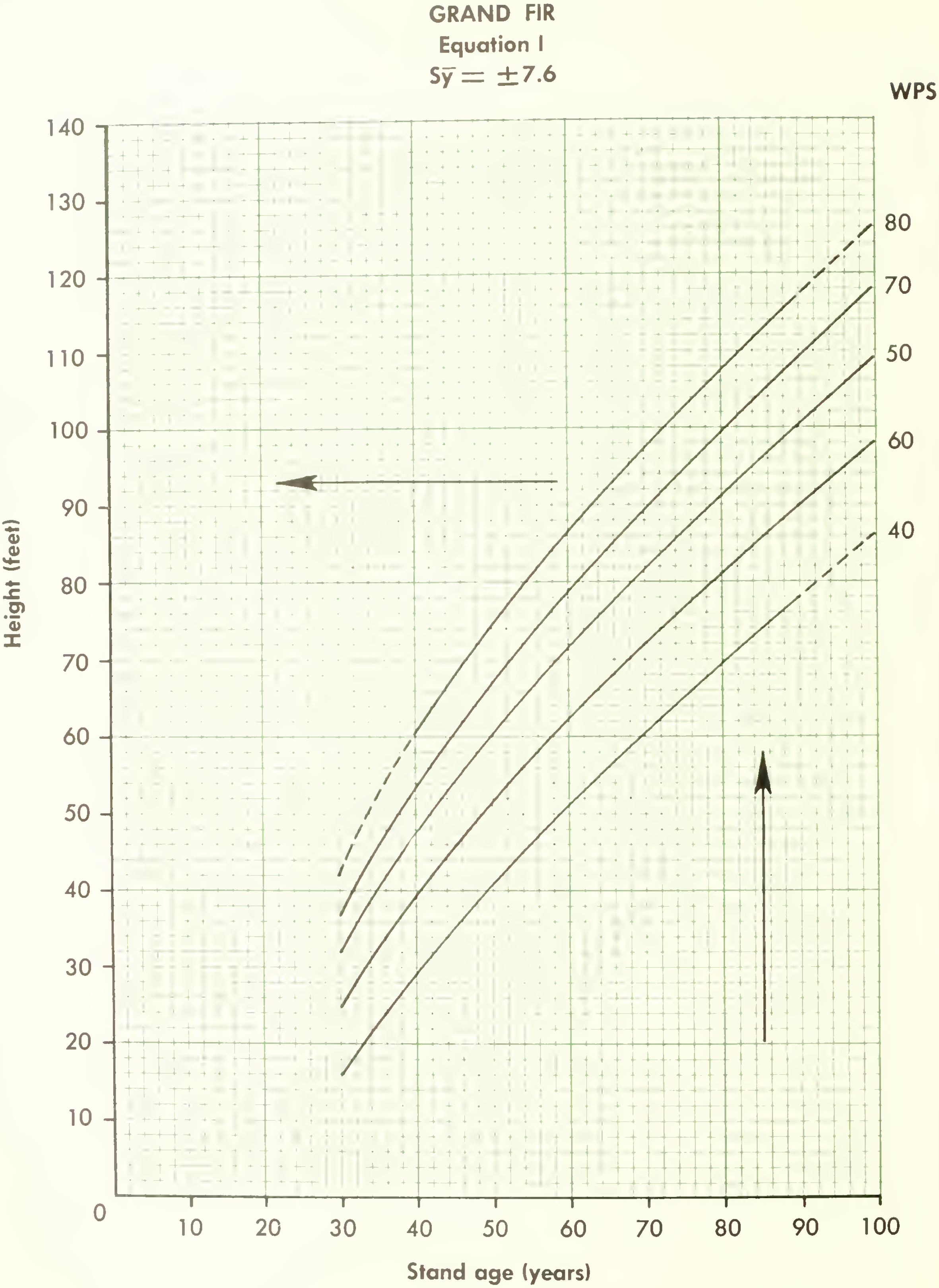

Figure 4. — Predicted average height of dominant and codominant trees by white pine site index and stand age.

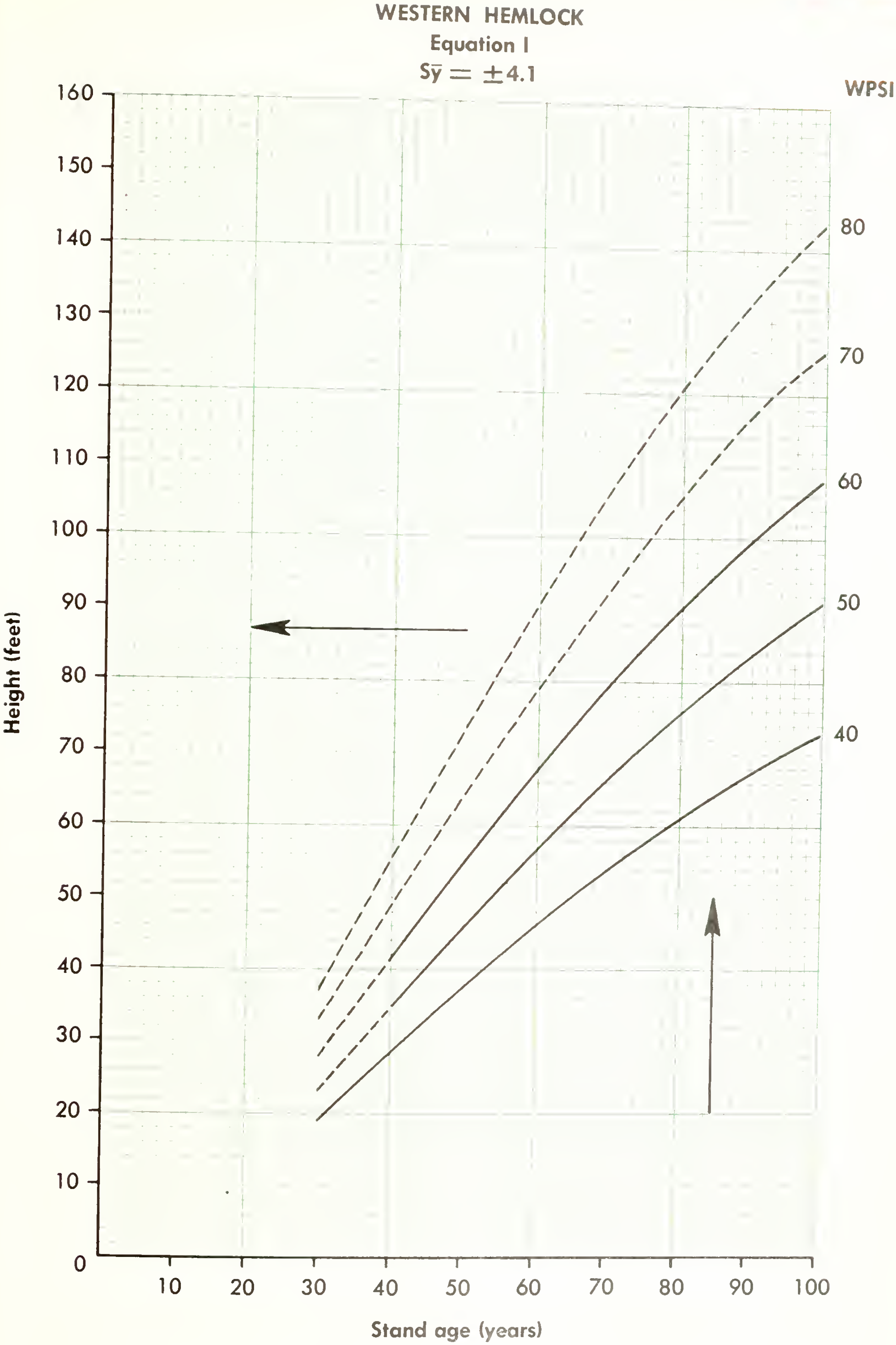

Figure 5. — Predicted average height of dominant and codominant trees by white pine site index and stand age.

Table 2.—Comparative heights of species by white pine site index and stand age
[Equation I series]

White pine site index	Stand Age	White pine	Western larch	Lodgepole pine	Douglas-fir	Grand fir	Western hemlock
	Years	Height (feet)					
40	20	10	5	24	--	--	10
	30	20	24	32	21	16	19
	40	30	37	40	33	29	28
	50	40	48	48	42	40	37
	60	49	57	55	50	50	45
	70	58	66	63	56	60	53
	80	66	75	69	62	69	61
	90	73	83	75	68	78	67
	100	78	91	80	73	86	73
50	20	12	10	26	--	4	12
	30	25	32	36	26	25	23
	40	38	46	47	41	39	35
	50	50	58	56	51	51	46
	60	61	68	65	60	61	56
	70	72	78	74	68	71	66
	80	82	87	82	75	81	75
	90	91	95	90	82	90	84
	100	97	104	96	89	98	91
60	20	14	14	27	--	9	13
	30	30	38	40	30	32	28
	40	45	54	52	46	47	42
	50	60	67	64	58	60	55
	60	73	77	75	69	71	67
	70	86	87	85	78	81	79
	80	98	96	95	87	90	90
	90	109	105	104	95	100	100
	100	117	114	111	102	109	108
70	20	16	16	29	--	12	15
	30	35	43	44	33	37	33
	40	53	61	59	51	54	49
	50	70	74	72	65	67	64
	60	86	85	85	76	79	79
	70	101	96	98	87	89	93
	80	115	105	109	97	99	105
	90	128	114	119	106	108	117
	100	137	123	128	115	118	126
80	20	19	18	31	--	14	18
	30	40	48	48	34	42	37
	40	60	66	64	54	60	55
	50	80	81	81	70	74	74
	60	98	93	95	83	86	90
	70	116	103	110	95	97	106
	80	132	113	123	106	107	121
	90	145	122	133	117	116	133
	100	156	131	144	127	126	144

APPENDIX B

The following tables are for predicting the average dominant-codominant height of five species other than western white pine from white pine site index, stand age, and other site data (Equation II series).

These tables are included to facilitate calculations by the longer formula. To the "base value" obtained in the first table for a given species, add "adjustment values" for each of the other variables from the following tables for that species. For example, to find the height of western larch where:

White pine site index is 60 and stand age is 70 years	Base value	=	−65
Aspect is south (180° azimuth)	Adjustment value	=	−3
Elevation is 4,000 feet	Adjustment value	=	+141
Topographic position is ridge	Adjustment value	=	+12
Habitat type is *Abies/Pachistima*	Adjustment value	=	−9
	Total		76

. . . so the estimated larch height would be 76 feet.

WESTERN LARCH HEIGHT PREDICTION
(Equation II)

Table 3a.—**Base values from stand age and white pine site index**

Stand age (years)	White pine site index				
	40	50	60	70	80
20	−128	−131	−136	−143	−149
30	−118	−115	−114	−113	−114
40	−109	−103	−98	−95	−92
50	−101	−92	−86	−81	−76
60	−93	−83	−75	−69	−63
70	−84	−73	−65	−58	−51
80	−76	−64	−55	−47	−40
90	−68	−56	−46	−38	−30
100	−60	−47	−37	−28	−20

Table 3b.—**Adjustment values for aspect**

Azimuth	Adjustment value
0(360°)	+3
45°	+2
90°	0
135°	−2
180°	−3
225°	−2
270°	0
315°	+2

Table 3c.—**Adjustment values for elevation**

Elevation (feet)	Adjustment value
2,000	+168
2,500	+152
3,000	+144
3,500	+141
4,000	+141
4,500	+143
5,000	+147

Table 3d.—**Adjustment values for topo position**

Position	Adjustment value
Ridge	+12
Upper slope	+1
Middle slope	0
Lower slope	−1
Flat or bench	−12

Table 3e.—**Adjustment values for habitat type**

Habitat type	Adjustment value
Abies/Pachistima	−9
Thuja/Pachistima	+6
Thuja-Tsuga/Pachistima	+3

LODGEPOLE PINE HEIGHT PREDICTION

(Equation II)

Table 4a.—**Base values from stand age and white pine site index**

Stand age (years)	White pine site index				
	40	50	60	70	80
20	−111	−110	−109	−108	−108
30	−97	−96	−95	−95	−95
40	−91	−90	−89	−88	−88
50	−87	−86	−85	−84	−84
60	−84	−83	−82	−82	−81
70	−82	−81	−80	−80	−79
80	−81	−80	−79	−78	−78
90	−79	−78	−78	−77	−77
100	−78	−77	−77	−76	−76

Table 4b.—**Adjustment values for white pine height**

White pine height (feet)	Adjustment value
10	7
20	13
30	20
40	26
50	33
60	40
70	46
80	53
90	59
100	66
110	73
120	79
130	86
140	92
150	99
160	106
170	112
180	119
190	125
200	132

Table 4c.—**Adjustment values for aspect**

Azimuth	Adjustment value
0(360°)	+6
45°	+4
90°	0
135°	−4
180°	−6
225°	−4
270°	0
315°	+4

Table 4d.—**Adjustment values for elevation**

Elevation (feet)	Adjustment value
2,000	+117
2,500	+108
3,000	+105
3,500	+105
4,000	+106
4,500	+110
5,000	+114

Table 4e.—**Adjustment values for topo position**

Position	Adjustment value
Ridge	−1
Upper slope	−3
Middle slope	+5
Lower slope	+4
Flat or bench	−5

Table 4f.—**Adjustment values for habitat type**

Habitat type	Adjustment value
Abies/Pachistima	+6
Thuja/Pachistima	0
Thuja-Tsuga/Pachistima	−6

DOUGLAS-FIR HEIGHT PREDICTION

(Equation II)

Table 5a.—Base values from stand age and white pine site index

Stand age (years)	White pine site index				
	40	50	60	70	80
30	19	24	27	28	29
40	29	37	42	46	49
50	37	47	54	60	65
60	44	55	64	72	79
70	51	63	74	83	92
80	57	71	83	94	104
90	62	78	92	104	115
100	68	85	100	113	126

Table 5b.—Adjustment values for topo position

Position	Adjustment value
Ridge	+4
Upper slope	−1
Middle slope	0
Lower slope	+1
Flat or bench	−4

Table 5c.—Adjustment values for habitat type

Habitat type	Adjustment value
Abies/Pachistima	0
Thuja/Pachistima	−1
Thuja-Tsuga/Pachistima	0

GRAND FIR HEIGHT PREDICTION

(Equation II)

Table 6a.—Base values from stand age and white pine site index

Stand age (years)	White pine site index 40	50	60	70	80
20	37	46	52	57	62
30	49	59	69	77	84
40	51	63	73	81	90
50	51	62	72	80	88
60	48	59	68	76	84
70	45	55	63	71	77
80	41	51	58	64	70
90	37	45	51	57	61
100	33	40	45	49	52

Table 6b.—Grand fir adjustment values for white pine height and stand age

White pine height (feet)	Stand age (years) 20	30	40	50	60	70	80	90	100
10	−25	−12							
20	−50	−24	−12						
30	−75	−36	−17	−6					
40		−49	−23	−8	+3				
50		−61	−29	−10	+3	+13			
60			−34	−11	+4	+15	+23		
70			−40	−13	+5	+18	+27	+35	+41
80				−15	+5	+20	+31	+40	+46
90				−17	+6	+22	+35	+44	+52
100					+7	+25	+39	+49	+58
110					+7	+28	+43	+54	+64
120						+30	+46	+59	+70
130						+33	+50	+64	+75
140							+54	+69	+81
150							+58	+74	+87
160								+79	+93
170									+99

Table 6c.—**Adjustment values for aspect**

Azimuth	Adjustment value
0(360°)	+2
45°	+1
90°	0
135°	−1
180°	−2
225°	−1
270°	0
315°	+1

Table 6d.—**Adjustment values for elevation**

Elevation (feet)	Adjustment value
2,000	+4
2,500	+6
3,000	+7
3,500	+8
4,000	+9
4,500	+10
5,000	+11

Table 6e.—**Adjustment values for topo position**

Position	Adjustment value
Ridge	+1
Upper slope	−2
Middle slope	+3
Lower slope	−2
Flat or bench	+1

Table 6f.—**Adjustment values for habitat type**

Habitat type	Adjustment Value
Abies/Pachistima	−1
Thuja/Pachistima	0
Thuja-Tsuga/Pachistima	+1

WESTERN HEMLOCK HEIGHT PREDICTION

(Equation II)

Table 7a.—**Base values from stand age**

Stand age (years)	Base values
20	−9
30	−6
40	−3
50	0
60	+4
70	+7
80	+10
90	+14
100	+17

Table 7b.—**Adjustment values for white pine height**

White pine height (feet)	Adjustment value
10	6
20	13
30	20
40	26
50	32
60	39
70	46
80	52
90	58
100	65
110	72
120	78
130	84
140	91
150	98
160	104
170	110
180	117
190	124
200	130

Table 7c.—**Adjustment values for elevation**

Elevation (feet)	Adjustment value
2,000	+22
2,500	+18
3,000	+15
3,500	+13
4,000	+11
4,500	+10
5,000	+9

Table 7d.—**Adjustment values for topo position**

Position	Adjustment value
Ridge	−1
Upper slope	+3
Middle slope	0
Lower slope	−3
Flat or bench	+1

APPENDIX C

Graphs for estimating western white pine site index from stand age and the average dominant-codominant height of another species.

THESE GRAPHS ARE NOT TO BE USED FOR PREDICTING OTHER SPECIES HEIGHT.

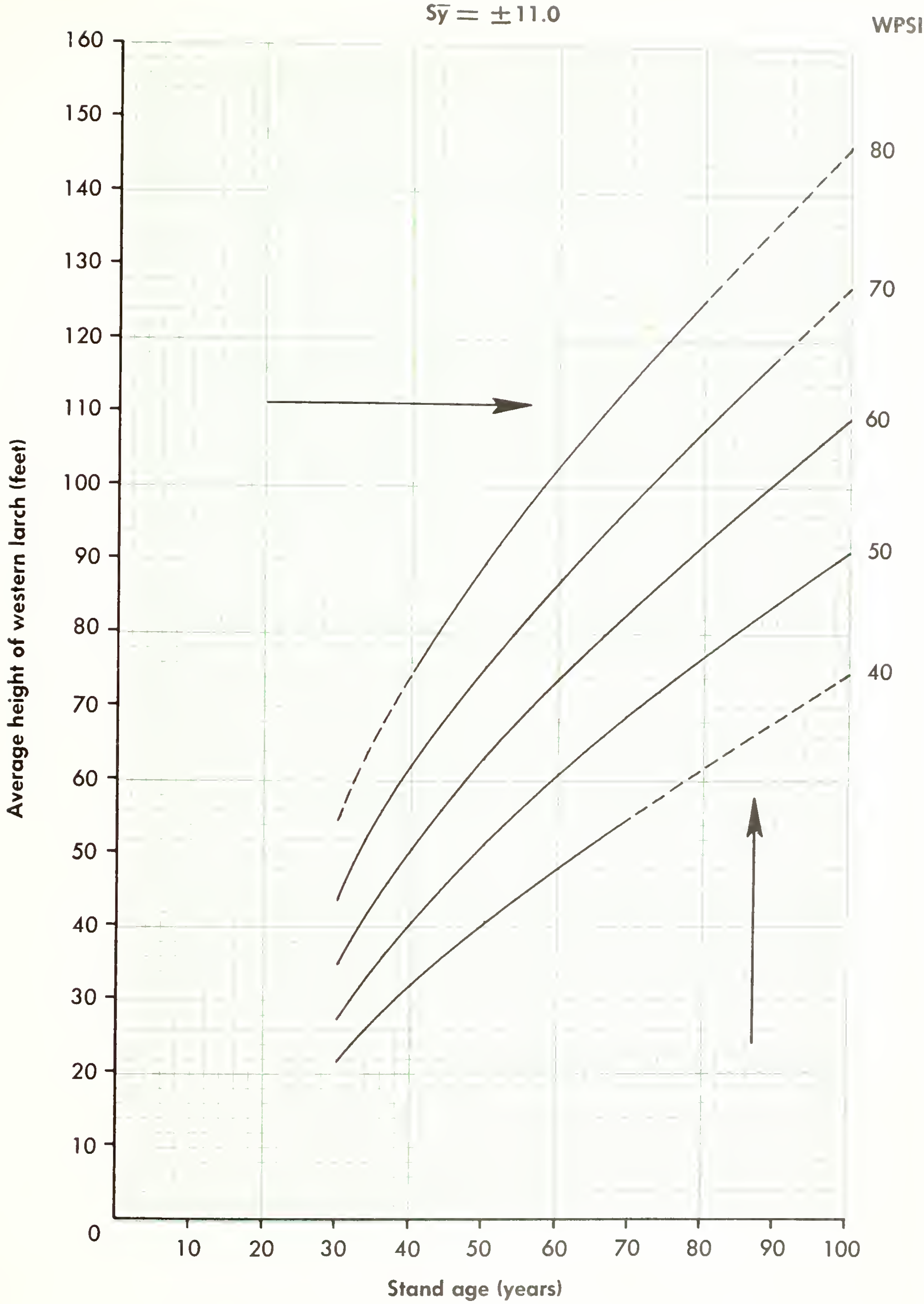

Figure 6. — Estimated western white pine site index by average height of dominant and codominant *western larch* and stand age.

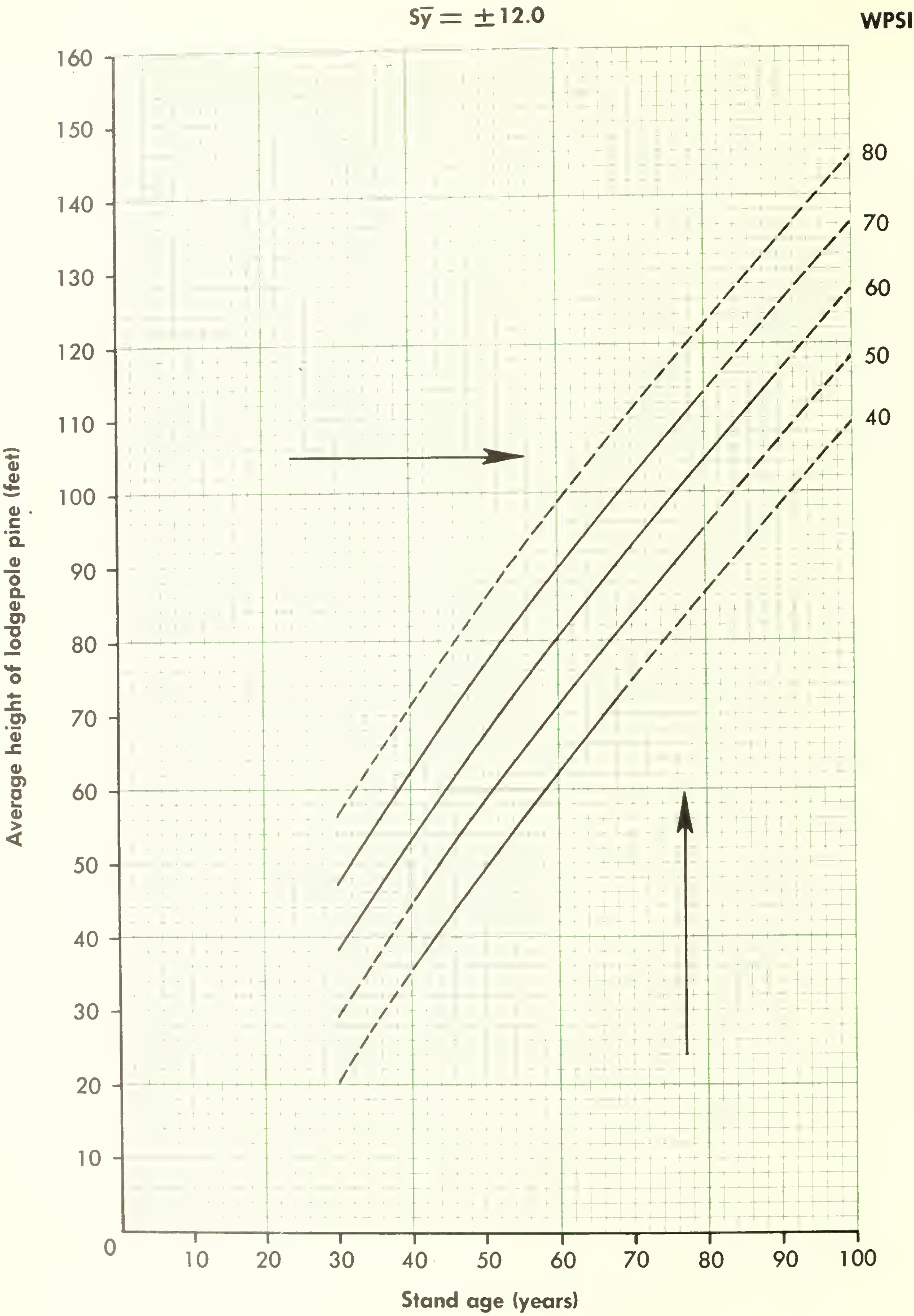

Figure 7. — Estimated western white pine site index by average height of dominant and codominant *lodgepole pine* and stand age.

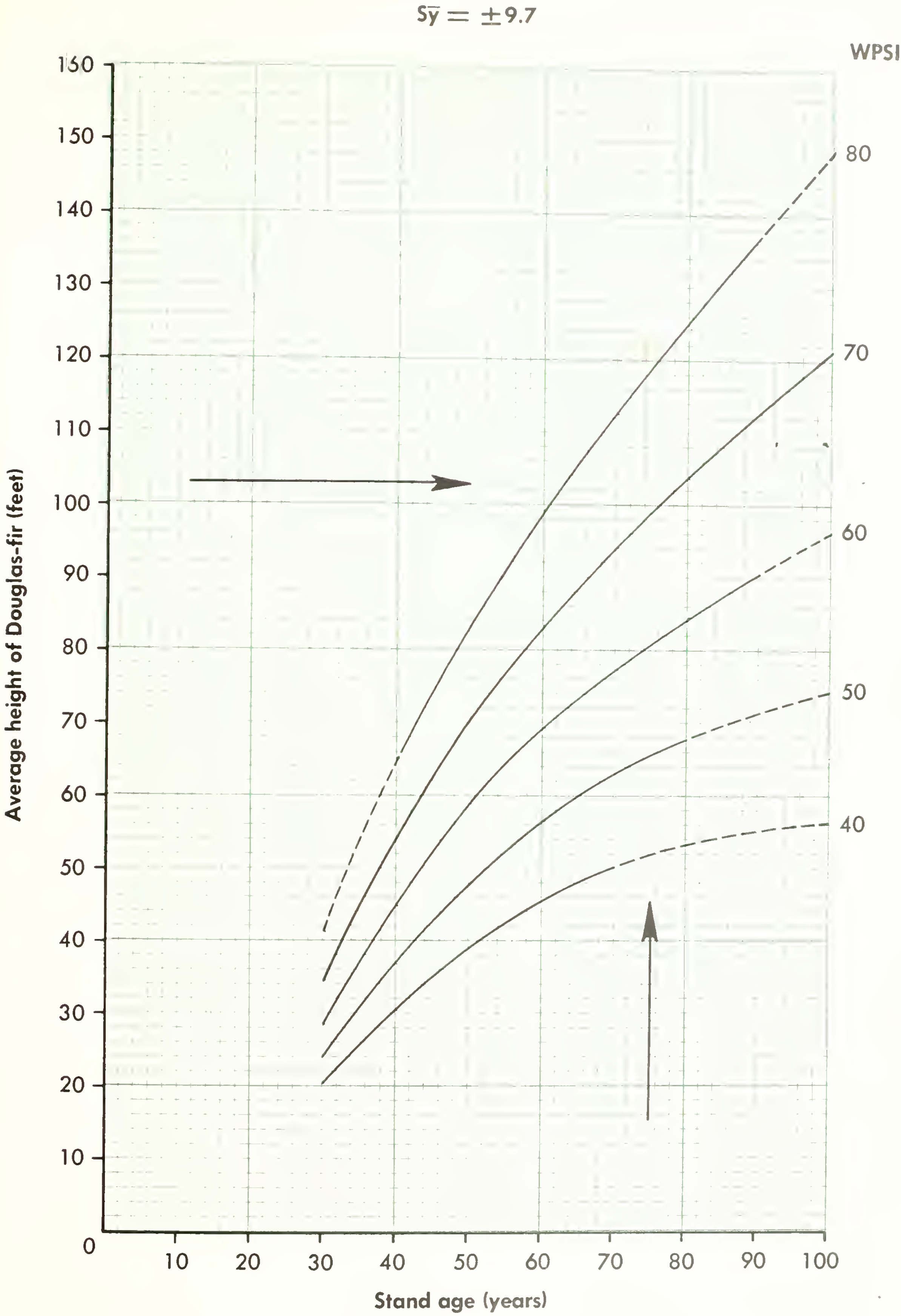

Figure 8. — Estimated western white pine site index by average height of dominant and codominant *Douglas-fir* and stand age.

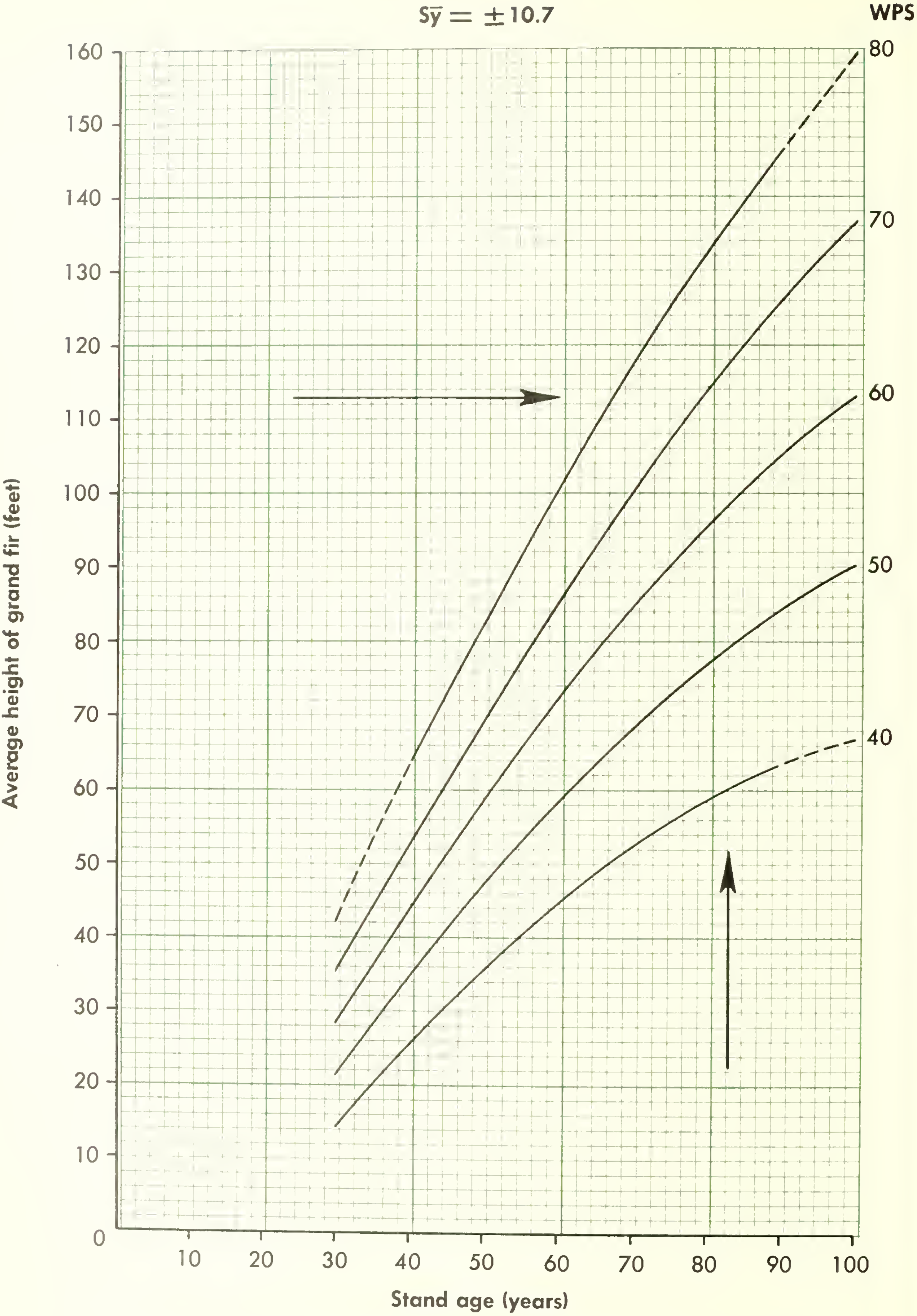

Figure 9. — Estimated western white pine site index by average height of dominant and codominant *grand fir* and stand age.

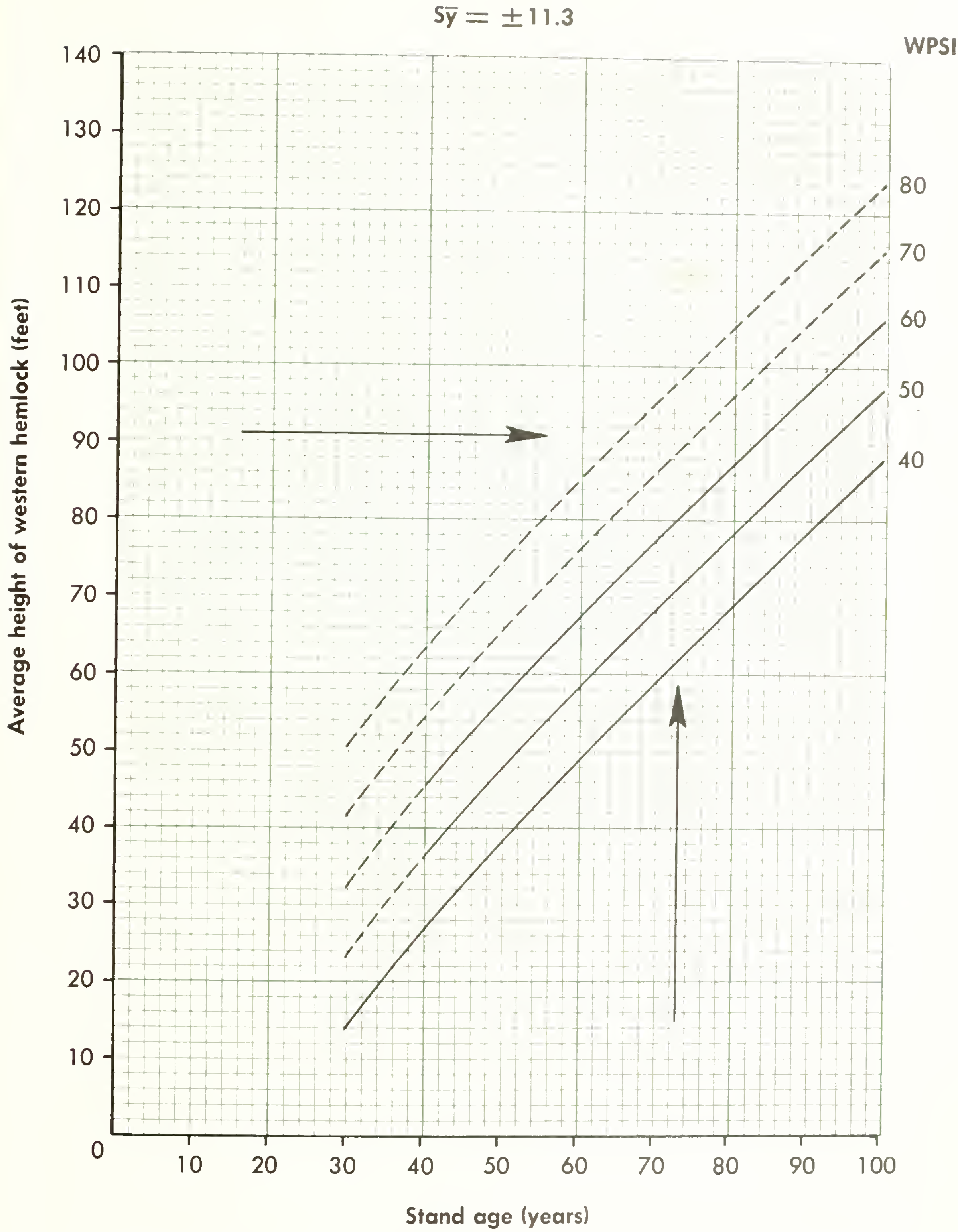

Figure 10. — Estimated western white pine site index by average height of dominant and codominant *western hemlock* and stand age.

FOREST SERVICE CREED

The Forest Service of the U. S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing nation.

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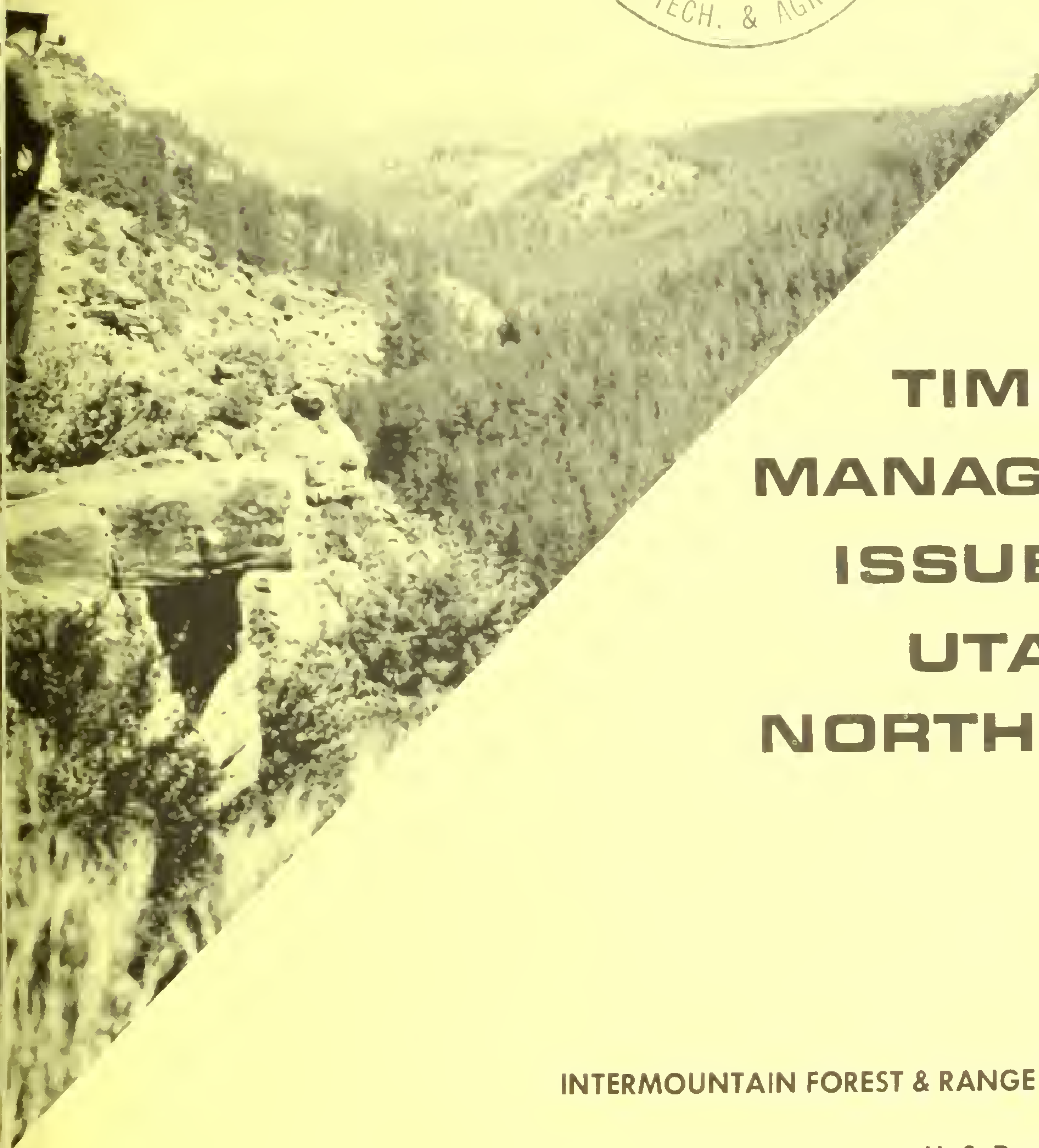

TIMBER MANAGEMENT ISSUES ON UTAH'S NORTH SLOPE

INTERMOUNTAIN FOREST & RANGE EXPERIMENT STATION
Forest Service
U. S. Department of Agriculture
Ogden, Utah

U. S. Forest Service Research Paper INT-23 1965

This publication represents the combined efforts of several men in Intermountain Forest and Range Experiment Station and the Intermountain Region of the Forest Service.

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Ogden, Utah
Joseph F. Pechanec, Director

The utility and value of any National Forest resource must be examined within the context of the multiple use principle. The timber resource pictured here on the shores of Dollar Lake in the Uinta Wilderness is an example. Although this lake is about 10 miles from the nearest road, hundreds of persons travel by foot or on horseback to it each summer. To exclude this lake from analysis of the timber resource would be as unrealistic as to exclude the timber from consideration of the recreation resource. More than 2,000 lakes and ponds are scattered through the North Slope area; nearly 400 of them are larger than 1 acre.

CONTENTS

INTRODUCTION

The forests of the Mountain States show a wide range of productivity. Almost 10 million acres have the capacity, if managed well, to grow more than 400 board feet per acre annually, thus ranking among the more productive timberlands in the Nation. Everything else being equal, these areas offer the best opportunity for profitable investment in timber growing.

At the other end of the scale, several millions of acres show much lower productivity. No prudent individual would be interested in such forests solely as timber investments. However, that point is academic because most of those lands are publicly owned. As the residual legatee of the land management responsibility, the public lacks any significant opportunity to divest itself of such lands. The issue instead is how to manage them.

Stumpage revenue is not the sole consideration or even the overriding one on public timberlands. Public interest involves an array of considerations, some of which are readily described and evaluated, some of which are not. The decision of how much to invest and where to invest in timber management is not therefore a simple matter of rates of return on the investment but is a complex matter involving many aspects of public welfare. Some of the issues involved are "sticky" indeed. Some aspects of future value cannot now be estimated with confidence. The relation of timber management to other land uses is broadly understood but the specifics have yet to be worked out. Yet, public land managing agencies—in this case the United States Forest Service—must arrange the various considerations on some logical basis if they are to make completely rational decisions as to what should be done and why.

The purpose of this publication is to describe the timber resource problem and the broad issues of management on the North Slope, which is a representative "low site" area in the Mountain States.

THE FOREST OF THE NORTH SLOPE

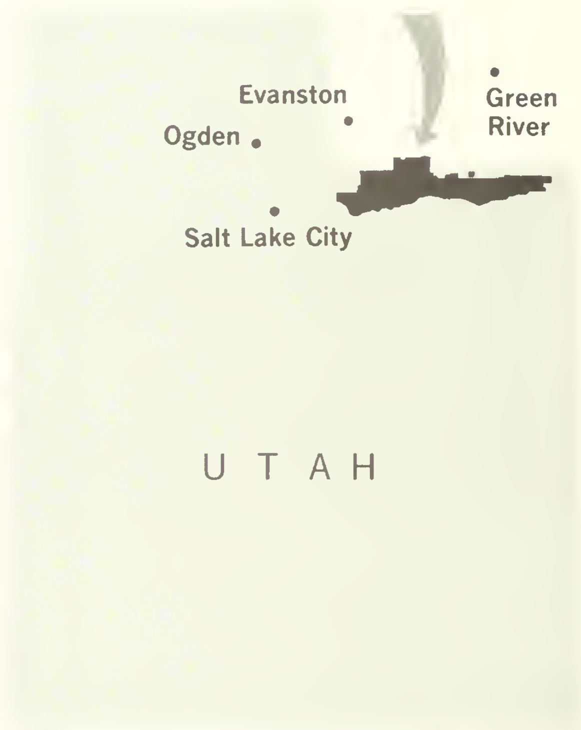


Figure 1

The North Slope is a strip of land 75 miles long by 20 miles wide. Most of its 677,000 acres are in National Forest ownership and lie within the Ashley and Wasatch National Forests. The area is divided into three Ranger Districts: the Manila District on the eastern end is in Ashley National Forest; the Mountain View and Evanston Districts are in Wasatch National Forest.

Although the first impression one gets of the North Slope is of an endless expanse of trees, nearly one-fourth is meadows, rockslides, and other nonforest land. Seventeen percent of the land area is classified as noncommercial; that is, it is either reserved in the High Uinta Primitive Area or is nonproductive forest, or both.

Sixty percent of the North Slope, or 404,000 acres, is classified as "commercial"; that is, it is suitable and available for timber production.[1]

Most of the commercial forest land area (70 percent) is lodgepole pine type. The remainder are spruce, ponderosa pine, aspen, and Douglas-fir types. During the construction of the Union Pacific Railroad, hundreds of thousands of railroad ties were logged on the North Slope but timber harvest since that time has declined. The drain on the forest has been minor in relation to the timber available, and as a result the area is relatively un-

[1]Land classed as commercial forest must be producing or capable of producing crops of industrial wood and not withdrawn from timber use. However, about 25,000 acres of land meeting this requirement is considered nonloggable, either because logging might damage watersheds, or because steep slopes or rock outcrops make logging impractical.

developed. It is a major watershed in Utah, an important big game area, and has considerable recreation potential. There are about 400 lakes and 600 miles of streams on the North Slope.

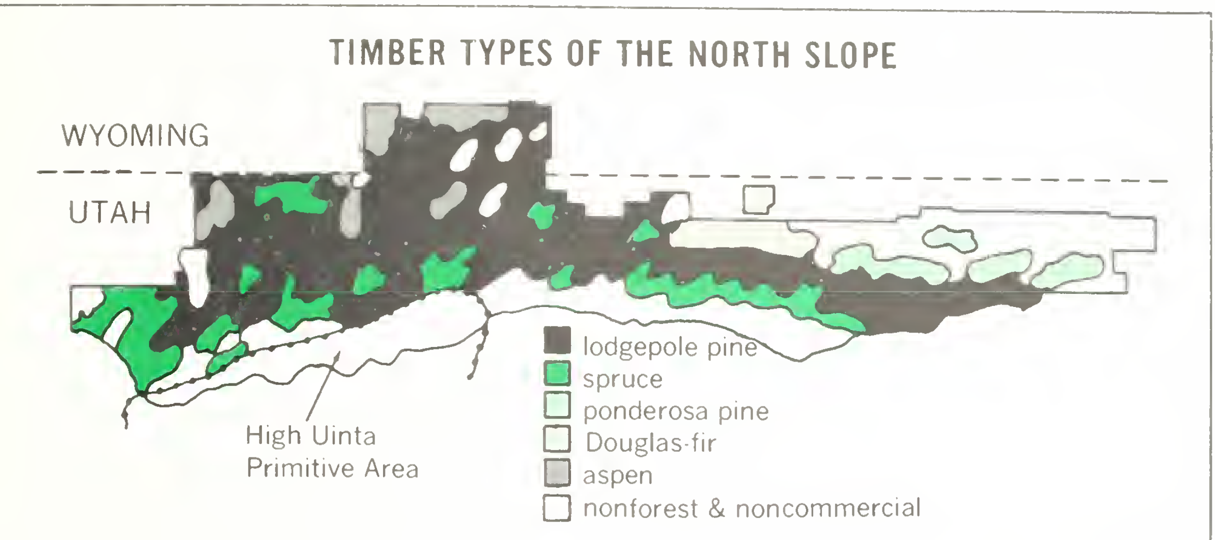


Figure 2

Table 1. — AREA BY LAND CLASS

Land class	Acres	Percent
Unreserved land		
Commercial forest		
Loggable	378,699	55.9
Nonloggable	[1]25,000	3.7
	403,699	59.6
Noncommercial forest	54,349	8.0
Nonforest	158,775	23.5
Reserved land		
Primitive area	[1]60,000	8.9
Total	676,823	100.0

[1]Estimated

Table 2. — AREA BY OWNERSHIP CLASS

Ownership class	Acres	Percent
National Forest	618,015	91.3
State	21,130	3.1
Private	37,678	5.6
Total	676,823	100.0

Table 3. — AREA OF COMMERCIAL FOREST LAND BY FOREST TYPES

Forest type	Acres	Percent
Lodgepole pine	283,296	70
Spruce (Engelmann)	52,623	13
Ponderosa pine	23,705	6
Aspen-cottonwood	20,899	5
Douglas-fir	18,660	5
Subalpine fir	4,516	1
Total	403,699	100

THE NORTH SLOPE FOREST RANKS LOW IN PRODUCTIVITY AND POSES DIFFICULT MANAGEMENT PROBLEMS

Except for some steep, rough areas along the Green River Canyon and just under the Uinta Peaks, most of the commercial forest land on the North Slope is nearly level or gently rolling.

However, the North Slope has more than its share of less productive land. More than three-fourths of the commercial forest is classified as "low site" or "very low site" land, on which tree growth is very slow (table 4). For example, lodgepole pine growing on low site land averages only about 11 inches in diameter and 55 feet in height even when trees develop free of such disturbances as fire, insects, and disease, and are not overcrowded. Figures 3 and 4 show typical low site areas.

These site estimates may be unduly minimizing, at least in the lodgepole pine type where overstocking tends to shorten height growth. No allowance was made for this factor in classifying the site of North Slope lands.

Table 4. — AREA OF COMMERCIAL FOREST LAND BY SITE CLASS

Site class[1]	Acres	Percent
Good	261	(2)
Medium	75,329	19
Low	225,133	56
Very low	82,640	20
Unclassified aspen	20,336	5
Total	403,699	100

[1] Forest Survey site class standards were used in conifer types. Most of the aspen growing on the North Slope is so poor that it cannot be considered for commercial purposes; so no site classification was attempted.

[2] Less than 0.5 percent.

Figure 3. — Seventy-seven thousand acres of lodgepole pine forest are on shallow soils of limited productivity. The trees on this ridge average only 5 inches in diameter and 26 feet in height, although they are 80 years old.

There is, of course, some more productive land on the North Slope. Nineteen percent is classified as medium site. Medium site lodgepole pine land such as is shown in figure 5 can produce about 19 thousand board feet per acre of sawtimber in a rotation period.

Figure 4. — The ponderosa pine forest in the Manila District includes a few small patches of excellent trees. However, this is more than offset by many acres of scrubby timber such as this. The growth rate is slow and the stand reestablishment rate is even slower on these rocky areas.

Figure 5. — The best timber-growing opportunity on the North Slope lies in the 75,000 acres of medium site land such as is pictured here.

If the North Slope were to be brought under management as a sustained yield unit, the task would be difficult because the age distribution is unbalanced and is dominated by overmature stands. More than half of the coniferous forest bears stands that are mature or overmature. Much of this timber is more than 200 years old, and a few stands are 3 or 4 centuries old. Annual losses are consequently high.

The situation is likewise unsatisfactory at the other end of the age scale, for there are very few young stands. Stands less than 60 years old occupy only 23,000 acres, and there is a very small area of timber less than 20 years old.

The bulk of the younger timber is from 60 to 100 years old. Most of these stands were established following tie cutting and subsequent fires before 1900 (table 5).

As in every other locality where there is much lodgepole pine, overstocking has created a principal management problem. This is not readily evident in present classifications, which indicate that only 13 percent is overstocked by basal area standards (table 6). However, a much greater area apparently was overstocked earlier in the life of present stands. This is shown by diameters of trees in relation to their age. For example, about 146,000 acres of lodgepole pine poletimber that are classed as medium or well stocked (by all sizes of trees) are actually only poorly stocked with larger or pole-size trees. Yet these stands are old enough to have a good stocking of poles.

Table 5. — AREA OF CONIFER FOREST BY AGE CLASS

Age class (years)	Acres
0 - 19	3,233
20 - 59	19,807
60 - 99	97,301
100 - 139	50,628
140 +	211,831
Total	382,800

Table 6. — AREA OF COMMERCIAL FOREST BY STOCKING CLASS

Stocking class	Acres	Percent
Overstocked	52,121	13
Well stocked	140,478	35
Medium stocked	184,574	45
Poorly stocked	24,074	6
Nonstocked	2,452	1
Total	403,699	100

The effect of overstocking in the past is also indicated by an estimate that almost one-fourth of the mature lodgepole pine stands are of less than sawtimber size. Some of these are on very poor sites, which accounts for the very small size of the trees but in many other cases the situation is simply the result of overcrowding. Often a natural but tardy

Figure 6. — This overstocked 80-year-old stand exemplifies the crowding problem at its worst. There are 10,000 stems per acre averaging about 2 inches in diameter. This site could grow trees 9 inches in diameter in 80 years if stocking were controlled.

thinning has removed evidence of past overcrowding; however, the size-age relationship of the remaining stems clearly reveals that this was the problem.

The most severe instances of overcrowding are in 4,119 acres of stagnated stands, such as shown in figure 6. These stands have been overdense for so long that they will never produce usable timber. However, the more important loss of productivity has occurred on many thousands of acres on which overcrowding has retarded but not stagnated the stands. Only 38 percent of the young timber on the North Slope qualifies as good growing stock (fig. 7). The main reason for the poor condition of the rest of the growing stock is excessive numbers of trees in stand after stand.

THE NORTH SLOPE FOREST IS IN A STATE OF RAPID ATTRITION

Were it not for the fact the North Slope timber is predominantly mature and overmature and that stand conditions have been aggravated by past cutting and fire protection practices, management decisions for the area could be deferred. Because more than half of the conifer timber is mature or overmature, the North Slope lodgepole pine has been under intermittent siege by mountain pine beetles for several decades. The most recent flareup began in the Hole-in-the-Rock area in 1956 and spread westward to the Blacks Fork River drainage. During this epidemic 165,000 acres were heavily attacked by beetles (fig. 8).

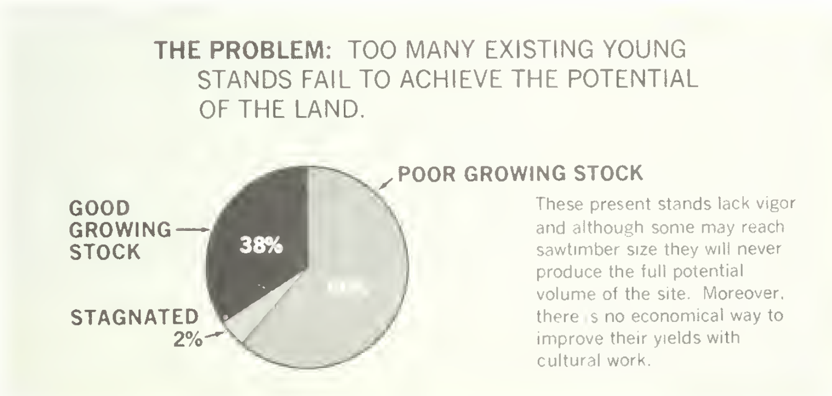


Figure 7

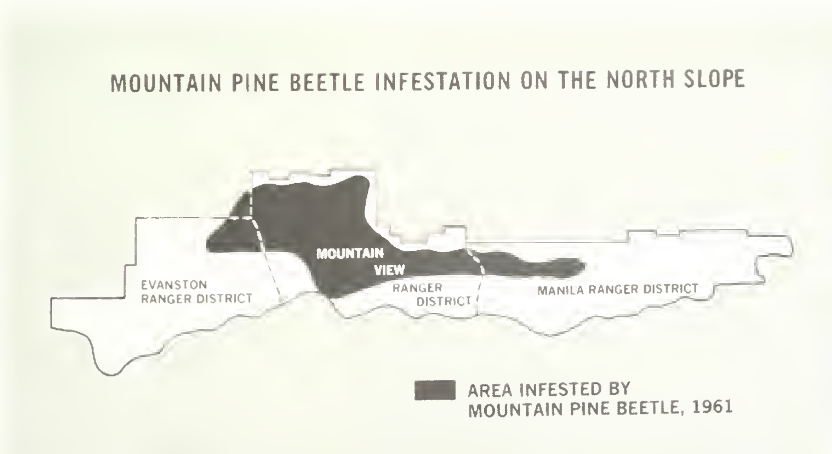


Figure 8

A large-scale program to contain the infestation was begun in 1958. Up through 1962, $3.2 million was spent in this effort, which was successful to the extent that the beetle population has been held approximately at a normal endemic level since 1963 (figs. 9 and 10).

Whatever reduction in insect numbers has been caused by cyclic changes and control programs, the respite must be regarded as only temporary. Forty-four percent of the 201,000 acres of mature and overmature timber is classified as "high risk" (table 7). Until this timber is logged or killed, periodic flareups of the mountain pine beetle and other insects must be expected.

Figure 9. — Though the mountain pine beetle is being blamed for the loss of millions of board feet of sawtimber on the North Slope, these losses are only the dramatic finale to a long history of stand deterioration. The buildup of the insect attack in this stand and others started in overage timber long past its prime.

Figure 10. — The strategy of pine beetle control has been based on destroying infested trees by spraying or other means. The most dramatic and imaginative approach was "Operation Pushover." The trees on several thousand acres of badly infested timber were pushed over, piled, and burned. This operation not only killed the insects, it also destroyed the dwarfmistletoe and cleared the ground for disease-free new stands.

Table 7. — AREA OF MATURE AND OVERMATURE CONIFER TIMBER BY FOREST TYPES AND RISK CLASS

Type	High risk	Low risk	Total
		Acres	
Subalpine fir	1,448	375	1,823
Douglas-fir	2,900	9,729	12,629
Lodgepole pine	75,511	57,059	132,570
Ponderosa pine	1,392	9,601	10,993
Spruce	7,530	35,076	42,606
Total	88,781	111,840	200,621

Table 8. — NUMBER OF LODGEPOLE PINE TREES KILLED BY MOUNTAIN PINE BEETLES, 1956—1961

Year	Thousands
1956	100.0
1957	108.6
1958	192.0
1959	199.2
1960	304.6
1961	300.0
Total	1,204.4

Losses during this epidemic varied from stand to stand. However, the damage was most severe in older stands, particularly the ones heavily infected with dwarfmistletoe. Between 1956 and 1961 more than a million lodgepole pine trees were killed by pine beetles (table 8). Since these insects usually concentrate on the larger trees, the volume loss has been high. Data are not available to show the exact volume of the utilizable-size trees that have been killed; however, many sawtimber stands have been reduced to ghost forests of dead trees. A few timber inventory plots examined in 1962 had lost about 40 percent of their sawtimber volume in the preceding few years.

Dwarfmistletoe is putting the finishing touch on the deterioration of many North Slope forests. This plant parasite has constantly plagued the lodgepole pine on the North Slope. However, it has become an increasingly serious problem in the past century. There are several reasons for this. In the first place, dwarfmistletoe thrives best where stands are open. Logging for railroad ties was largely a selective process that opened up stands. The substantial losses in older stands due to insects and other agents have created more openings; thus, conditions have been ideal for spread and intensification of dwarfmistletoe infection. Effective fire control in the past half century has aggravated the problem because fires had periodically destroyed the timber on infected areas and thus cleared the way for dwarfmistletoe-free young stands.

Almost 157,000 acres of lodgepole pine in the North Slope have 10 percent or more of their stems infected by dwarfmistletoe (table 9). The principal damage from this pest is reduction in tree vigor and growth. Analysis of 346 lodgepole pine trees in undisturbed stands on the North Slope indicated that trees with infection in all four quadrants of the crown are currently growing 80 percent as rapidly as uninfected trees. These data probably understate the problem because the uninfected trees used as a basis of comparison have subnormal vigor because of old age and past overcrowding. Studies elsewhere indicate that heavy infection reduces cubic-foot growth of the individual tree by half or more, and that a light infection reduces it more than one-third.[2] Figure 11 shows dwarfmistletoe destruction in the North Slope at its worst.

Table 9. — AREA OF LODGEPOLE PINE TYPE BY DEGREE OF DWARFMISTLETOE INFECTION

Percent of trees infected		Acres
0 - 9		126,590
10 - 29		65,748
30 - 54		38,711
55 - 79		22,495
79 - 100		29,752
	Total	283,296

PRODUCTIVITY OF THE NORTH SLOPE FOREST CAN BE GREATLY INCREASED

The deteriorated condition of the North Slope forest and the difficult problems that face the land manager tend to obscure the fact that this area could produce a substantial output of timber. The average volume of future stands could be more than twice that of present stands with appropriate management. Table 10 compares the volume per acre in sawtimber trees in present mature stands of each type with what appears to be a reasonable estimate of potential yield for these areas.

Table 10. — PRESENT AND POTENTIAL VOLUMES PER ACRE IN MATURE STANDS ON THE NORTH SLOPE

Forest type	Present	Potential[1]
	- - - -Board feet- - - -	
Lodgepole pine	4,200	13,000
Spruce	9,900	21,500
Ponderosa pine	5,000	13,500
Douglas-fir	5,200	11,500
Subalpine fir	8,100	12,500

[1]Weighted average for all site classes.

[2]Kimmey, James W. Dwarfmistletoes of California and their control. U. S. Forest Serv., California Forest & Range Exp. Sta. Tech. Paper 19, 12 pp., illus. 1957.

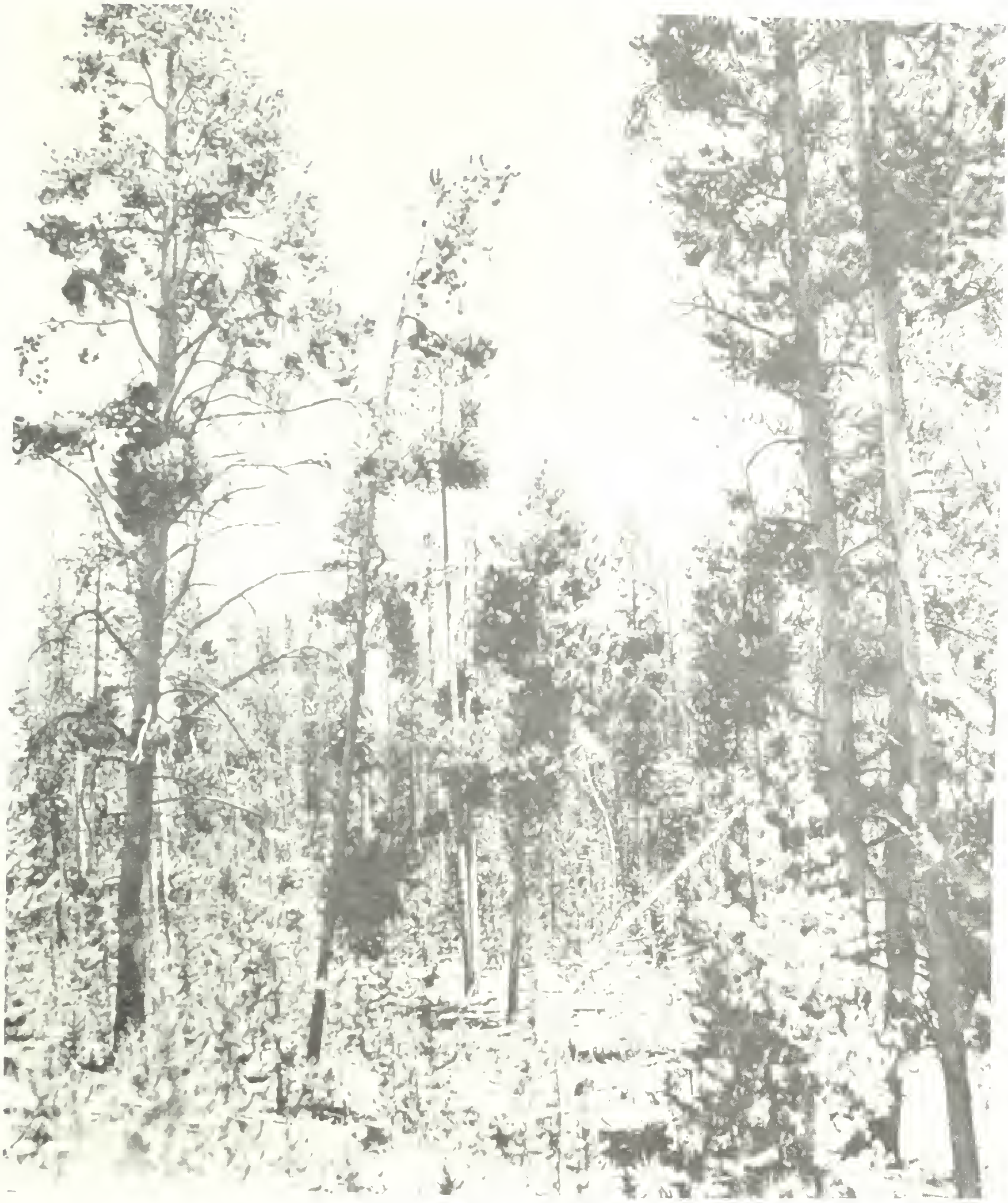


Figure 11. — Dwarfmistletoe probably has been present in the timber of the North Slope for centuries. However, partially cutting the lodgepole pine stands lets more light into the stand canopy and encourages the parasite to spread. Young trees established under infected old trees, as shown here, are generally loaded with dwarfmistletoe.

Undoubtedly, the greatest single requirement for growing these potential volumes is to control stocking, especially in lodgepole pine stands. Loss of growth caused by overcrowding is virtually certain in lodgepole pine stands unless they are thinned at the proper time. Another important requirement, of course, is to prevent mistletoe from infecting future stands (fig. 12).

Figure 12. — This lodgepole pine stand shows that the North Slope can produce good timber. Sawtimber trees in this stand range up to 18 inches in diameter and average about 80 feet in height.

A LARGE EXPENDITURE WILL BE REQUIRED TO RESTORE THE NORTH SLOPE FOREST TO PRODUCTIVE CONDITION

The commercial forest of the North Slope includes thousands of acres that produce so little timber that they are not likely to be considered economically operable in the future even though publicly owned. How large that area is depends upon operating costs that can be estimated with some realism, future values that can only be guessed, and the acceptable relationship between the two. In this study, economically operable areas were assumed to be those in which stumpage values in the next rotation would exceed costs for development and rehabilitation. Seventy-five of the 94 compartments are operable on this basis. These 75 compartments include 252,000 acres of the 404,000 acres of commercial forest in the North Slope.

The cost of restoring these 252,000 acres to a productive condition will probably run higher than $80 an acre, exclusive of future insect control costs.

Since the North Slope is still relatively undeveloped, the additional road system required to utilize and manage the operable timber will cost about $7 million. However, a 600- to 900-mile road network, costing about $5 million, has tentatively been planned for the area, and nearly all of this system is primarily for recreation and other purposes not related to timber management. This can now be regarded only as a rough estimate of road needs for multiple use management and the specific portions chargeable to various functions are partly a matter of arbitrary judgment. Yet, it is important that uses not related to timber management will undoubtedly bear much of the development cost. If construction of these roads is charged to other uses, there still would remain $2 million of additional road construction required to utilize the timber.

If the operable timber area on the North Slope is to be devoted to timber growing, the big cost during the first rotation will be for land management measures required to convert the presently decadent timber into a vigorous young forest. More than $7 million will be required to clean up dead and unutilizable timber and logging debris. Another $9 million will be needed for subsequent site preparation and stand regeneration. Thinning to prevent overstocking in the new timber crop will add another $2.6 million of costs.

These road development and management costs add up to $21.1 million (table 11). Basic costs of land administration are not included as they will continue whether or not this area is devoted to timber growing.

Table 11. — COST OF DEVELOPING THE TIMBER RESOURCE AND RESTORING THE LAND TO PRODUCTION

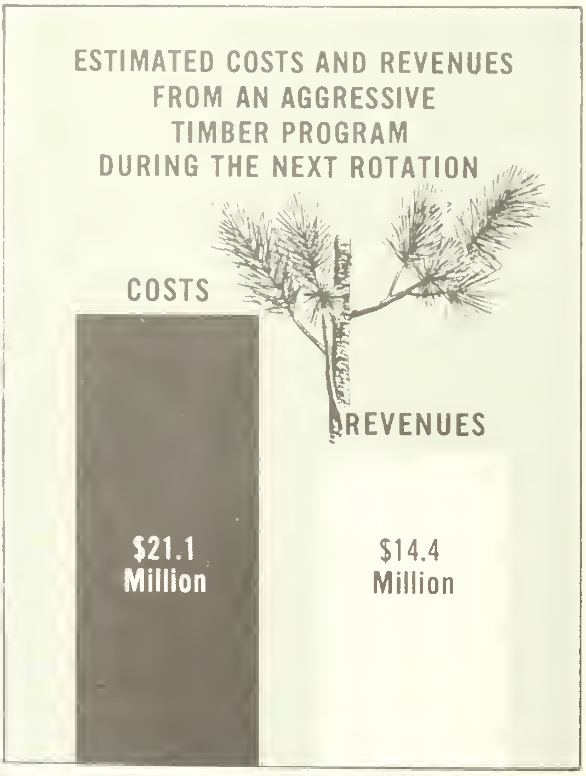
	Million dollars
Additional roads chargeable to timber	2.0
Slash disposal	7.2
Site preparation and stand regeneration	8.8
Thinning	2.6
Erosion control	.5
Total	21.1

PRINCIPAL ISSUES THE LAND MANAGER MUST CONSIDER

After the public land manager has systematically excluded those areas that he believes will not be operable under any circumstances, he continues to face the issue of economic feasibility. In the North Slope the central issue is simple. Are the benefits to be realized from an intensive timber growing effort on 252,000 acres great enough to justify spending $21.1 million?

In this case there can be no refuge in the financial calculations. There are about 2 billion board feet of sawtimber on the North Slope today. Assuming that this volume could be logged from present stands during the first rotation (a generous assumption in view of recent losses) and assuming the average value of this stumpage would be $7 per thousand board feet (the average sale price in 1963 was $3.04 in the Intermountain Region), these timber yields are worth about $14.4 million (fig. 13). In other words, from a strictly financial point of view, the venture has all the earmarks of a losing proposition. Thus, the desirability of timber growing on the North Slope must be determined by weighing the excess of costs over stumpage values against other considerations, which can be grouped under four headings:

1. Future national need for wood
2. Local need for income
3. Relation of timber growing to the total land management operation
4. Relation to national development



Future national need for wood

This subject has aroused and will continue to provoke considerable argument because future needs for wood cannot be measured. Estimates of long-range national demands for timber have been made periodically during the past several decades. All indicate a rising demand for wood. However, no estimates have been projected beyond the year 2000, and it is anyone's guess how great the need for timber products will be 100 years and more hence.

Since facts about this distant future are obviously not obtainable, present public policy cannot be based on *what will happen*, but must instead be related to the possibility of need. Policy decisions related to such long-range planning become more realistic if they are viewed as steps in meeting uncertainties.

In developing public timber policy the following line of reasoning seems realistic insofar as future national demands for wood are concerned: The population of the United States is definitely headed upward, and nothing short of catastrophe will change that. A median estimate of the Nation's population in the year 2000 is 325 million people. There is no present indication that the number of people in the United States will not rise above that level in later years.

Although a progressively higher proportion of the total national effort will go into services, the need for raw materials will undoubtedly continue to mount along with population, if living standards are to be maintained and improved. Timber needs in the United States to the year 2000 are discussed in a recent report.[3] Wood is only one essential raw material, and the future demand for wood therefore will depend partly on the availability of the other materials.

Availability itself is a complex consideration dependent upon physical supply, technological progress, and restrictions imposed by national boundaries. No long-range analysis has yet pieced together a reliable picture of total resource availability a century hence and the resultant likely need for wood. However, there is a possibility that other raw materials may become economically less available in the next century, a factor that might substantially increase needs for wood above the level that can now be anticipated. Much of the case for timber growing on the North Slope and areas like it rests on this possibility.

There is the further problem of priorities between regions and areas. This may not be a one-sided matter. Two main liabilities of this region are a large area of low site land and long distance to principal markets. These liabilities may be more than offset by an important advantage—a high proportion of public ownership. To increase the quality and quantity of timber yields substantially in any region will require considerable acceleration of forestry. Whether it is possible to achieve and maintain a high level of forestry on millions of small private holdings which predominate in the East remains to be seen. This is feasible on public lands.

Local need for income

A perennial issue in parts of the Mountain States is the problem of providing economic opportunity. As in other parts of the Nation, economic growth has been more rapid in metropolitan areas than in rural areas and in small communities where the economy

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[3] U. S. Forest Service. Timber trends in the United States. U. S. Dep. Agr. Forest Resource Rep. 17, 235 pp., illus. 1965.

is often closely tied to the harvest or primary use and processing of such natural resources as crops, minerals, and timber.

For example, between 1950 and 1960 the population of the Salt Lake City metropolitan area increased nearly 40 percent compared with only a 22-percent increase in the three counties adjacent to the North Slope (Sweetwater and Uinta Counties, Wyoming, and Daggett County, Utah). During this same period, median income in this three-county area rose only two-thirds as much as in nearby Salt Lake City.

In some areas where economic growth is slow the resource base is already being utilized as fully as present technology permits. The opportunity to expand economic growth in these areas rests largely on new technology that will expand the resource bases or upon developing economic activities that do not depend on primary use of resources.

In other areas, however, some of the existing resources are not being fully utilized and may provide an opportunity for expanding economic growth and preventing the development of depressed communities. The forest resource of the North Slope is an example.

The timber in this locality could contribute significantly to the local economy. Only a few small sawmills are now cutting North Slope timber. The saw logs and poles cut by these mills amount to about one-fourth of the annual cut that the present stands could support (fig. 14). There is enough wood in trees 5 inches d.b.h. and larger of the North Slope to support a 200-ton sulphate pulpmill for 65 years.[4]

Relation of timber growing to the total land management operation

However much it may be desirable to discount timber values as such in the North Slope —water, recreation, and wildlife values on this area are extremely important.

The North Slope is one of the more productive watersheds in the State of Utah, which in the main is a moisture-deficient area (fig. 15).

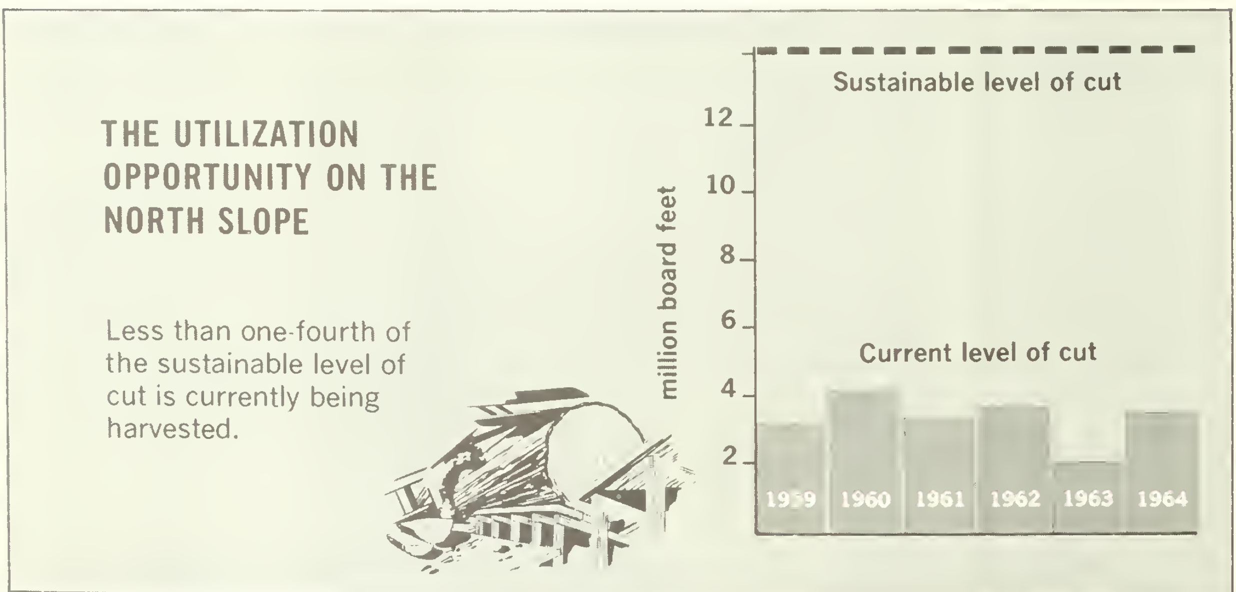
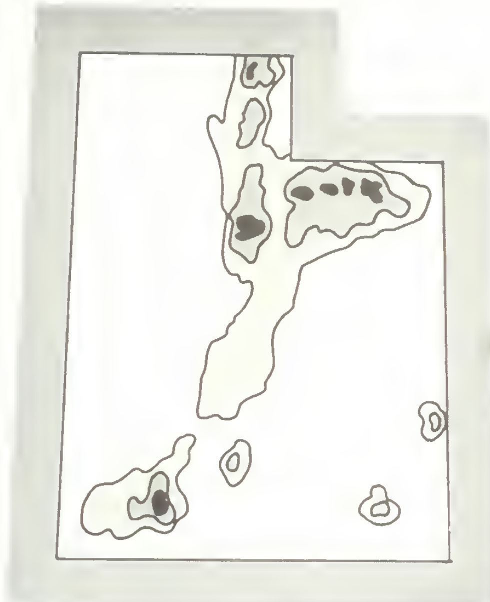


Figure 14

[4] Hutchison, S. Blair, and John H. Wikstrom. Industrial opportunities in the headwaters timber development unit. U. S. Forest Serv., Intermountain Forest & Range Exp. Sta. Res. Paper 45, 70 pp., illus. 1957.



ANNUAL PRECIPITATION IN UTAH

Over 40 inches
20 - 29 inches
30 - 39 inches
Under 20 inches

Figure 15. — Annual precipitation on the North Slope ranges from less than 12 inches to more than 40 inches.

Lakes and streams are also an important recreational asset. About 400 lakes in the North Slope are larger than 1 acre and there are about 600 miles of streams. The area is close to the population centers of Utah, a short side trip off one of the main east-west highways across the United States, and adjacent to the Flaming Gorge dam and reservoir. This combination of factors promises to make it a heavily used area for outdoor recreation (fig. 16). A preview of what may happen is provided by the Flaming Gorge reservoir itself. Although recreation facilities on this 91-mile-long reservoir on the Green River were only partly developed in 1964, at least 300,000 visits were made to the campgrounds, boat ramps, and other facilities adjacent to this manmade lake in that year. Recreation opportunities are enhanced by the wildlife population. Like many other parts of Utah, this is an excellent hunting ground for deer.

Decisions on managing North Slope timber must take account of these other values and the total land management operation. At present the land manager has only some broad principles to guide him. Research has shown that the timing, quality, and quantity of water flows can be influenced by the manner of timber management.[5] Nobody is in a position to say precisely what this means in the way of the specifics of cutting and handling the timber in the North Slope. More study will be needed to answer this question. However, there is every reason to believe that some sort of positive timber management will be necessary as part of water management on the North Slope.

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[5]Annual report, U. S. Forest Serv., Rocky Mountain Forest and Range Exp. Sta., 1961.

Figure 16. — On peak days more than 200 campers and fishermen ring this 50-acre lake which, like several other heavily used recreation lakes on the North Slope, is also a reservoir that is drained down during the summer.

The issue with regard to game management is perhaps a bit more clear-cut. Some portions of the North Slope are not now satisfactory for recreational use or wildlife habitat because of the condition of the timber. In some localities the timber growth is so dense the area has become poor habitat for big game and upland game birds. Lack of access and dense timber, moreover, make orderly game harvest very difficult. Likewise, recreationists other than hunters find it difficult to use some of the area because the stands are so dense or because the down timber has become a jungle. Thus, any timber-growing program could improve recreation and wildlife management outside the Uinta Primitive Area.

Not the least of the considerations is the opportunity to make the North Slope financially self-sufficient in the more distant future. Although the values involved are presumed to justify the costs of administering the National Forest lands on the North Slope, the cost has always exceeded the direct financial return to the Federal treasury. Timber management offers a means for making the North Slope financially self-sufficient one rotation hence when the initial task of rehabilitation has been completed.

This is illustrated by the following tables and charts that present the hypothetical situations with and without timber management. These must be regarded as hypothetical primarily because of present uncertainty as to what timber will be worth 100 years and more in the future.

Under the assumptions that have been made, if the North Slope forest is rehabilitated the gross value of the timber harvested annually during the second rotation would be about $266,000. This would more than cover the annual timber growing expenditures on the North Slope for stand reestablishment, stocking control, and related costs. In addition, these annual timber revenues should cover all the basic costs of administration, fire protection, and maintenance, and about $32,000 would be left over for roadbuilding and other improvements (fig. 17). The assumptions of cost and value behind these calculations are shown in tables 12 and 13.

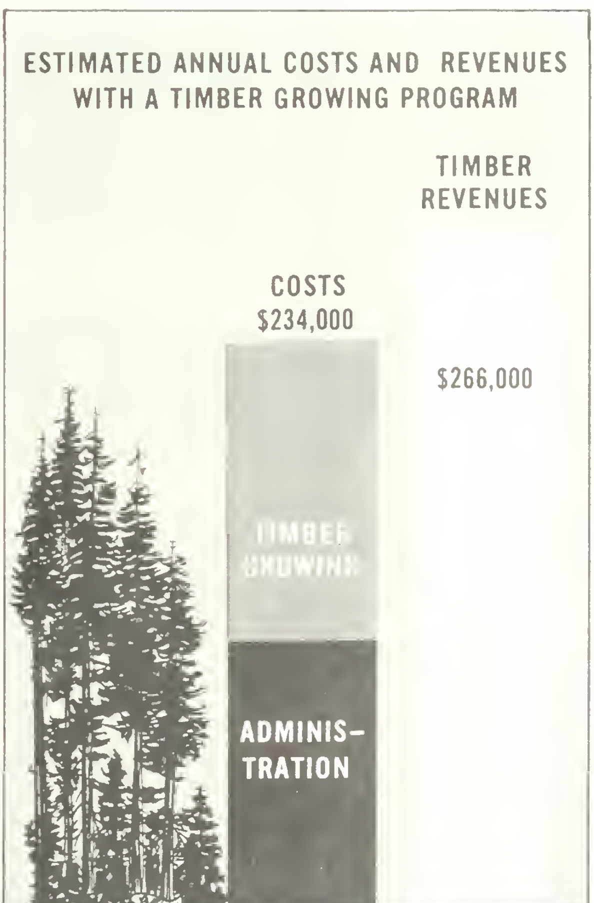

Figure 17

Table 12. — PROBABLE COSTS OF TIMBER GROWING BY FOREST TYPE[1]

Type	Slash disposal	Site preparation and planting	Stocking control	Erosion control	Total
	Dollars per acre				
Ponderosa pine	25.00	45.00	5.00	1.50	76.50
Subalpine fir and spruce	35.00	60.00	5.00	1.50	101.50
Douglas-fir	25.00	45.00	5.00	1.50	76.50
Lodgepole pine	17.00	26.50	15.00	1.50	60.00

[1]Source: Adapted from U. S. Forest Service, Regions 1 and 4 records.

Table 13. — PROBABLE VALUE OF HARVEST YIELDS FROM MANAGED STANDS BY FOREST TYPE AND SITE CLASS

Type	Medium site	Low site	Very low site
	Dollars per acre		
Ponderosa pine	515	196	30
Spruce	517	164	68
Douglas-fir	310	71	39
Lodgepole pine	227	79	25
Subalpine fir	184	72	32

If, on the other hand, the North Slope forest is not rehabilitated during the coming years, the long-run outlook will presumably be quite different. Total annual costs, after the first rotation, will be lower if no efforts are made to manage the timber. However, the timber revenues produced by an unmanaged forest will not begin to cover even the basic administration costs (fig. 18).

Other uses, particularly recreation, are beginning to produce revenue. These uses could greatly change the financial situation on the North Slope. Nevertheless, if the forest is managed for its timber, revenues from that timber would go far toward paying for the administration of this area.

Relation to national development

The wedding of the computer with increasingly sophisticated production machinery has been increasing man-hour productivity at the rate of 30 percent per decade. This mounting productivity has become a menace as well as a boon because undirected it can solidify and already has to a degree solidified the depressed segments of our society by increasing unemployment. Public programs to aid depressed people and depressed areas, and programs to beautify cities, rehabilitate slums, and remove billboards from highway rights-of-way are manifestations of both the national capability to do more in the neglected public sectors of our economy and of the need to provide additional productive employment.

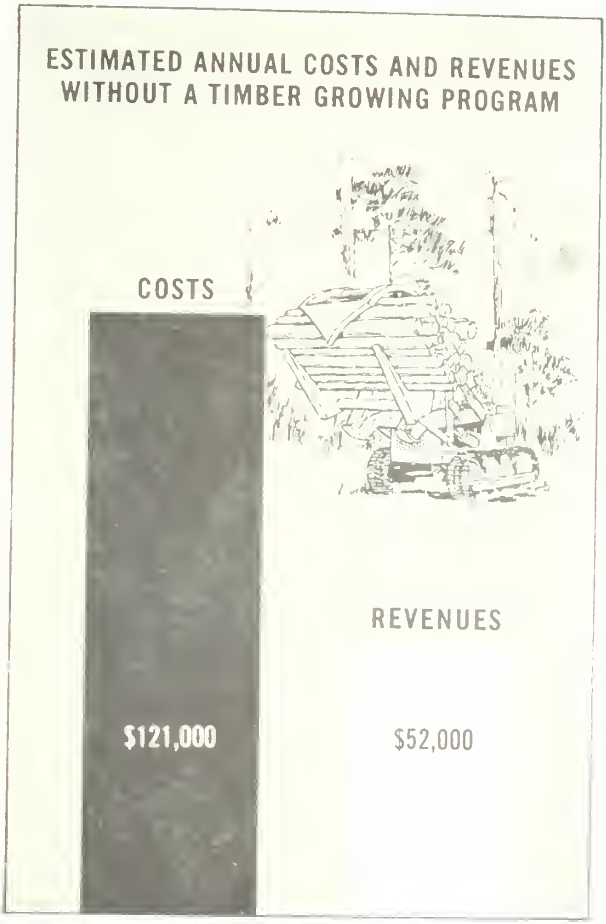

Figure 18

How surplus human energy will be utilized in creation of a better society and stronger nation remains to be seen. However, the "North Slopes" of the West have a readily identifiable employment opportunity. Surplus labor can be utilized not only to enhance current resource values, but to build up and stockpile productivity for the indeterminate needs of the future.

SUMMARY

The North Slope is typical of many public forest areas in the West. Its timber productivity is low but could, with special effort, be increased. The public is in no position to walk away from this activity if for no other reason, because water, recreation, and other values require some timber management. How much and what kind of timber management these values require is not yet fully understood. How far forestry effort should be carried beyond the minimum level necessary to meet current demands for water, recreation, etc., depends on several considerations. One is much longer range evaluations than are now available of future requirements for wood, water, and other values. Another is the extent to which it is feasible to maintain a viable local economy.

Mushrooming capabilities for industrial production free the human energies required to greatly accelerate conservation effort should this loom high enough in national priorities.

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Project headquarters are also at:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
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- Moscow, Idaho (in cooperation with the University of Idaho)
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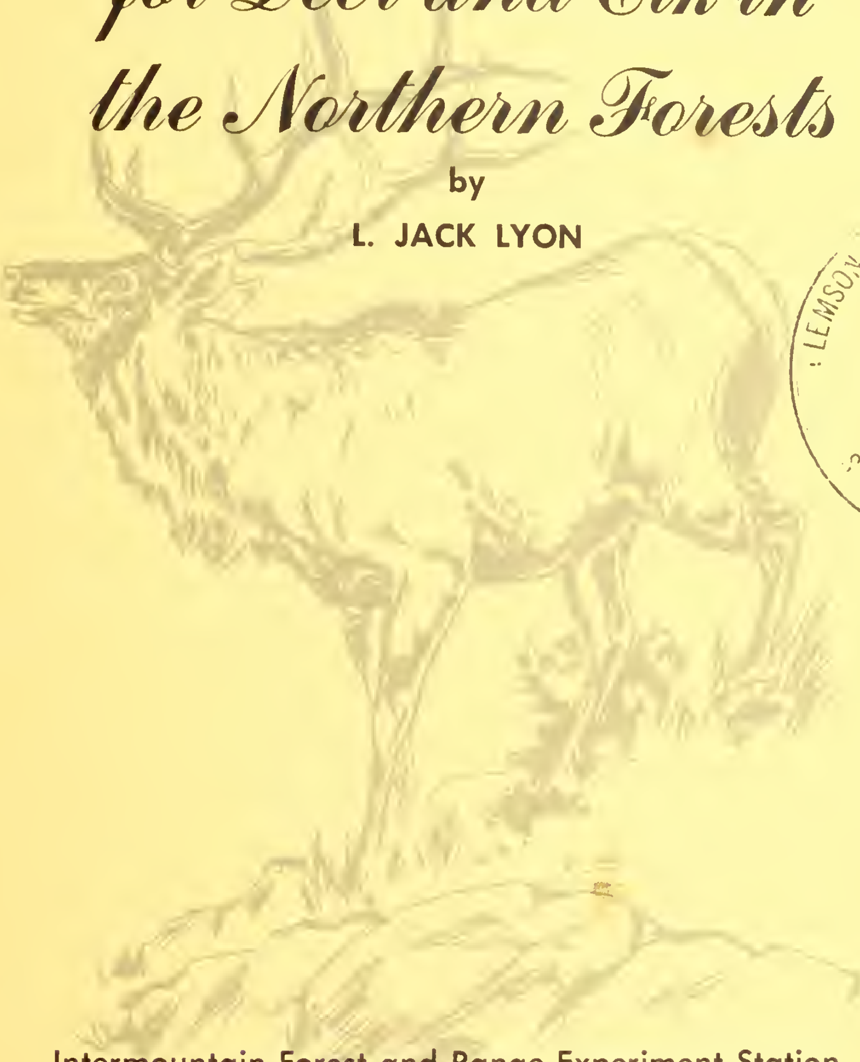
The Forest Service of the U.S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's Forest Resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing Nation.

Problems of Habitat Management for Deer and Elk in the Northern Forests



by

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Forest Service
U.S. Department of Agriculture
Ogden, Utah

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INTRODUCTION

Montana west of the Continental Divide and Idaho north of the Salmon River is a vast region of timbered mountains containing nearly 27 million acres of forested land. Glacier National Park, 12 National Forests encompassing three large wilderness areas, and several million acres of private holdings combine to form a spectacular wildland area famous throughout the world for wildlife and outdoor recreation.

In this region, more than 300,000 hunting and fishing licenses are sold annually. Sportsmen kill 100,000 deer and elk every year, and there are open seasons on black and grizzly bears, moose, mountain goat, and bighorn sheep.[1] Hunters shoot turkeys and four species of woodland grouse on forested lands, and in the lakes and streams fishermen catch more than a dozen kinds of game fish including trout, salmon, and steelhead.

Wild animals, in addition, provide enjoyment and entertainment for thousands of tourists, photographers, hikers, campers, and just plain Sunday drivers. To Montana, to Idaho, and to the Nation, the abundance and diversity of wildlife in the northern Rocky Mountains is a heritage and a recreational resource without equal.

[1] *Data summarized from surveys and annual reports by the Idaho and Montana State Game Departments.*

The Problem

While the northern Rockies probably have more wildlife on a larger acreage of wildland than any part of the United States except Alaska, sheer abundance is not an unmixed blessing. Wild animal populations are not always compatible with timber production, grazing, or watershed protection; and complicated interactions among animals, vegetation, and soils often produce conflicts for which the land manager has no acceptable solution.

In certain areas, for example, food requirements of existing deer and elk herds far exceed the available supply of forage. Animals damage conifer plantations, cause serious soil erosion, and sometimes destroy their own range. Paradoxically, there are also areas in which the quality of elk hunting is dwindling; in some areas deer herds are barely adequate to sustain an annual harvest by sportsmen; in some streams fishing has been virtually destroyed—there are even a few places where the continued existence of one or more wildlife species is threatened. And, whether associated with overabundance or deficiency, an unhealthy condition in wildlife is usually symptomatic of conflict with other resource values.

Each year, as the demand for all forest products rises, the areas of conflict between wildlife and other forest uses will become increasingly serious. The wildlife heritage of the northern Rocky Mountains must be continued, but unless land management activities are well coordinated, it is virtually inevitable that the quality of the wildlife resource, and other resources as well, will be reduced.

The Solution

The key to wildlife abundance and diversity in the northern Rockies is good management of forest habitat. It is obvious that the number and variety of wild animals in any area is determined by the food and cover available, but it is sometimes less obvious that all habitat is not equally productive. Still less apparent is the fact that forest vegetation has a constantly changing value for wildlife because the vegetation is constantly changing. No forested area ever remains static.

Some changes, particularly those caused by fires, logging, and dam or highway construction, are sudden and obvious; but even in the absence of drastic alteration, the normal growth of trees and shrubs produces significant shifts in the plant composition of a forest. Whether drastic or subtle, these changes determine the amount of food and cover available and, consequently, the numbers and kinds of wild animals present. If wildlife habitat is to be managed successfully, the influence of such environmental alterations on animal populations must be understood. The wildlife heritage of the northern Rockies can be maintained and enhanced, but the private landholder and the public administrator both need substantiated facts on which they can base management decisions favoring wildlife.

The Need For Research

Research is needed to provide the background information for integrated management of wildlife and other forest resources. Many appropriate studies are already in progress. Game and fish departments of most western states, several federal agencies, universities in both Canada and the United States, and several lumber and power companies are studying problems of wildlife management on forested lands. Despite the number of sponsors for these investigations, however, the simple fact is that habitat research is years behind the current needs of land managers in this region. Moreover, the problems associated with fluctuating animal populations and the conduct of research on steep, inaccessible mountain slopes are complex and difficult. We cannot escape the conclusion that the total research effort, when compared to the amount of information needed and the difficulty of obtaining reliable data, seems far from adequate.

HABITAT PROBLEMS AND RESEARCH NEEDS

The following discussion of wildlife habitat problems and research needs in the northern Rocky Mountains is focused primarily on habitats of deer and elk. The important wildlife resources of this region are not, of course, limited to these big-game animals or even to animal species that furnish outdoor recreation and table fare for sportsmen. Nevertheless, two kinds of wildlife, the antlered game and fish, form the basic structure for a distinct and significant recreation industry in this region. And, although hunting and fishing are about equally important,[2] land animals are much more directly dependent on forest habitat and the way habitat is managed.

The reader should recognize that even though this presentation concentrates on problems of the habitat of deer and elk, many elements of forest habitat management apply equally to other game animals, to the forest grouse, and, in some degree, to fish. In a figurative sense, changes in forest habitat can be compared to the circular waves created by a pebble dropped in still water. As the distance from the source increases, the force of disturbance fades away, but at the same time more and more things are affected.

History of the Habitat

Historical references to wildlife and its habitat in the northern Rocky Mountains reveal conditions very different from those existing today. Before settlement, many North American big-game animals occupied the valleys, foothills, and plains, while the high-country forest was nearly devoid of game. In 1805, Lewis and Clark reported an abundance of elk, deer, bighorn sheep, antelope, grizzly bear, and buffalo from eastern Montana to the three forks of the Missouri River. When these explorers crossed Lolo Pass into the Lochsa drainage of Idaho, however, game was so scarce the men butchered their horses for food *(6)*. A half century later, the Montana pioneer Granville Stuart wrote that the Bitterroot Mountains were still a

> " . . . howling wilderness of yawning canyons and huge mountains, covered with a heavy growth of . . . timber, and affording a home to a few elk and large numbers of grouse, but of no earthly use for any thing but the mineral wealth they contain . . . " *(20)*.

Early settlers and prospectors killed many game animals for food, and as more people moved into the northern Rockies, deer and elk were severely overhunted. By 1900,

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[2]*Records of numbers of trips to National Forests show that more effort is spent fishing than hunting (a ratio of about 1.6 fishing trips to each hunting trip (21). (Italic numbers in parentheses refer to numbered references in the "Literature Cited" section of this paper.) Hunters, however, spend more money on each trip so that the annual average expenditure of hunters and fishermen is roughly equal (12).*

the State Game Warden of Idaho reported elk becoming "scarcer every year," and in 1911 most of northern Idaho was closed to elk hunting *(11)*.

During this same period, the northern forests were almost continuously ravaged by fires. Indians and miners were notoriously careless with fire *(10)*, and early prospectors deliberately burned thousands of acres of timber to facilitate their search for gold *(9)*. Finally, between 1910 and 1920, a series of devastating wildfires burned more than 4.5 million acres of forest land west of the Continental Divide *(1)*.

All of these developments had direct and important effects on wildlife. Settlement and hunting drove deer and elk into the less desirable habitat of the mountain forests. There, fires killed some animals outright and destroyed large areas of productive game habitat. Finally, the ash-laden runoff from burned-over lands was deadly to fish.

In short, the tremendous changes caused by man and nature early in this century were almost all initially detrimental to wildlife.

In time, however, the forests recovered. Charred hillsides were transformed into grassy slopes and brushfields, and streams ran clear again. The postfire vegetation proved to be quite favorable for wildlife, and large areas of western Montana and northern Idaho became excellent game habitat. Numbers of deer and elk increased tremendously *(11)* as did grouse, rabbits, and small rodents. Following a short period of blackened devastation, then, many of these changes in the forest habitat proved highly beneficial to wildlife.

Over the past 4 decades, wildlife habitat in the northern Rockies has continued to change, and many recent developments have not been beneficial to game animals. Some wildlands have been lost to agriculture or urban expansion, water storage projects and highways have severely altered streams and bottomland habitat, and increasingly efficient fire suppression has permitted the uninterrupted development of mature forest vegetation on many thousands of acres. Overall, this latter factor has had the greatest single influence on game habitat and game numbers since the wildfires of 1910.

Ecology of the Habitat

In order to understand the importance of fire suppression, it is helpful to examine what happens on forest land following fires. The changes in vegetation, one plant community replacing another in successive steps, is a dramatic display of harmony in nature. A generalized schematic drawing of this succession is presented in figure 1.

In the years immediately following a severe fire, blackened stumps and burned snags dominate a barren landscape, but this situation is transitory (figure 2). As early as the first year, some seedling plants may appear, and plants not killed by the fire begin to revive. Before many years have passed, forbs and grasses cover the area (figure 3).

Eventually, shrubs begin to appear. Some come from seeds or rootstocks that survived the fire (figure 4) and others grow from seed carried by wind or animals. As these plants increase in size, they crowd out smaller vegetation. The resulting brushfield (figure 5), if the shrub species are palatable, provides good forage for big-game animals. Normally, this is also the most productive habitat stage for small-game animals.

Shrub dominance in the northern forest region may continue from 10 to 100 years, but shrubs are eventually displaced by trees in the same way grasses and forbs were displaced by shrubs (figure 6). The end product of plant succession in the northern forests is a mature stand of trees *(5)*. In the shade of such a stand, ground vegetation is either lacking or thinly distributed (figure 7). Almost without exception, this stage is the least desirable for wildlife.

Figure 1 represents only one version of an infinite number of variations on forest succession. On some sites, lack of a seed source for trees may prolong the shrub stage for hundreds of years. On other sites, conifer reproduction may be so dense that no other vegetation ever appears. Under certain circumstances, the forb and grass stage, or the shrub stage, may be missing entirely. The only thing consistent about forest vegetation is that it changes constantly.

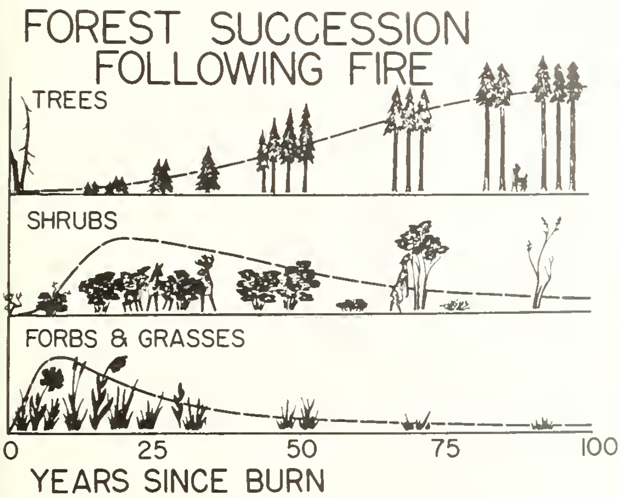

Figure 1.—Schematic description of forest succession following fires.

Figure 2.—Shortly after a forest fire, the burned area appears almost devoid of any form of plant life. (Bitterroot National Forest, Montana.)

Figure 3.—A few years after the fire, grasses and forbs are dominant. Shrubs have not yet begun to appear on this site. (Bitterroot National Forest, Montana.)

Figure 4.—Some shrubs recover very quickly following fire. This willow sprouted from unburned rootstocks 1 year after a burn. (Sawtooth National Forest, Idaho.)

Figure 5.—On this winter range shrubs are dominant today, but seedling trees can be found throughout the area. (Clearwater National Forest, Idaho.)

Figure 6.—Trees eventually replace shrubs. In this mixed stand, trees are not yet dominant, but in 5 to 10 years shade will begin to inhibit growth of the shrub understory. (Lolo National Forest, Montana.)

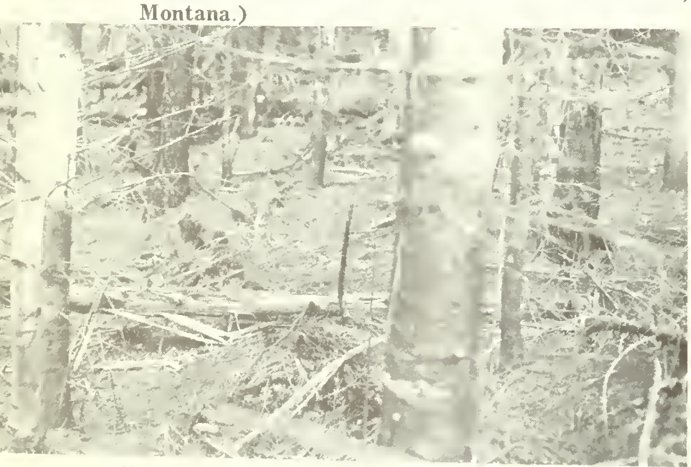

Figure 7.—This is a relatively young stand of timber, but shade from the tree canopy has already eliminated grasses, forbs, and shrubs from the understory. (Clearwater National Forest, Idaho.)

The forest succession pattern described here represents a natural course of events. And since nothing in nature is static, vast areas of brush range in Montana and Idaho are today reverting to forest. Many of the browse ranges created by fires and logging a half century ago are disappearing under a closed canopy of trees. Overuse of the remaining habitat by big-game animals has created a variety of land-management problems. In some areas, deer starve or damage timber plantations because they lack sufficient forage, and in other areas soil erosion and compaction are caused by large numbers of elk concentrating on limited ranges. More important, perhaps, is the fact that the loss of game habitat has been followed by a decline in game numbers. The great elk herds of the Selway-Bitterroot Wilderness and the Bob Marshall Wilderness are striking examples: despite comparatively light hunting and lack of competition with livestock for range and space, both herds are notably smaller today than they were 20 years ago *(13, 19)*. Deer and elk herds outside the wilderness areas have followed much the same pattern *(8)*.

Fortunately, the trend is not all unfavorable. As old wildlife ranges disappear some new habitat is created each year. Uncontrolled wildfires are practically a thing of the past, but clearcut logging, as practiced by most timber managers in the northern Rockies, starts a plant succession pattern very much like that pictured in figure 1. Artificial planting is sometimes substituted for natural seeding, but unless timber management is very intensive, plant growth on a logged-over site will cycle through stages dominated, first, by forbs and grasses (figure 8), then shrubs, and finally by trees. And again, almost without exception, the earlier stages of succession support more wildlife than the mature forest. If the majority of plants in the shrub stages provide food as well as cover, the increases in numbers of deer, elk, and small game can be spectacular.

One point should be emphasized: neither logging nor wildfire is always dependable in

Figure 8. A clearcut logging area. Note the similarities between this area and the wildfire area pictured in figure 3. (Clearwater National Forest, Idaho.)

producing good wildlife ranges. More often than not, the plants that flourish after tree removal are only partially suitable as forage and cover. Clearcut logging, however, does have one vital advantage over wildfire: following logging, it is theoretically possible to control slash disposal or site preparation to favor desirable plants and create high-quality game range. Not all timber sites, of course, are capable of producing game range, and not all game-habitat areas are managed for timber production. Nevertheless, it seems logical that the land areas being logged each year could provide habitat for more wildlife than we now have. The missing factor is the combination of knowledge and techniques for managing vegetation so as to produce a superior environment for animals.

Specific Problems

In concept, the management of forest vegetation to provide big-game habitat seems relatively simple. Both deer and elk consume leaves and twigs of woody shrubs as a normal part of their diet, and we already know that removal of trees by logging, fire, or any other method usually produces shrubs. Big-game food and cover requirements, however, are not limited to shrubs and at the same time are restrictive even within this plant group. Many of the common woody plants, such as ninebark and oceanspray, are unpalatable. Other species are eaten only in small quantities. Even highly palatable plants, such as serviceberry and redstem ceanothus, are more desirable in mixtures with other shrubs than in pure stands. And, finally, all big-game animals seem to require a certain amount of cover in and adjacent to feeding areas.

The management problem is further complicated by seasonal variations in food habits and range requirements. Deer and elk seek grasses and forbs in the spring and summer, and many herds migrate each year from a lowland winter range to a high altitude summer environment. Thus, habitat requirements in the summer may be physiologically as well as geographically remote from habitat requirements of animals in winter.

Seasonal differences in game ranges provide a logical division for discussion—even though separation of summer and winter ranges is more easily accomplished on paper than in the forest. For the purposes of this presentation "winter range" includes heavily used areas in which animals are concentrated for relatively short periods in winter and early spring. Forage on these areas is mostly woody browse because it must be available despite deep snows. Shelter from wind and cold is also important. "Summer range," on the other hand, must produce a wide variety of herbaceous and woody forage for relatively long periods of the year, but shelter is less of a consideration except as needed to protect young animals from predation and to provide adults with cover during the hunting season. An obvious extension of these definitions suggests that it may be necessary to dedicate limited wintering areas to permanent management for big game while summer ranges will probably be managed for many interrelated uses.

Winter Ranges

Almost without exception, wildlife biologists in Montana and Idaho consider winter range to be the weakest part of the big-game environment. Summer ranges for both deer and elk are considerably larger than wintering areas, and animals that use only a portion of available summer forage are concentrated on winter ranges that have only limited capacity to support big game. There are, in fact, very few winter ranges in the northern Rockies that are not occasionally overused. In severe winters, certain areas may be so crowded with animals that the vegetation is destroyed and starvation strikes down a significant portion of the herd.

The determining and complicating factor is the severity of winter weather. In a normally cold winter, with average or light snowfall, forage may be adequate to sustain herds with little damage to plants and only minor losses by starvation. In a severe winter, however, all forage but tall woody shrubs is buried, and deep snows restrict animals to a few small areas where range damage and starvation become excessive. If the damage and associated death losses are to be prevented, new methods for managing winter range, particularly concentration areas, must be discovered. We need to determine how to rehabilitate overused ranges, how to maintain browse ranges under stabilized but constant use, and how to create new winter ranges.

Rehabilitation

In many parts of Montana and Idaho, repeated overuse of browse plants has produced disastrous results. The best forage plants, such as redstem ceanothus and serviceberry, have been literally "beat into the ground" by repeated browsing (figure 9). These plants either die or have so little vigor that they simply do not produce new stems. Other species such as willow and mountain maple grow so tall that normal animals cannot reach the edible twigs (figure 10) and only the largest of bull elk is able to bend the stems down by walking over the plant. Rehabilitation therefore presents three problems: (1) replacing dead plants,

Figure 9.—Severe browsing of chokecherry. Plants that have been so heavily utilized are often incapable of producing new growth. (Montana Game Department photograph.)

Figure 10.—Willow and maple may grow to 20 feet or more. When this occurs, forage is almost totally unavailable to wildlife. (Clearwater National Forest, Idaho.)

(2) rehabilitating weak plants, and (3) reducing the height of plants too tall to provide winter food.

1. One obvious means of replacing dead vegetation on overused winter ranges is direct planting of native or exotic shrubs. In some areas, a considerable amount of work has already been done in selecting adaptable species and developing planting methods and equipment. Artificial revegetation, however, is always expensive and usually is feasible only on level ground *(7)*. We must develop more methods for rehabilitating steep slopes and inaccessible areas in the northern Rockies. To do this, we must find out how much viable seed is already lying dormant on the ground and how to revitalize plants so they will produce seed. It may even be possible to distribute seed from helicopters or airplanes on suitable sites. The most important point, however, is that we must determine how to provide site conditions suitable for germination of seed and for survival of seedling plants.

2. The second rehabilitation problem, restoring the vigor of decadent plants, has occasionally been solved by decreasing the browsing pressure. A mild winter or herd reduction often accomplishes the desired result; but just as often it does not. For example, some serviceberry plants along the flats above the Kootenai River have been protected by deerproof exclosures for 10 years—but have shown no response at all to the relief from browsing pressure. Rehabilitation of these plants will require some other technique.

Surprisingly, one method that might succeed requires even further mutilation of low-vigor plants. We already know that many healthy plants respond to complete destruction of the crown with vigorous shoot growth and basal sprouting. Possibly, this reaction could be used in rehabilitating low-vigor plants. Potential methods of treatment might include cutting, crushing, burning, or spraying with herbicides. However, some species of shrubs do not resprout. Would fertilization benefit such plants, or are there chemical growth regulators that might stimulate a response? Before these

questions can be answered, we need to understand the physiology of both healthy and low-vigor plants and the combinations of circumstances and treatments that cause extreme decadence.

3. Finally, there are browse ranges, particularly in Idaho, where the height and density of vegetation should be reduced. Total forage production is actually quite high in these areas, but most of the growth is out of reach of animals. Wildlife biologists in California have reported successful reduction of chamise brushlands using fire, bulldozers, and chemicals *(2)*, but similar testing has only begun in the northern Rockies. One recent investigation, for example, was conducted by an ecologist of the Intermountain Experiment Station on the Clearwater National Forest in Idaho *(15)*. There, the herbicides tested did produce crown-kill and subsequent basal sprouting on several browse species. However, the most desirable browse plant tested also proved to be the most sensitive to chemicals. Redstem ceanothus was invariably killed by applications that gave highly satisfactory results on willow and maple.

Tests using fire as a tool to reduce tall vegetation are also in progress in northern Idaho, but no results are yet available. In the initial phases of study a south-facing hillside was burned off in spring when snow still covered the ridgetops. Crown-kill of serviceberry, willow, and redstem ceanothus appeared to be good; but until resprouting of individual plants is evaluated, until the technique is tested on a wide variety of sites, and until it is possible to judge potential long-term influence of burning on the site, the use of fire must be considered experimental.

Maintenance

Possibly the most important long-range problem of winter range management is maintaining good ranges in continuous production. Browse plants seem to age, as all other living things do, and on some winter ranges the process is accelerated by repeated overuse by animals. In addition to surviving an annual removal of twigs, plants must compete with unpalatable shrubs and with trees for light, water, and nutrients. Management techniques are needed to assure continuous and vigorous forage production despite these hindrances.

Several studies have already shown that plant vigor and production are actually increased by moderate browsing. For most of the important browse species, the accepted tolerance to browsing is about 50 to 65 percent of annual production. It is nearly impossible, however, to manage game herds so that this level of utilization is attained but not exceeded. Thus, in a severe winter, 80- to 100-percent utilization is sometimes recorded. We need to determine how many times a plant can tolerate such abuse without losing vigor and what techniques can be used to restore declining production. We must determine how to prevent premature decadence in heavily browsed plants, and we must learn how reproduction of palatable browse species can be encouraged for continuous natural replacement of aging plants. At the same time, we must discover techniques to prevent unpalatable shrubs and trees from occupying winter range sites. Long-term maintenance of small but permanent winter-range browse fields will, in many areas, be the only method by which we can assure stability of game herds occupying a large, transitory summer range.

One important management tool that needs more investigation is prescribed fire. We already know that conifers can be temporarily or even permanently removed by repeated burning. However, the other post-fire responses of vegetation have been only partially investigated *(14, 17)*, and the use of prescribed fire without a greater background of research could be foolhardy. We do not know, for example, whether repeated fires might favor undesirable browse species or cause erosion problems, whether some burning patterns will provide better growth response than others, or, in fact, whether other treatments, such as spraying with conifer-specific herbicides or harvesting small conifers for Christmas trees might not be more efficient. In addition, we need to know how often burning or other treatments would be necessary and the best time of year to do this work.

Creation

A third group of winter range problems is associated with the need to create new winter ranges where old ranges have disappeared or where none ever existed. As the seemingly inevitable construction of campgrounds, four-lane highways, and water impoundments destroys existing winter ranges, we must either create new ranges or sacrifice a part of the wildlife resource. New winter-range areas might also be needed to reduce the utilization of existing but limited forage or to relieve animal use on areas better suited to uses other than winter range.

Most of the research needed to provide background information for rehabilitation and maintenance of browse plants will also be valuable in creating new ranges. Techniques for removing trees and favoring palatable browse plants, in particular, would be applicable. Some questions, however, are peculiar to this problem alone. The most basic question, perhaps, is simply defining the site and vegetation characteristics that determine winter range. Game managers already have techniques for measuring the amount of use by animals and thereby judging the importance of existing winter ranges. The land manager, however, needs techniques by which he can judge the potential values of an area that is not winter range. After this evaluation has been made, he will still be faced with the problem of achieving conversion.

It seems logical that any area that can be converted to winter range would already be winter range unless (1) it is covered by a mature stand of timber, (2) all the shrubs on the site are unpalatable or, (3) habitual migration patterns are so firmly established that animals simply do not appear in what might otherwise be a satisfactory wintering area.

The obvious answer in the first case is logging, and this in fact may be the single most satisfactory method available for creating new winter ranges. However, it is also possible that removing the timber overstory will only produce unpalatable shrubs. In this case, we need to discover management techniques for removing existing undesirable plants and replacing them with browse species not even present in the existing vegetation. Surprisingly, it may already be possible to attain this objective on some sites without resort to direct planting. We already know that seeds of both redstem ceanothus and evergreen ceanothus lie dormant in the soil for many years after the plants have died. We also know that burning usually creates the soil and site conditions required for germination and production of new plants. Once we determine how to identify sites on which sufficient ceanothus seed is already present, prescribed fire could become a very useful tool in the creation of big-game winter ranges. Intensive studies of the life histories and reproductive mechanisms of other browse species will eventually give us the management tools necessary to create winter ranges with desirable combinations of plant species on virtually any suitable site.

A potential for manipulating animal movement instead of forest vegetation is suggested because deer and elk are conservative and traditional in their habits *(16)*. Animals learn migratory routes and hereditary ranges early in life, and they may suffer chronic malnutrition on these traditional ranges before they seek a better environment. Thus, techniques for influencing animal movement would be valuable in preventing overutilization, in distributing utilization evenly, and, possibly, in attracting animals to previously unused range areas.

In recent years, research workers in both Idaho and Washington have conducted experiments aimed at influencing animal movement. In one project, biologists of the Idaho State Department of Fish and Game and the Idaho Cooperative Wildlife Research Unit distributed salt blocks on the slopes above the Lochsa and Selway Rivers *(4, 22)* in an attempt to regulate elk use of winter ranges. The salt was heavily used, but there was no clear indication that either time of migration or rate of herd movement was changed. In the Washington experiment, Game Department hayfields proved highly attractive to elk after commercial fertilizers had been applied *(3)*. Initially, the fertilized fields were sufficiently attractive to keep elk from damaging adjacent private hayfields. However, when the local ranchers applied fertilizers to increase yields, elk resumed traditional feeding patterns.[3]

Obviously, discovering techniques for influencing animal movement is not going to be easy. Both of these studies demonstrate the degree that elk will go in their own bullheaded way in the face of efforts to improve land management. However, the fact that animals did react to both salting and fertilizer treatments is some measure of success. Future research along these and other lines should produce methods capable of influencing the most stubborn game animals.

Summer Ranges

Most of the winter range problems already discussed are applicable to big-game habitat any time of the year. Summer habitat, however, does present some management challenges that have no winter counterpart. For example, on summer ranges, many plant species in addition to woody shrubs must be

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[3]*Personal conversation with E. Reade Brown. 1962.*

considered in research studies and management planning. More important is the fact that summer ranges in the northern Rockies generally include timber sites. This means that very few summer range areas could be managed, even on a restricted basis, for the primary benefit of wildlife. It also suggests that research should be concentrated on developing coordination between game management and timber production and on reducing existing conflicts in the use of game and timber resources.

Coordination

Much of the research needed to guide summer range habitat management is related to the fact that we lack specific information about the vegetation that develops following fires and various types of logging. We know that some game forage usually develops when overstory trees are removed, and we know that logging is a common and commercially rewarding method of removing overstory trees. These two facts could lead to the conclusion that logging is a successful technique of habitat management — except that results very often fall far short of the obvious potential.

In order to realize this potential, we must learn which plants recover after a logging operation, the amount of forage they produce, and the length of time they will provide food for wildlife. These facts are essential. For as the new timber crop matures, the logged-over sites will lose their value to big game, and until we can predict production and longevity of transitory ranges it will not be possible to promote stable herd levels by management.

With the basic descriptive information as a foundation, we can then determine why some plants respond better than others and, most important, how to favor those species with the greatest utility for wildlife. Site preparation for a new timber crop can include a wide variety of treatments ranging from scalping of small spots in which nursery stock is planted through broadcast burning of slash and natural seeding from uncut trees. The nearly infinite variety of these treatments offers a tremendous potential for managing transitory range for the benefit of wildlife within basic silvicultural objectives. Fire, in particular, may prove to be an important tool simply because so many different degrees of treatment can be applied using essentially the same technique.

The significance of logging as a potential habitat management technique should not be passed over lightly. In the absence of wildfires, the only significant recurring disturbance of mature forests will be caused by logging and, except for the maintenance of winter-range areas dedicated primarily for wildlife, this single activity will have major importance in determining big-game numbers in the northern forests.

Coordination of timber production and big-game management does not appear to be impossible. Instead, it is a desirable objective and an opportunity for the land manager to obtain optimum yields of both resources from forested lands. What is missing is the knowledge required to accomplish the job effectively.

Conflicts

If optimum yield of both timber and game is to be achieved, several areas of conflict must also be reduced. Big-game damage to conifer reproduction, for example, must be evaluated, and some solution more sophisticated than chemical repellents or herd reduction must be discovered. Since forage on summer ranges is usually adequate, it seems logical that deer do not need to eat pine seedlings to survive. Yet deer do sample young pines in about the same way humans eat pickles. We should determine the nutritional role played by conifers in the animal diet and examine methods of supplying physiological condiment with less valuable vegetation.

There are several ways in which research might contribute to solution of this problem. Seeded forage plants, for example, could be tested to see whether they will relieve browsing pressure on small conifers. Research designed to determine why deer feed on small conifers would be another useful approach. Such investigations might reveal a dietary deficiency that could be relieved with properly prepared food supplements or salt blocks.

In addition, the potential influence of silvicultural thinning on big-game feeding habits should be explored. We know that thinning of pole-size timber stands often causes a resurgence of growth in suppressed understory vegetation as well as in selected crop trees. Properly timed, such a thinning might help to relieve browsing pressure on nearby, newly planted timber stands. Finally, deer and elk might be attracted from area to area over a period of years by systematic scheduling of logging operations. In all of these investigations, we must determine the composition of the vegetation which occurs naturally and, if this is not the best combination, discover methods of favoring desirable forage species.

Another area of continuing conflict is the controversy regarding the application of pesticides for forest insect control, particularly by aerial spraying. Surveys by the U. S. Fish and Wildlife Service have shown residues of common insecticides in the body tissues of Montana deer *(18)*, and poisoning of fish and grouse have been reported. The effect of insecticide residues on wildlife populations, and on humans eating wild meat, is unknown. We do not know how much time is required for the forest environment to eliminate chemical residues, and research on breakdown rates of various chemical compounds is just beginning.

Broad-scale research programs involving entomologists and wildlife and public health scientists from several related federal and state agencies have been initiated to study insecticide influences, but this is only part of the problem. The herbicides used to control weedy vegetation along roadsides, the fungicides used to control white pine blister rust, and the poisons used to reduce rodent populations in timber plantations are all pesticides, and we know very little about their lingering effects in the forest environment. Progress is being made, but these are complicated questions and much work will be required before definitive answers are available.

Conclusion

The intention in this paper has been to review some of the problems of wildlife habitat management in the northern Rockies and to point out the important questions that must be answered before land managers can provide the consideration wildlife should receive in multiple use planning. Since 1900, we have witnessed the development of hundreds of thousands of acres of browse range on lands where forests were destroyed by disastrous wildfires. We have seen the explosive expansion of big-game populations into this newly created habitat — and we have enjoyed a resulting game abundance greater than any in the recorded history of the northern Rockies. More recently, we have observed a deterioration of wildlife environment as the inevitable development of forest vegetation progresses toward mature plant communities. Productive wildlife habitat is disappearing under a closed canopy of trees, some browse ranges are overused or too tall for animals, and much of the game habitat currently being created is an unplanned byproduct of logging. Throughout the northern Rockies, a general deterioration of wildlife habitat and an increasing demand on other forest resources has caused land management problems that include declining game populations, conflict with timber management and grazing, and damage to soil and vegetation.

Wildlife will continue to be one of the significant forest resources of the northern Rockies, but to obtain the best use of all resources, some forest vegetation should be managed for specific wildlife values. The land manager cannot simply accept the habitat produced by logging any more than he can permit forest fires to rage unchecked in the hope that game habitat will be produced. In order to maintain and enhance the wildlife resources of western Montana and northern Idaho, research must discover management techniques that will maintain existing browse fields in permanent production, that will replace old ranges which are disappearing, and will integrate wildlife production into overall forest management planning.

The discussion here has been confined primarily to big-game habitat problems, but this does not relegate other wildlife to a less important status. The research needed to provide habitat management tools for deer and elk will be equally applicable to the habitat of other forest game and, indirectly, to fish.

Continuation of the wildlife heritage of the northern Rockies in competition with other increasing demands on forest lands is not an impossible objective. We are facing, rather, a challenge to the ingenuity of the land manager and the ability of all men to live in harmony with the forest environment.

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PROJECT FIRE SCAN
FIRE DETECTION INTERIM REPORT

April 1962 to December 1964 (Work Unit 2521A)

U.S. Department of Agriculture — Forest Service
Intermountain Forest and Range Experiment Station
Northern Forest Fire Laboratory
Missoula, Montana

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U.S. FOREST SERVICE
RESEARCH PAPER INT-25, 1966

PROJECT FIRE SCAN
FIRE DETECTION INTERIM REPORT

April 1962 to December 1964

by
Ralph A. Wilson, Physicist
and
Nonan V. Noste, Research Forester

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

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NORTHERN FOREST FIRE LABORATORY
MISSOULA, MONTANA

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PROJECT FIRE SCAN

INTERIM REPORT

April 1962 to December 1964

This work was accomplished under Work Order OCD-OS-62-174. This agreement outlined a three-phase test program to evaluate airborne infrared devices as tools for use in fire control. After Phase II was completed, the tasks were more specifically defined. At that time the program was administratively divided into its two natural components — fire mapping and fire detection.

This report summarizes the fire detection work from April 1962 to December 1964. The fire mapping effort will be discussed in a later report.

INTRODUCTION

The original program objectives were to develop and test a heat-sensitive system capable of: (1) locating small fires, (2) mapping fire perimeters, and (3) measuring rates of fire spread. The usefulness of infrared mappers was to be examined by surveillance of fire sources in forest environments. The capability for locating fire perimeter and detecting incipient fires was to be compared with that of aerial patrol and methods of ground observation now in use.

The work agreement outlined a three-phase test program. After Phase II was completed, the tasks were more specifically defined and the program was divided into its two natural components — fire mapping and fire detection. This separation allowed both programs to concentrate on development of systems specifically adapted to their unique problems. The goal of the detection program is to develop the capability for precisely locating small fire targets over extended land areas.

PHASE I TEST PROGRAM

INTRODUCTION

Preliminary work included acquiring the necessary instrumentation and familiarizing project personnel with the equipment and test procedures. The infrared instrumentation used during the period covered by this report was designed and built for other uses, and hence required considerable modification for use in fire surveillance.

EQUIPMENT

The scanner system used during this phase of the program consisted of a receiver unit and control-readout console. The infrared optical-mechanical receiver was installed in the nose hatch of a modified Beechcraft AT-11 aircraft. The optical receiver scanned an 80°-wide field (40° to either side of vertical in normal operation) perpendicular to the aircraft's line of flight. Continuous-strip photographic recordings of the cathode ray tube (C.R.T.) readout gave map-like imagery of the terrain's thermal detail. The optical resolution at this time was approximately 4 milliradians. The scanning geometry was similar to that discussed in Appendix IV.

The receiver unit could be rotated into a "side-looking" mode, i.e., from the vertical to 80° on one side of the flight path. This modification was necessary in order to examine the feasibility of wider flight paths.

The control-readout console was mounted in the passenger cabin of the aircraft. Monitors included C.R.T. presentations of the raw video signal ("A"-scan) and an auxiliary TV-like raster scan of the thermal imagery ("B"-scan). Controls adjusted the video signal on the C.R.T. readout for proper photographic exposure and aircraft flight parameters. Electronic "gain" and "level" adjustments controlled the photographic contrast and film density, respectively. A V/H (Velocity/Height) control of the strip film drive speed provided imagery of minimum distortion (see Appendixes III and IV).

Control settings were not optimized prior to or during the test flights. The test imagery was unobservable until the film had been returned to the Laboratory and developed. These recording limitations seriously hampered evaluation of the test results that were directly dependent upon the imagery.

Five types of detectors and optical filters of six different spectral bands were obtained with the scanning equipment. The detector-filter combinations used during the fire detection tests were chosen by subjective evaluation of image quality.

DEVELOPMENT OF TEST PROCEDURE

Instrumented aircraft flew tests over forested test plots that contained artificial fire targets. Very little was known about the specific radiation characteristics of fires burning under marginal conditions. A heat source of arbitrary size and temperature simulated an incipient forest fire. The target had to be uniform, repeatable, portable, and safe to use in a forest environment during high fire-danger periods. A 14-inch-diameter bucket, 9 inches deep, partially filled with sand, then filled to the brim with 10 pounds of charcoal, was selected as the standard target. Burning charcoal temperatures, measured with a thermocouple, ranged from 700° F. to 1,190° F., and averaged 892° F. A radiometer measurement of 895° F. (effective radiometric temperature) agreed closely.

A time-history record showed the source emission to be steady between one-half hour and 5 hours after ignition. Variation of radiant energy, measured as a function of vertical angle and plotted as a cosine function, showed that this source closely approximates a Lambertian radiator. These targets have proved quite satisfactory and have been used throughout the program, although at times sparks from them are a fire hazard.

The first night and day flights were conducted over a relatively flat, barren target area adjacent to Missoula, Montana. The operators were familiarized with equipment, and the several detector-filter combinations were examined. Unfiltered indium antimonide, lead sulfide, and lead telluride detectors were used in combination with a 3-micron, long-pass filter. Initial tests showed the lead sulfide detectors[1] with a 3.4- to 4.1-micron filter gave the best imagery during the daytime tests; however, these results were not acceptable. Subsequent searching for a suitable daytime detector-filter combination showed that an indium antimonide detector and a 4.5- to 5.5-micron filter were the best available, but daytime results were still marginal.

For best results at night no filter was used. Little difference was apparent between lead sulfide and indium antimonide detectors. The detection tests that followed utilized both lead sulfide and indium antimonide detectors for night operation, and indium antimonide with a 4.5- to 5.5-micron filter during daytime conditions.

Measurements made by the Materiel Branch, Electronic Research Development Laboratory, Fort Belvoir, Va.,[2] showed that coniferous foliage and tree bark are opaque to energy radiated in the infrared portion of the spectrum. However, no data were available concerning the obscuration of small fires by a forest canopy. The distribution, size, shape, and total number of transmission paths through a canopy were likely to vary with forest type, site quality, age, stand density, and other factors that affect stand morphology.

A major objective of the program was to determine the effect of timber cover on detection probability. Another was to develop a stand measurement to predict the obscuration effect of the various timber stands. An optimum vertical angle, within 20° of the zenith, was anticipated at which the canopy would least interfere with detection. A maximum angle beyond which detection would be virtually impossible was also predicted.

Only four coniferous species were considered initially — lodgepole pine (*Pinus contorta* Dougl.), ponderosa pine (*Pinus ponderosa* Laws.), Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco), and Engelmann spruce (*Picea engelmannii* Parry). These species were selected on the basis of shade tolerance. Tolerance[3] is an expression of a species' ability to endure shade. Thus, tolerance is a good guide to canopy density since species that require less light are more likely to develop very dense canopy covers. The species selected sampled the range of canopy densities found in western Montana.

Four timbered areas were selected to test the effect of timber cover on detection probability. Flight tests provided data on three types of forest cover — ponderosa pine, Douglas-fir, and Engelmann spruce. Relatively pure, but nonhomogeneous, stands were selected to provide a large variation in stand form, stand density, and canopy characteristics. For example, the ponderosa pine test area contained units of open grown, overmature, thrifty mature, and small stagnated trees.

Also considered in selecting test areas were: (1) recognizable terrain features to facilitate navigation, (2) peaks and ridges that make night air operations hazardous, (3) level topography within the area, and (4) distance from Missoula.

Twenty plot centers in a 4 by 5 pattern were systematically located 500 feet apart throughout each test area. Each plot was described according to slope, aspect, and basal area within a variable radius (Bitterlich[4])

[1] *Identification of the lead sulfide detector must be questioned by the sensitivity parameters required for this performance. The best PbS detectors now available have peak responses at 3.2μ and time constants of greater than 1 msec. (for optimum responses, less than 5μ sec. is required). This identification was made by printed labels on borrowed equipment.*

[2] *Unpublished report.*

[3] *Baker, Frederick S. A revised tolerance table. J. Forest. 47: 179-181. 1949.*

[4] *Grosenbaugh, L. R. Plotless timber estimates — new, fast, easy. J. Forest. 50: 32-37. 1952.*

plot. Total height, percent of live crown, crown diameter, diameter at breast height (d.b.h.), and species were recorded for each tree within the plot, and two timber crown photographs were taken from each plot center. This description aided the qualitative analysis of the flight data.

At three plots within each test area a theodolite measured the portion of the hemisphere over the plot center covered by forest vegetation. The theodolite was mounted on a standard tripod, and leveled. The telescope was pointed toward the zenith (90°) and the observer would estimate the percent of the 2° field of view filled by boles and foliage. The percent of open canopy was estimated at each 2° interval, from 90° down to 20° above the horizon. The telescope was again pointed toward the zenith, the azimuth lock released, and the theodolite rotated to another random azimuth angle.

This procedure was repeated eight times at each plot. Figure 1 is a plot of the curves generated by averaging the eight readings for each vertical angle. The curves show no tendency to peak below the zenith (0°). Although they are not well defined, the transmission curves decline steadily toward the horizon. Ponderosa pine and Douglas-fir are similar, with the Engelmann spruce significantly more dense.

Data acquisition flights were coordinated between the aircraft crew and ground crew. The ground crew ignited the 20 charcoal fires at least 30 minutes prior to the time the aircraft was scheduled over the area. The aircrew consisted of a pilot and one operator; occasionally a third member acted as observer and relief operator. Passes were flown from altitudes of 2,000 feet to 10,000 feet over terrain. Courses were charted to position the aircraft directly over the test area and to place all targets within the field of view of the scanner at the proper vertical aspect angles.

DISCUSSION OF RESULTS

Aircraft navigation over the test area (dependent upon the map presentation of a 5-inch monitor scope) was not satisfactory

Figure 1. — Percent transmission versus vertical angle for four coniferous species.

because of the high degree of coordination required between the scanner operator and the pilot. A technique of flying compass bearings from visible reference points approximately 4 miles from the test area was more satisfactory. Flight passes were flown from two checkpoints such as towns, ranger stations, or other landmarks that were identifiable during night operations.

Because these test flights were exploratory, many variables were introduced that were eliminated in later test design. Detectors were changed during flights, altitude was not held constant, and equipment settings were not optimized. These factors made it possible to draw only general conclusions from the data.

Imagery obtained from flight tests was examined on a microfilm reader, and the flight passes containing usable data were analyzed. Identification of individual targets depended upon recognizing landmarks or observation of enough targets to recognize the 4 by 5 pattern. The interpreter was required to use considerable judgment in extracting data from the film strips. Target signatures on the images were often questionable because of improper film exposure. The film density was too dark if video levels were set too high.

The percent of targets detected was used as the dependent variable in evaluating the separate effects of stand density, forest type, altitude, vertical angle, and horizontal ground distance.

A summary of detection results of the three timber types is shown in figure 2. Targets in ponderosa pine and Douglas-fir were detected easily at vertical angles less than 10°, but in the Engelmann spruce detection was only 50 percent. Detection in spruce is very low for angles greater than 30°; however, 40- to 50-percent detection was observed for the other two types. During the four flights represented by these data, no targets were detected beyond 40° except in the Douglas-fir stand, where 33 percent were detected between 40° and 50°. None of the detection data in this report are corrected for the inherent dependence of slant range and Lambertian effects on aspect angle (see scanning geometry, Appendix IV).

A single mission, flown in cooperation with the Infrared Physics Laboratory, Institute of Science and Technology, University of Michigan, indicated their 2-milliradian scanning system would consistently achieve better results; this was especially true in the denser portion of the stand (fig. 3).

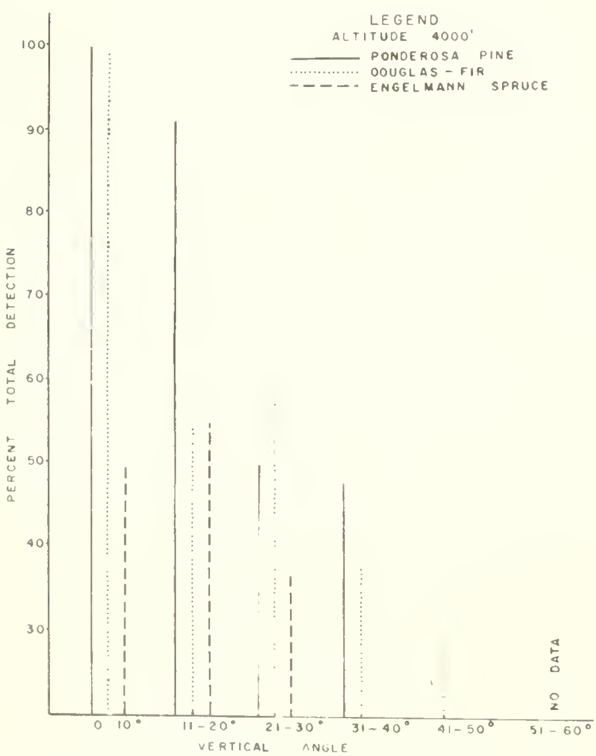


Figure 2. — Percent total detection versus vertical angle for three timber stands.

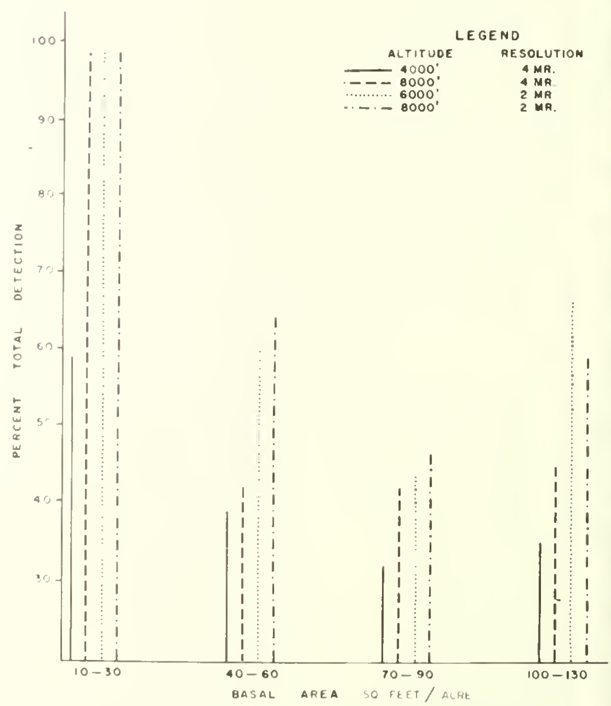


Figure 3. — Percent total detection versus basal area classed for three altitudes and two system resolutions.

The effects of increased stand density and vertical angle were examined by using the data from all altitudes and timber types. This lumping of data was necessary because of the small sample size. These data showed: (1) The extremely low probability for detecting targets in the densest plots for vertical angles greater than 30°; and (2) the difficulty encountered at angles greater than 50° in all but the least sparse portions of the stand.

SUMMARY, PHASE I

The first season's work produced very few definitive results. The problem was attacked with the information and instrumentation at hand, and both proved inadequate.

Deficiencies included: (1) The shortage of pertinent timber canopy ground truth, (2) crude navigational procedures, (3) inadequate data readout, and (4) very poor infrared system sensitivity and resolution.

Positive results were: (1) The project personnel were initiated into airborne infrared experimentation, and (2) personnel obtained a better knowledge of specific program requirements. Using this background knowledge, reasonable program goals were formulated and the necessary modifications of instrumentation were determined.

PHASE II TEST PROGRAM

INTRODUCTION

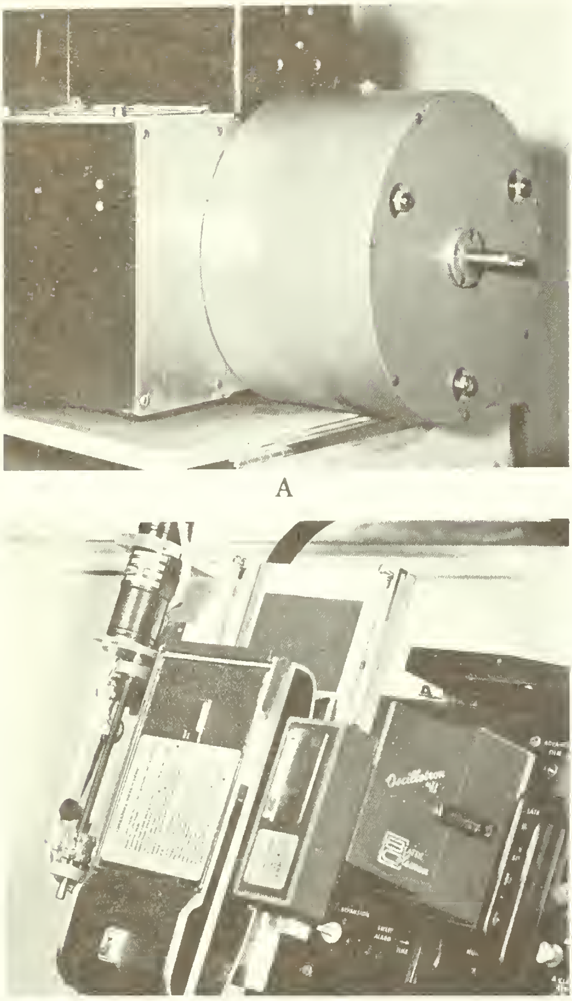
Objectives of Phase II were to implement the modifications suggested by the Phase I results, and to make quantitative measurements of fire detection probability in the representative timber types. Test plans were made incorporating the necessary revisions. Arbitrary goals of 90-percent detection probability and 10-mile-wide coverage were established as realistic objectives for fire patrol.

DEVELOPMENT OF EQUIPMENT

Experience gained during the 1962 test program demonstrated the need for a higher resolution scanner. Replacement of the standard 35 mm. recording camera with a Polaroid camera facilitated control of image quality. A wider scan angle was needed to eliminate the need for offsetting the scanner. The original scanner was modified to provide 120° scan angle by machining a slot on each side of the scanner housing and modifying the scan-sweep trigger circuitry.

Adding a housing extension that holds a 10-inch focal length objective mirror (fig. 4*A*) increased the focal length of the optical system. A higher resolution tube replaced the C.R.T. printer tube. The video amplifiers were modified to provide the necessary bandpass. A modified Beattie Coleman oscillorecord camera, incorporating a Polaroid back (fig. 4*B*) replaced the camera. The Polaroid film pack was mechanically driven perpendicular to the camera axis to provide the vertical sweep. This mechanical sweep drive simulated the conventional 35 mm. strip film drive. Addition of a 1/4- by 1/4-millimeter indium antimonide detector produced a calculated system resolution of 1 milliradian.

The mount built in the nose escape hatch of the AT-11 aircraft provided for two modes of operation. The normal mode of operation placed the scanner in a fixed vertical position to attain a full 120° scan. The scanner also could be manually rotated around the lateral axis to direct the scan plane forward of the vertical to a maximum "tilt" angle of 60°. The latter provided variation of the aspect angle while repeatedly flying the same flight path directly over the target area. This eliminated the need for offsetting the aircraft flight paths — an extremely difficult task to accomplish accurately.



A

B

Figure 4. — Equipment modification: *A*, Infrared receiver modified to a 10-inch focal length system; *B*, Polaroid image recording camera.

TEST PROCEDURE

The Phase I timbered test areas were selected for diversity of stand density and stand form. The tests produced useful fire detection information, but the limited number of samples precluded good quantitative results.

During Phase I the ability to detect the 1-square-foot targets proved very limited. A target array designed with five 1-square-foot charcoal buckets on the circumference of a circle was judged to reasonably approximate an incipient spot fire. The radius of this circle necessary to make the fire detectable then becomes one of the observables of the program.

The Phase II test stands were selected to eliminate as much variation as possible. The test program proposed flight experiments over light, medium, and heavy density stands within each of the four timber types; however, time restricted the actual tests to one stand within each type.

The number of randomly located targets required to determine detection probability within ±10 percent was estimated to be unreasonably large.[5] The number of targets had to be reduced to a practical number that could be handled in the field. Instead of locating the targets at random, we selected dense locations. Biasing of the target locations by selecting the worst cases provided a basis for establishing a lower limit for detection probability, and thereby eliminated some questions of reliability inherent in a small sample size.

The establishment of a lower limit for detection probability was judged to be a realistic goal for Phase II because of the time and effort required for system modification.

For describing forest stands in this report, it is useful to review forest-type terminology used by foresters. The Society of American Foresters[6] defines forest type as:

> A descriptive term used to group stands of similar character as regards composition and development due to given physical and biological factors, by which they may be differentiated from other groups of stands. The term suggests repetition of the same character under similar conditions . . .

During the test program of 1963, the following types as described in "Forest Cover Types of North America,"[7] were sampled to represent typical western forest types: Type #237 Interior Ponderosa Pine, Type #218

[5] *A discussion of sample size and detection probability is included in the Phase III section.*

[6] *Society of American Foresters. Forestry handbook, p. 6. 24. New York: Ronald Press. 1955.*

[7] *Committee on Forest Types. Forest cover types of North America (exclusive of Mexico). Pp. 42, 46, 48, and 57. Washington: Soc. Amer. Forest. 1962.*

Lodgepole Pine, Type #212 Larch—Douglas-fir, and Type #206 Engelmann Spruce—Alpine Fir (*Abies lasiocarpa* (Hook.) Nutt.).

Species in the types named usually form 50 percent or more of the composition. Predominants are judged on the basis of number of stems in the dominant and codominant classes combined.[8]

During the field season of 1963, four new test areas were chosen to determine the effect of timber cover on probability of detection. Relatively pure stands of ponderosa pine, lodgepole pine, larch—Douglas-fir, and Engelmann spruce—alpine fir were selected which met the following criteria:

1. Timber type must be typical of the descriptions used by the Society of American Foresters.[9]

2. Area must be about 40 acres or larger.

3. Flight path (in either a north-south or east-west direction) must provide for safe aircraft navigation.

4. Vehicular access must be available at each end of the area for placement of aircraft navigational devices.

5. Slopes in the area should not exceed 20 percent.

[8] *Ibid, p. 3.*

[9] *Ibid, pp. 42, 46, 48, and 57.*

A test area 1,500 feet long by 1,000 feet wide was delineated on the basis of the above criteria. Within this area the timber was cruised by the variable plot wedge prism (Bitterlich) method. The basal area factor for this cruise was selected to give a 50-percent sample of the standing timber on the site. The cruiser recorded the total height, diameter breast high, percent live crown, and species of each tree selected by this method on each plot within the test area. The number of plots varied because of the characteristics of the stand, but was always sufficient to give an accurate representative sample of the stand according to standard cruise techniques for merchantable timber.

Two sets of cruise data were compiled for these areas — one based on merchantable volume, the description most easily visualized by a field forester; the other including all trees with 4-inch and larger diameters. Merchantable volume probably relates more closely to a stand's detection potential. A complete description of the cruise data is included in Appendix I, and is summarized in table 1.

Table 1. — Cruise information from Phase II test areas by timber type

Measurement	Test areas: Lodgepole pine	Ponderosa pine	Larch - Douglas-fir	Engelmann spruce - alpine fir
Trees per acre	161.2	67.1	120.8	160
Board-foot volume per acre[1]	9,050	5,330	16,923	41,208
Average d.b.h. (inches)	10	14.5	14.9	17.5
Average tree height (feet)	62	58.1	82	86
Average crown thickness (feet)	44	40	47	62
Cumulative stem density (inches per acre)	2,662	6,622	2,224	10,344
Crown cover density[2] (percent)	80	60	80	100

[1] *Scribner log rule was used for all merchantable volumes. Cruise includes all merchantable trees 8 inches d.b.h. and larger (by 2-inch classes).*

[2] *Estimated by aerial photos over test areas.*

A four-man ground crew placed charcoal heat sources within each of the test areas. Five standard target buckets were used in each fire array; total target surface area thus amounted to 5 square feet. The fire array locations, as previously mentioned, were selected within the stand to afford maximum obscuration. The locations were spaced to assure separation of arrays on the imagery and allow target identification. At each location a random compass bearing was determined and the first bucket in the target array pattern placed on this bearing at either 3, 6, 9, 12, or 15 feet from the chosen plot center. The remaining four buckets were then spaced as evenly as tree boles would permit (fig. 5) on the circumference of this circle. Subsequent placing of the buckets on the circumference of larger circles simulated a slow burning fire as it spreads over a larger area.

Aircraft altitude was maintained at 8,000 feet over terrain. Navigation along the flight path was accomplished by visually alining the

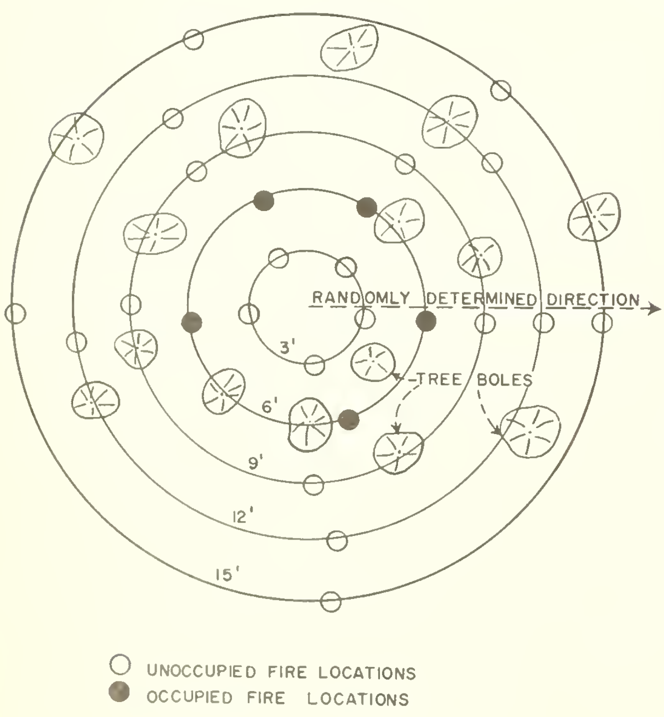


Figure 5. — Fire array target pattern.

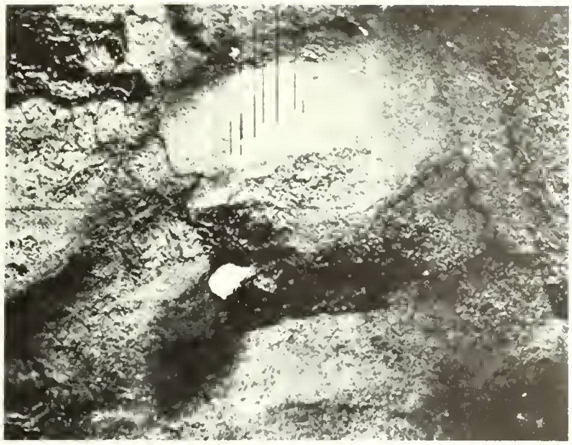
aircraft with three high-intensity rotating beacons. One beacon was located within the test area and the other two were placed 2 miles from the test area in either direction along the flight path. The equipment operator was aided in starting the Polaroid camera at the proper point by an unobscured signal fire that appeared on the 5-inch monitor as the aircraft approached the area.

Eight fire arrays were used on each test. At the beginning of each test the five buckets were arranged on the circumference of a 3-foot circle. With the scanner oriented straight down, a pair of passes was completed from opposite directions and the imagery examined. If 14 of the possible 16 detections were accomplished, the scanner was tilted forward an additional 10° and the fires viewed from this larger angle on the next two passes. If fewer than 14 fire arrays were detected, the scanner was left in the same position, the fire radius increased by 3 feet and the imagery from the next two passes examined. Fire radius was increased in 3-foot increments and passes were repeated until satisfactory results (14 out of 16 targets) were attained, or until a 15-foot maximum radius circle was reached at each aspect angle. After tests over the eight fire arrays were completed, the fires were moved to eight alternate locations and the test cycle repeated.

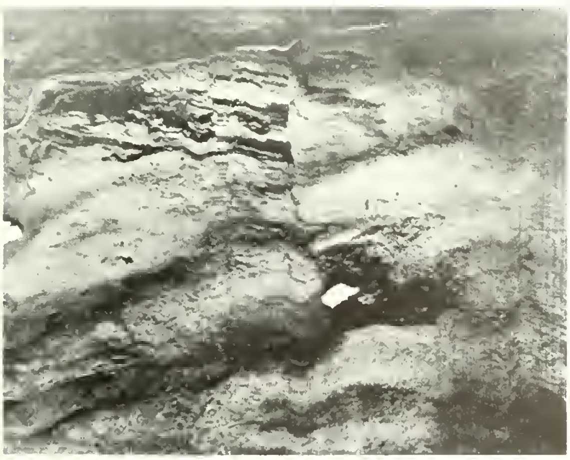
DISCUSSION OF RESULTS

If horizontal ground coverage (pathwidths of 10 miles) was to be attained from the normal operational altitude of propeller-driven aircraft, it was essential to accomplish detection at angles approaching 60°. Satisfactory data were limited to vertical angles of 50° in spite of every effort to obtain reliable data on the critical 60° vertical angle. The increment from 50° to 60° was important because of the increased ground coverage per degree at these large oblique angles.

Two samples of imagery of the larch—Douglas-fir test area are shown in figure 6. Figure 6*A* shows the raw data from one of the passes that established the detection probability at 20°. This sample shows successful



A



B

Figure 6. — Samples of flight test imagery: *A*, Imagery obtained with scanner tilted at 20°; *B*, imagery with scanner tilted at 50°.

detection of each of the eight fire arrays. Figure 6*B* shows two targets detected at 50°; close examination reveals at least four targets from which radiation penetrated the canopy, yet the system failed to separate them adequately from the background. These four targets were considered submarginal because an image interpreter on a fire patrol mission would have trouble making a positive identification. Marginal targets could be made more prominent by adding a pulse-height discrimination capability to the system.

In an effort to simulate a spreading fire, five 1-square-foot heat sources were placed on a 3-foot-radius circle and subsequently moved by 3-foot-radius increments to a maximum radius of 15 feet.

Data were recorded by fire radius classes, scan angle increments, and flightpass numbers. The raw data were then refined into composite values for each fire radius class within each of the 10° scan angle increments. These data are shown graphically (figs. 7 through 10). This analysis shows an increase in detection probability corresponding to an increase in fire radius. The maximum detection probability occurs in the range between 9- and 12-foot radius fire arrays.

Proper interpretation of these results, as they relate to a spreading fire with hot spots remaining inside the perimeter, excited considerable discussion. An extrapolated percent detection was calculated in the following manner.

For each timber type and aspect angle, the imagery was examined by consecutive 3-foot-radial increments. An individual target array detected at a given fire radius was assumed to be detectable at all larger radii. Positive detection results were accumulated by 3-foot-radial increments at each of the eight target locations in the test area. The final radius at which 90+ percent detection for the test area occurred was recorded for each aspect angle and timber type. Table 2 is a synopsis of the accumulative detection results.

It is important to remember that the 3-foot fire size represents 5 square feet of fire; the 6-foot fire size, 10 square feet of fire; etc. Figures 11 through 14 give the accumulative detection probabilities versus aspect angle for the several test areas. The ratio of detected targets to a total number of targets in the sample is included on each graph.

The detection probability thus measured is conservative. The fire plots were selected in the densest portions of the test stands. This analysis does not account for any energy radiated in less than threshold amounts. The results of this accumulative detection analysis establish lower bound detection probabilities for fires in timber stands similar in density and composition to the test stands.

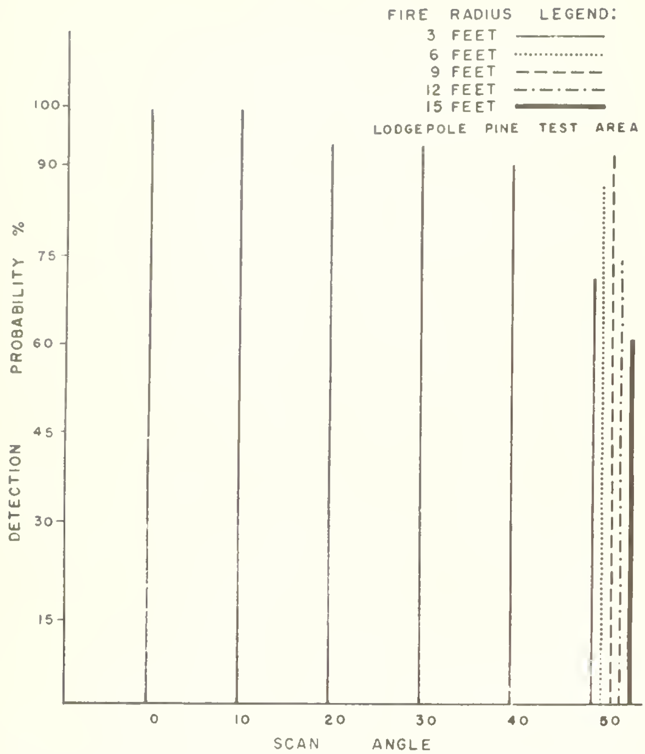


Figure 7. — Detection probability as a function of vertical angle and fire radius for lodgepole pine test area.

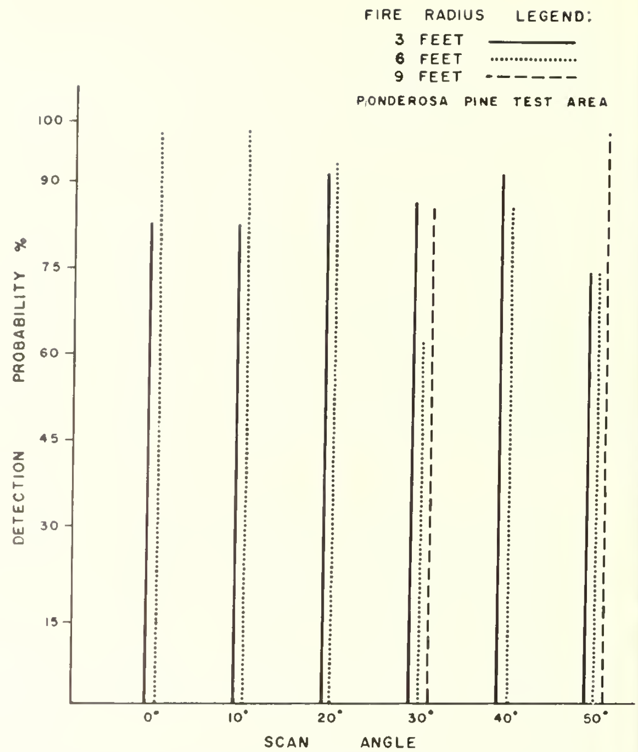


Figure 8. — Detection probability as a function of vertical angle and fire radius for ponderosa pine test area.

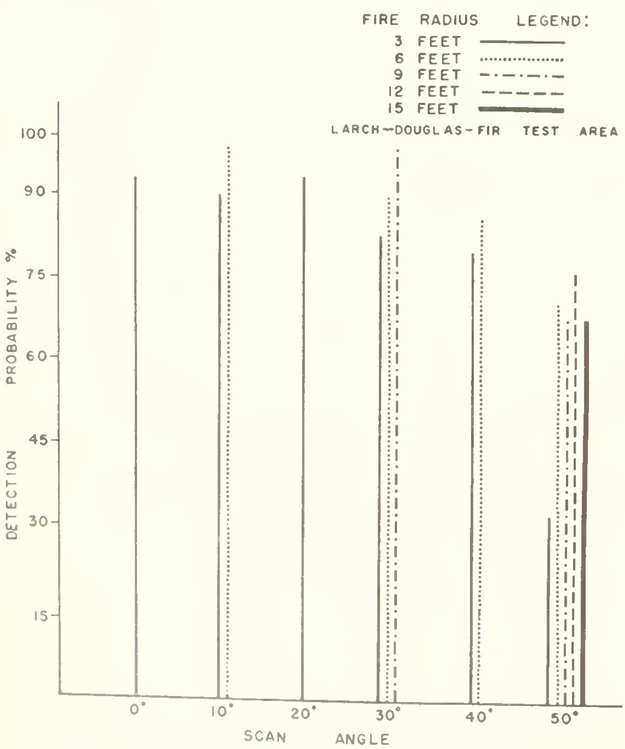


Figure 9. — Detection probability as a function of vertical angle and fire radius for larch—Douglas-fir test area.

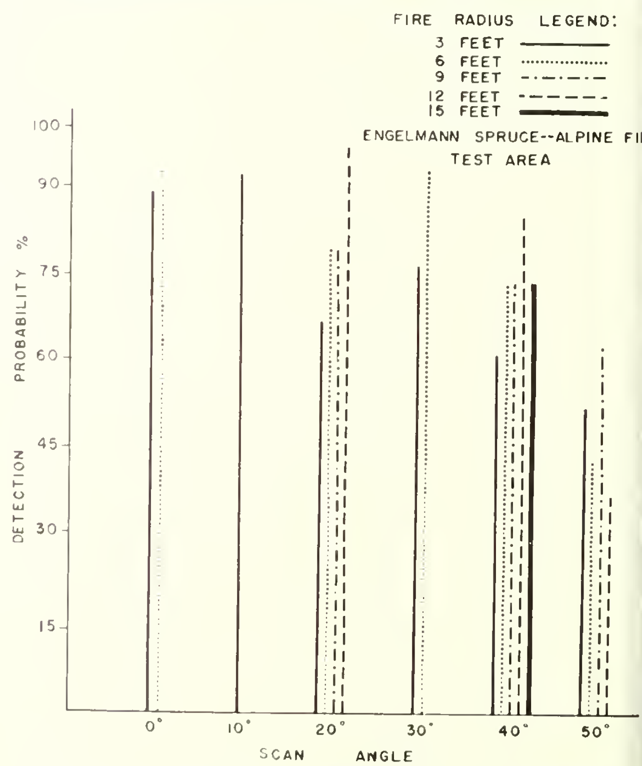


Figure 10. — Detection probability as a function of vertical angle and fire radius for Engelmann spruce — alpine fir test area.

Table 2. — **Accumulative detection results for multiple target configurations**

Species	Detection results		
	Fire size	Scan angle	Detection probability
	Feet	Degrees	Percent
Lodgepole pine	3	0-40	90+
Lodgepole pine	6	40-50	90+
Ponderosa pine	3	0-40	90+
Ponderosa pine	6	40-50	90+
Larch - Douglas-fir	3	0-20	90+
Larch - Douglas-fir	6	20-50	90+
Engelmann spruce - alpine fir	3	0-10	90+
Engelmann spruce - alpine fir	6	20-30	90+
Engelmann spruce - alpine fir	9	40-50	90+
Engelmann spruce - alpine fir	12	50	80—

Preliminary results of the studies of target fire detection in the various timber types indicated detection probabilities were lower in the denser timber types and higher in the lighter types. However, within each stand there existed several qualitative ambiguities between percent detection and timber canopy characteristics that were visually estimated. To resolve these difficulties, the timber canopy of one test area was studied in more detail.

At the larch—Douglas-fir test area, the canopies in the immediate vicinity of each of the 16 target arrays were examined. Measurements included d.b.h., tree height, percent live crown, and profile of individual tree boles.

No correlation existed between the canopy measurements and the flight data.

The major difficulty in determining significant factors of timber canopy obscuration was the inability of the ground crew to determine the precise optical path through the canopy at the moment the test plot was in the field of view of the scanner. A more detailed study of canopy obscuration could be made from an elevated, fixed-scanner platform.

Plans were made to fly simulated patrol missions before the start of the fire season. The aircraft was equipped with a dual-omni navigation system. The pilot was to fly compass bearings between checkpoints that were to be calculated by triangulation from two known omni stations. During several simulated missions, this technique proved inadequate for navigation over a contiguous strip-patrol pattern.

Charcoal fires were placed within the patrol area at locations unknown to the aircrew. The aircraft navigated omni fixes and compass bearings and attempted to follow designated north-south paths. The scanner operator monitored the infrared image on the face of a 5-inch scope for potential fire targets. The potential fire locations were not recorded on film because the Polaroid camera, being a single-frame camera, could not obtain continuous real-time imagery. When a potential target was observed on the monitor, the pilot was instructed to start a standard figure-eight flight pattern. This maneuver placed the aircraft over the potential fire twice more with the final leg being a continuation of the original course. By keeping track of elapsed time, the operator was to record the imagery over the potential spot fire. This procedure was not satisfactory because the timing and coordination necessary

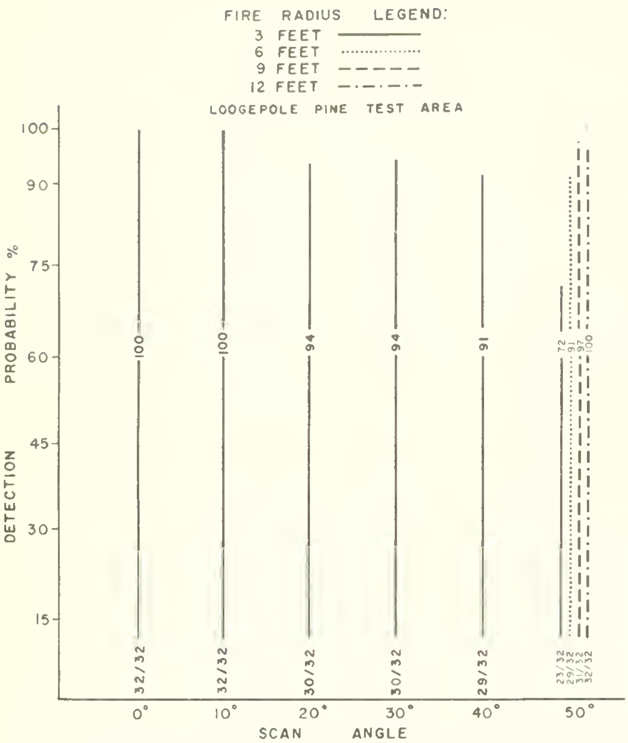


Figure 11. — Accumulative detection probability versus vertical angle and fire size for lodgepole pine test area.

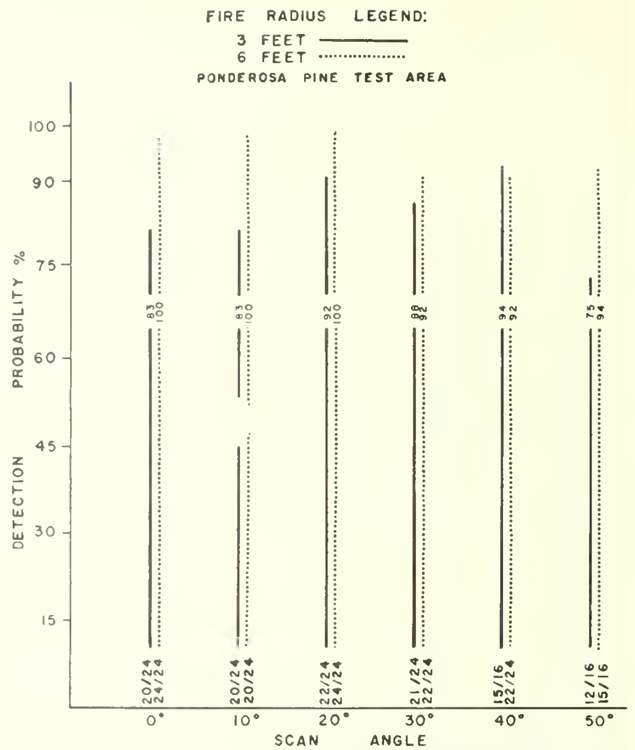


Figure 12. — Accumulative detection probability versus vertical angle and fire size for ponderosa pine test area.

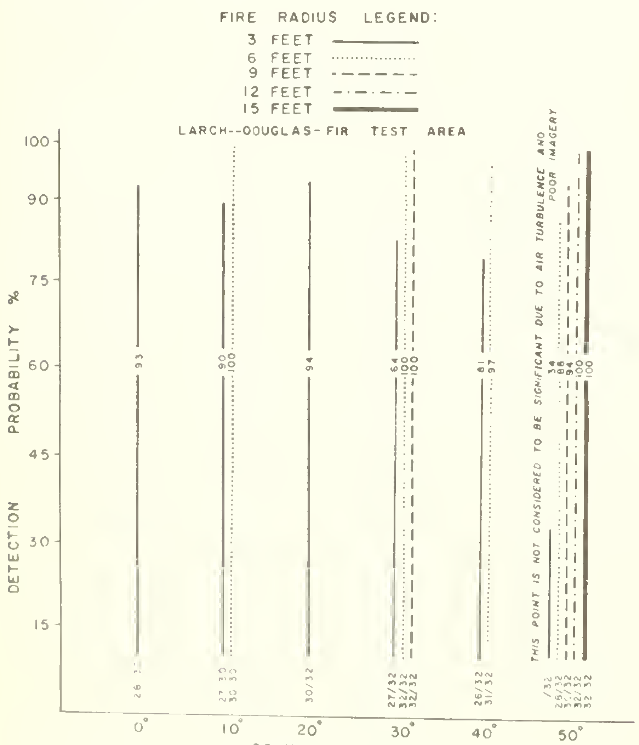


Figure 13. — Accumulative detection probability versus vertical angle and fire size for larch—Douglas-fir test area.

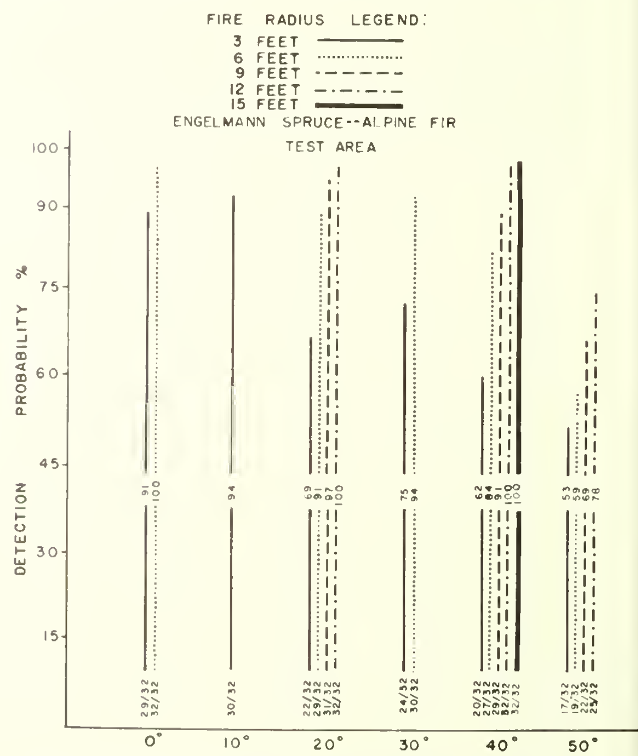


Figure 14. — Accumulative detection probability versus vertical angle and fire size for Engelmann spruce — alpine fir test area.

to precisely locate the target area during the maneuver could not be achieved.

One mission detected one out of five charcoal fires (each was a five-bucket array) placed in the 900-square-mile patrol area. The ground crew observed that the navigation techniques used did not place the aircraft in position to detect the remaining four. Four other hot spots were detected on the mission, however; these targets coincided with known campground locations. The one test fire detected was accurately located through use of infrared imagery and existing aerial photographs. The fire detection patrol flights during Phase II demonstrated that the relatively simple navigation techniques used will not satisfy patrol requirements.

The Beechcraft AT-11 aircraft was unable to operate at 15,000 feet above terrain, the altitude needed to attain 10-mile-wide coverage utilizing a 120° scan. Limitations on aircraft fuel and oxygen supply made attempts to perform extended high altitude tests impractical. The aircraft could not attain altitudes necessary to investigate the detection limits for unobscured 5-square-foot sources. The unheated, unpressurized, and cramped instrumentation space seriously degraded the performance of the equipment operators.

SUMMARY, PHASE II

At the end of Phase II many factors were evident that affected the realization of the project goals. Their scope is best presented in the following outline:

1. Accomplishments

a. Equipment performance and data acquisition techniques provided reproducible detection measurements.

b. Information about detection probability was obtained for the four representative coniferous timber types.

c. A qualitative list of requirements for an operational system was being acquired.

2. Problems yet unsolved

a. Instrumentation and navigation problems limited the detection data to aspect angles of less than 50°.

b. The large number of submarginal target observations indicated inadequate system sensitivity.

c. The high speed nature of flight tests does not facilitate precise observation of timber obscuration factors.

d. Aircraft navigation and altitude capabilities of the present aircraft are inadequate.

3. Proposed equipment modifications

a. An aircraft capable of flying at higher altitude and providing at least a minimum of operator comfort must be acquired.

b. The aircraft must have a better navigation capability.

c. The scanner system modifications should include:

(1) an increased electronic bandpass,

(2) the addition of a pulse-height discrimination circuit, and

(3) the addition of a rapid process, continuous strip photographic readout.

4. Proposed program modifications

a. The technical competence of the project should be broadened by acquiring additional professional personnel, including U.S. Forest Service pilots and technical personnel.

b. Experimental reorganization should include:

(1) the addition of a mountaintop-fixed platform study of canopy obscuration parameters and

(2) the division of the flight program into two separate studies:

(a) Fire detection studies in the various timber types and

(b) Wildfire patrol and navigation problems.

PHASE III TEST PROGRAM

OBJECTIVES

The goals of the 1964 season, delineated in a test plan, are summarized as follows:

1. The infrared system modifications were to be checked out. Correlation was to be established with previous test results by reruns on the lodgepole pine test area. Data gathering and flight test operational procedures were designed similar to those of Phase II.

2. When equipment performance proved satisfactory, flight tests were to be run on white pine (*Pinus monticola* Dougl.) and coastal Douglas-fir. Also, flight measurements were to be extended to 15,000 feet over terrain and 60° aspect angles in representative timber types. This would complete the preliminary survey of fire detection probabilities for northwestern coniferous timber types.

3. During the lightning fire season (July 15 to September 1) the problems of fire patrol were to be investigated. The immediate goals included familiarization with the navigation system and comparison of effectiveness of infrared surveillance with present Forest Servive methods. Observations were to include the feasibility of early detection of incipient fires and immediate dispatching of fire suppression forces.

4. After the lightning season, the scanner was to be removed from the aircraft and mounted at the previously selected mountaintop-fixed platform test site. The mountaintop program included: (1) Extension of the larch—Douglas-fir detection probability curve to beyond 60° and (2) the detailed investigation of forest canopy obscuration factors.

FIRE DETECTION TESTS

A Convair T-29 aircraft, equipped with a Doppler radar navigation system, was acquired on loan from the U.S. Air Force. The infrared instrumentation was modified as proposed at the conclusion of the 1963 program and installed in the aircraft.

The first instrumentation checkout flight was not made until June 22, primarily because the Convair T-29 aircraft arrived late. On June 24, the first extended night checkout flight proved very encouraging. The aircraft and radar navigation system performed beautifully. The electronic instrumentation seemed adequate at that time. Intermittent use of the pulse-height discrimination circuit indicated satisfactory performance.

On June 25, the first attempt was made at reproducing 1963 data for the lodgepole pine test area. The scanning system included a new rapid process, continuous strip photographic readout (moving window display), and a modified video electronic system. Preliminary system sensitivity measurements were marginal. During the first week in July, a new high resolution cathode ray tube was installed in the moving window display. This modification worked very well and the photoprocessor readout continued to perform impressively for the rest of the season.

In the middle of July the aircraft's electric, hydraulic, and navigation systems became unreliable. During the next two months the aircraft went through five extensive maintenance periods.

The flight test program continued through July and into August. Tests were made in the lodgepole pine test area and the white pine test area at Priest River, Idaho. A single fire patrol mission was flown on August 21. The infrared receiver and video electronics continued to demonstrate intermittent reliability because of excessive modification.

During the third week of August it was apparent that continued efforts to increase the sensitivity of the present electronic and receiver system would not succeed. Flight operations were terminated and the instrumentation removed from the aircraft.

Bench tests of the infrared receiver indicated it would still operate satisfactorily in a stable ground environment. It produced satisfactory results during the mountaintop test series.

FIRE PATROL

Equipment and Test Procedure

The Doppler navigation system, which reads out directly in latitude and longitude, provided a suitable navigation capability. Specifications for the accuracy of Doppler systems are commonly within 2 percent of track. If this accuracy could be attained, the Doppler system would keep the aircraft within 2 miles of the proposed flight path on a 100-mile patrol run. This accuracy is near limits which could be tolerated on patrol missions.

A 1:60,000 aerial photomosaic was made of the proposed patrol area and used as a navigational aid. The photomosaic was cut into strips that included the area to be covered on each patrol run. Latitude and longitude lines were marked on the photostrips to describe locations.

The moving window display provided rapidly available strips of infrared imagery that could be compared to the aerial photomosaic to determine aircraft location.

During the detection missions it became evident that cumulative errors in the Doppler system would exceed the accuracy requirements for patrol work. Infrared-aerial photointerpretation could not provide the precise information in reasonable time for patrol navigation. A combination of the two systems offered a better chance for success. Plans were made to navigate with the Doppler system, and to use the comparison of the aerial photo-infrared imagery to determine periodically true aircraft location. True location provides a basis for correcting accumulated errors in the Doppler system. If navigational procedures worked satisfactorily, patrol missions would be flown after periods of lightning activity.

Patrol Area

A 6,000-square-mile patrol area southwest of Missoula was selected because it was sparsely populated and had a history of frequent lightning occurrence. A sparsely populated area is less likely to give false alarms attributable to campers, vehicle exhaust, and similar disturbances. The 60-mile-wide patrol area was bordered on the east by a 100-mile line extending from Alberton, Mont., south to the Salmon River.

The area was divided into seven 8-mile-wide patrol strips. This width was chosen to give ample overlap on adjacent passes, and to provide simplicity for navigation because adjacent flight lines would be separated by 10-minute increments of longitude.

At least three prominent topographic features, such as road intersections or lakes, were selected on each proposed flight path to serve as checkpoints for purposes of establishing true location during the flight.

Patrol Flight

A single patrol was flown on August 21. The aircraft's operational ceiling of 18,000 feet m.s.l. limited the flight altitude to 12,500 feet over average terrain. At this altitude the 120° scan angle gave 4-mile coverage to either side of the flight path.

During the first pass, on a southerly heading along strip 1, we relied on the Doppler system entirely. The aircraft began the pass on course and drifted consistently to the west. This drift was detected by comparing the infrared image to the aerial photomosaic. When the pass was completed, the Doppler navigation was corrected by addition of 4 minutes longitude. The pilot was able to correct his heading on the second pass and the drift was eliminated.

The Doppler and scanning equipment were both functioning poorly during the flight; however, it was still possible to navigate the desired course. Patrol flights were terminated at this point because of equipment troubles.

MOUNTAINTOP TESTS

General Discussion

A fixed-mountaintop scanner site was established to examine in detail those factors which obscure targets and extend detection data beyond the critical 60° (fig. 15).

Two advantages of a fixed site are: (1) Operation is more economical and (2) test measurements can be observed for a much longer time than is possible from a fast moving aircraft.

The only location with suitable elevation (aspect angle) and timber stand within reasonable distance of Missoula is in the Bear Creek Drainage west of Victor, Mont. (fig. 16). This precipitous area provides: (1) Vertical aspect angles between 45° and 70°, (2) slant ranges of 3,400 to 7,400 feet, and (3) a well-stocked mature larch—Douglas-fir stand associated with grand fir, Engelmann spruce, and alpine fir.

Figure 15. — Mountaintop scanner installation.

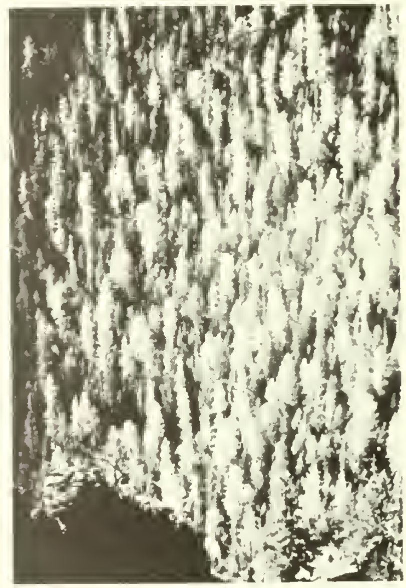


Figure 16. — Test area from scanner location.

Preparation of Program

The mountaintop test was designed to supplement and extend the results of the flight program. Lack of previous experience made the first effort largely a trial run, and most procedural details were worked out on the spot. The initial objectives of the program were:

1. The detection probability curves were to be extended to larger aspect angles. Flight program data had been limited to angles less than 50°.

2. The spatial distribution of sizes and types of canopy obscurations was to be determined over an extended area.

3. The effects of background temperature, target emissive area, and scanner field of view on the target-to-background signal (S_T/S_B) ratio were to be determined.

4. Identifiable foliage and timber patterns were to be related to detection probability and signal strengths.

5. Correlation was to be determined between target signal strengths and detection probability.

Test plots at angles between 45° and 60° at 2° intervals were planned. Plot locations were chosen to provide a homogeneous timber canopy. Each plot was 100 feet long and oriented at right angles to the scanner azimuth (fig. 17). The ground was cleared of obstructions for access and preliminary timber cruise data were taken for each plot. Test plots were initially prepared at 45°, 50°, 52°, 54°, 56°, 58°, and 60°, but because of ambiguities in preliminary data at these plot locations, additional plots were constructed at 51°, 53°, 55°, 56½°, 57°, 60½°, 61°, and 69°.

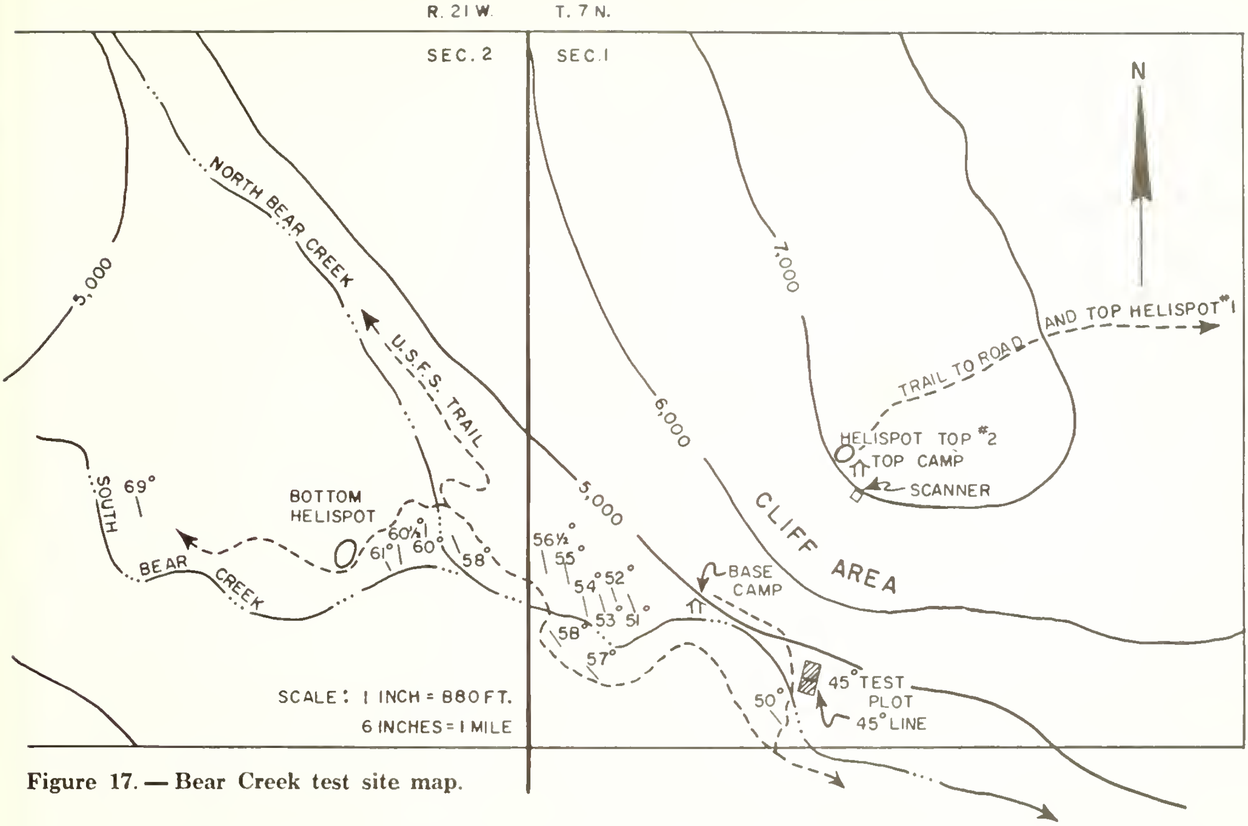


Figure 17. — Bear Creek test site map.

To facilitate detailed canopy measurements, a two-dimensional plot (50 feet by 200 feet) at the 45° aspect angle was prepared.

Instrumentation

Figure 18 is a block diagram of the scanner instrumentation. The video electronics used during the flight program were discarded and simple video amplifiers substituted. This provided an adequate but much less sophisticated video electronic and readout system. The scanner was mounted so that the scanning sweep started 30° above the horizon and swept down through 120° of elevation angle to the vertical. The scanning mirror rotated at approximately 3,600 r.p.m. and gave two scan sweeps per revolution. Precise control of scanner azimuth allowed detailed observation of individual optical paths. Relative radiant intensity was measured in volts at the oscilloscope. Rough system calibration is described below.

To eliminate the effects of reflected solar radiation, radiometric test measurements were made only at night (1930 hours to 2400 hours). A 100-watt incandescent light was located close to the scanner so that the crew on the target area could locate the scanner at night and make subjective estimates of canopy obscuration.

The test targets were 14-inch diameter (1.07 square feet) fire buckets, each filled with approximately 10 pounds of burning charcoal briquettes. The same sources are used in the flight program and have proved to be near black body, Lambertian radiators.

Figures 19 and 20 are representative Polaroid photos of the oscilloscope readout. Table 3 gives measurement data for each illustration. Figures 19*A* and *B* show the change in background signal level over the 5-3/4-hour period just after sunset. Figures 19*C* and *D* are of the same 1/16-square-foot calibration target. In figure 19*C* the labeled points indicate (A) the beginning point of scanner sweep, (B) the horizon, (C) target signal spike, and (D) end of sweep. The space D to A′ is sweep dead time before the beginning of the next sweep at A′. On 19*D* the sweep was expanded and delayed for more precise signal observation.

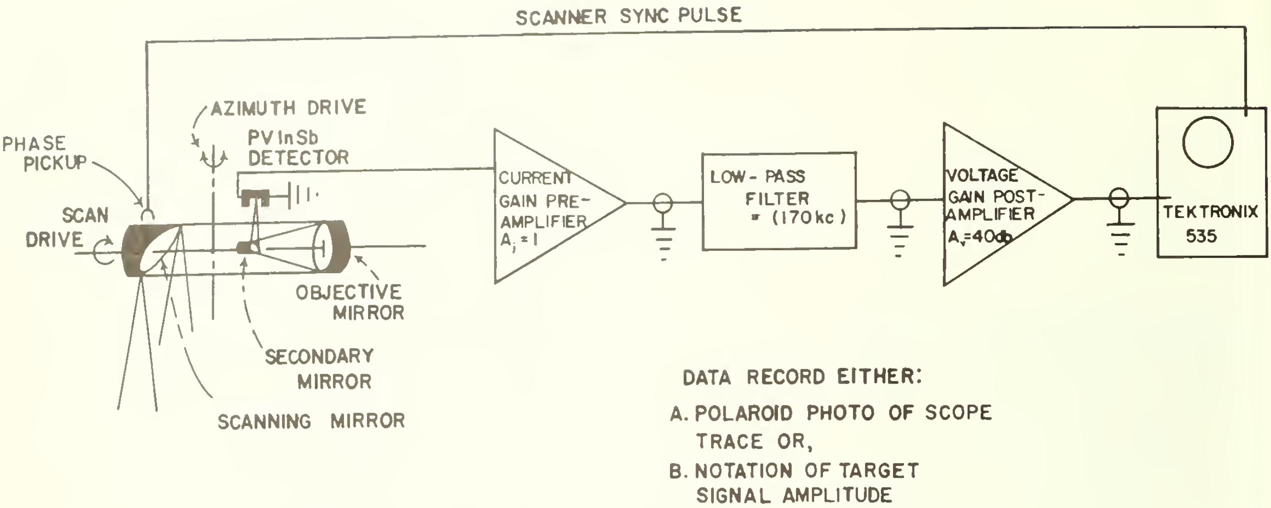


Figure 18. — Block diagram of mountaintop scanner instrumentation.

Figures 20*A* and *B* indicate enhancement of system signal-to-noise (S/N) ratio by use of electronic filtering with 12 db per octave rolloff above 150 kc.

Figures 20*C* and *D* are measurements of scanner resolution; two 12-briquette fires were placed 1.7 milliradians and 2.6 milliradians apart, respectively, along the scanning line.

On-the-spot calibration was provided by signals from line arrays of a small number of individual 1-3/4-inch-square glowing briquettes. Figure 21*A* is a typical calibration curve (in this case from 50° plot); 0.2 volt was the observed signal from one briquette, and 2.5 volts was the signal from 12 briquettes. The system saturated at approximately 3.5 volts (fig. 21*B*, taken at 69° plot), indicating lack of sufficient dynamic range in the voltage gain post amplifier. Compensation is necessary for slant range and Lambertian effects between calibrations at the different test plots.

Rough calculations from inadequate calibration techniques indicate: (1) The total radiant emission from the standard targets is approximately 1.7 watts/cm^2, or about 35 watts per briquette; (2) the "calibration" on the linear portion of the response curve in the spectral region of measurements gives a system output voltage response to effective target emission of 0.125 volt/(watt/steradian).

Table 3. — **Measurement parameters associated with figures 19 and 20**

Figure no.	Signal	Sweep scale		Date	Time of day
		Time	Scan angle		
	Volts/div.	Sec./div.	Degree/div.		
19*A*	.2	2 msec.	45.0	10/13	1825
19*B*	.2	1 msec.	22.5	10/14	0012
19*C*	.2	1 msec.	22.5	9/28	1850
19*D*	.2	50 μsec.	1.12	9/28	1853
20*A*	.2	50 μsec.	.45	9/14	2255
20*B*	.2	20 μsec.	.45	9/14	2250
20*C*	1.0	10 μsec.	.22	9/16	—
20*D*	1.0	10 μsec.	.22	9/16	—

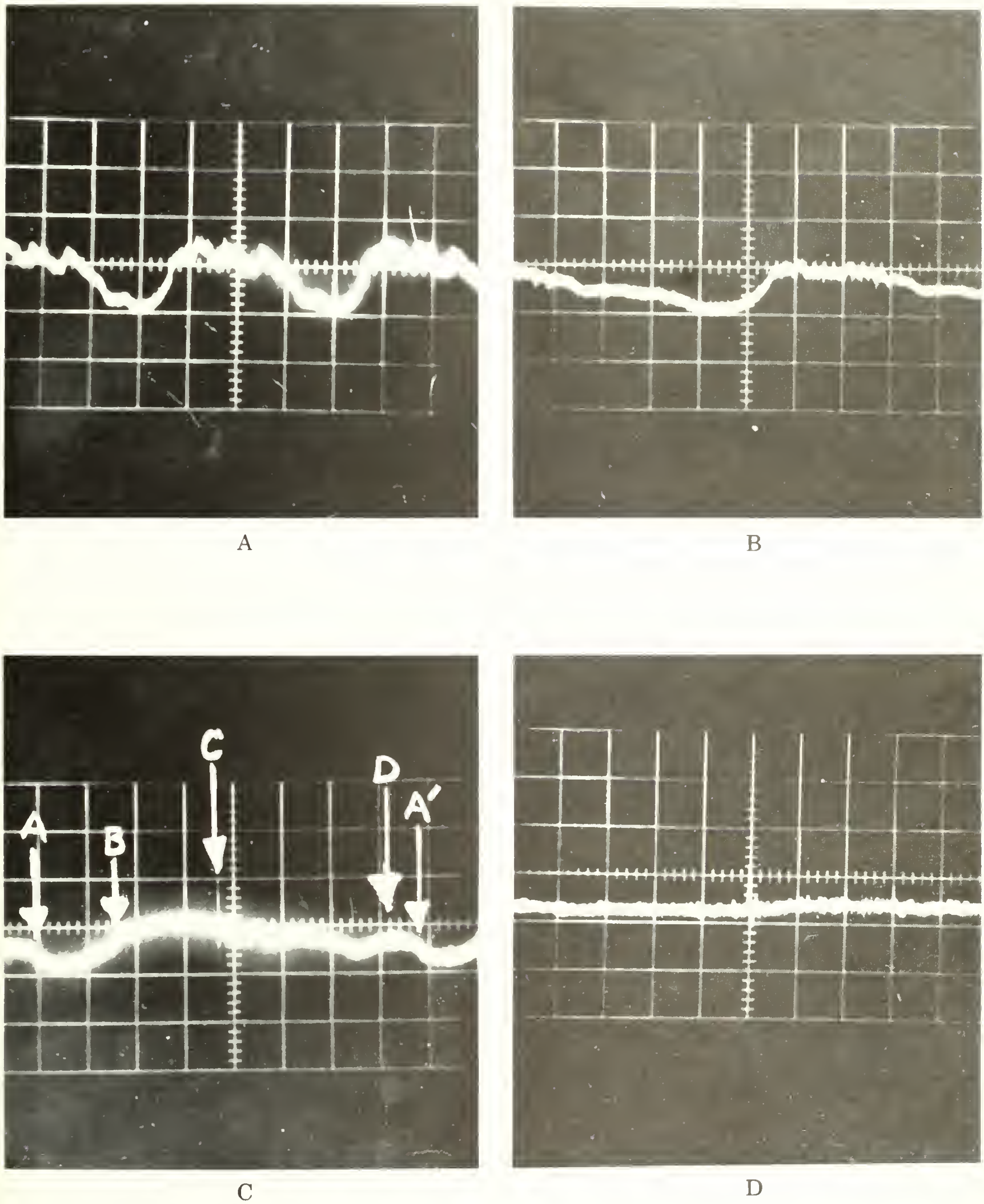


Figure 19. — Polaroid photographs of oscilloscope readout: *A* **(1825 hours, 10/13) and** *B* **(0012 hours, 10/14), change in background signal level over a 5-3/4-hour period;** *C* **and** *D* **(1/16-square-foot target), full scan sweep on** *C***, sweep expanded and delayed for more precise signal observation on** *D***.**

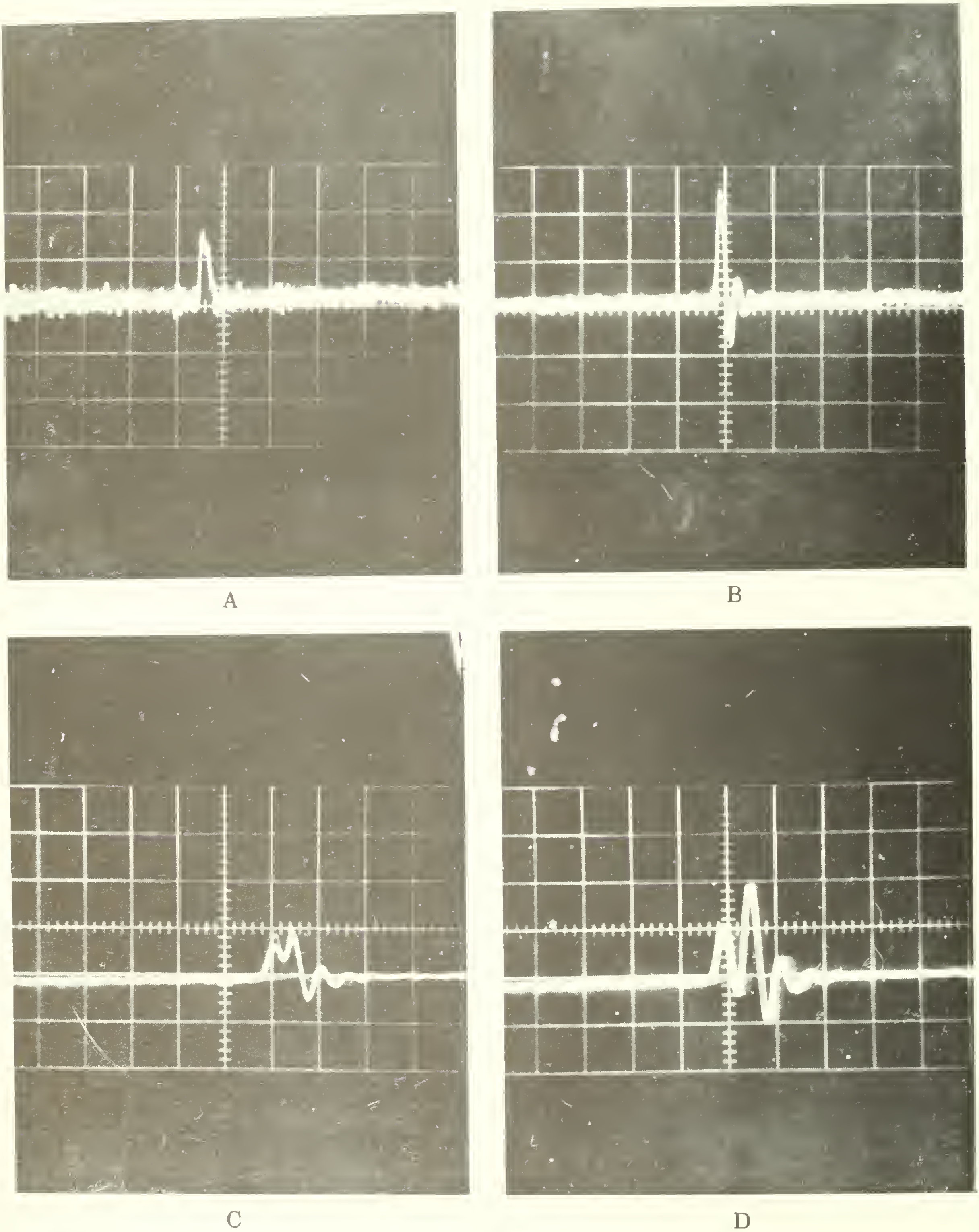


Figure 20. — Polaroid photographs of oscilloscope readout: *A*, target (35, 75) signal and system noise with no electronic filter; *B*, same sweep with 150 kc. low-pass electronic filter; *C*, measurement of scanner resolution, two fires 1.7 milliradians apart; *D*, measurement of scanner resolution, two fires 2.6 milliradians apart.

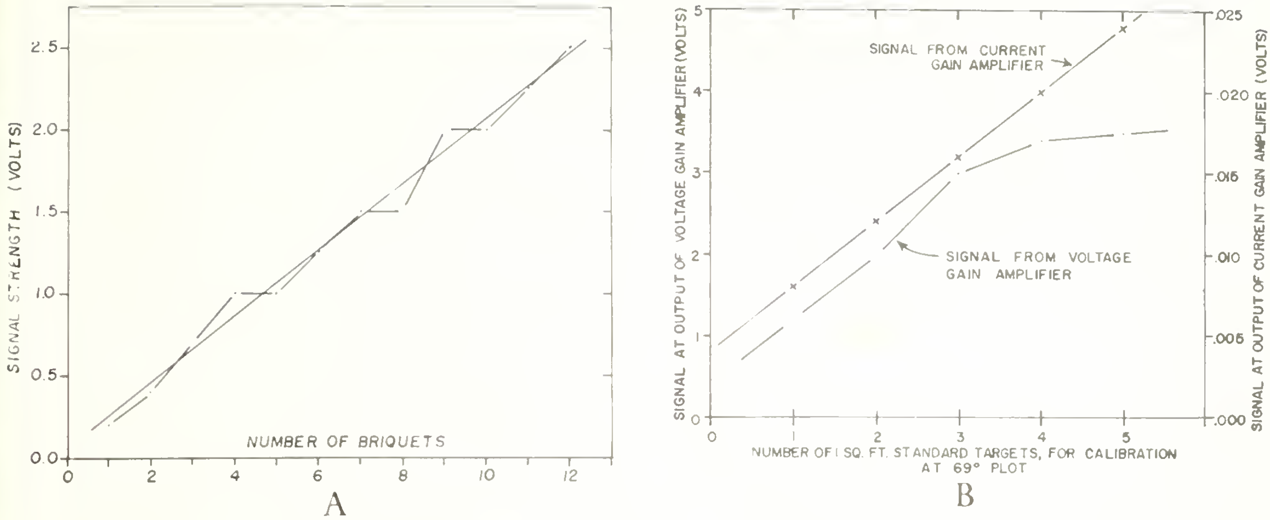
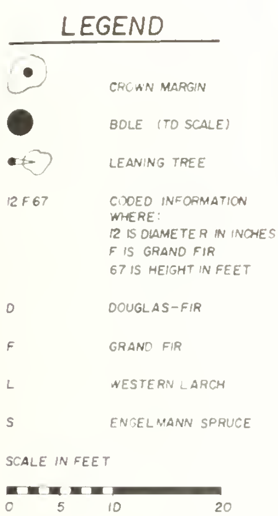


Figure 21. — *A*, Instrument calibration curve; *B*, calibration curve showing nonlinear response of the voltage gain amplifier.



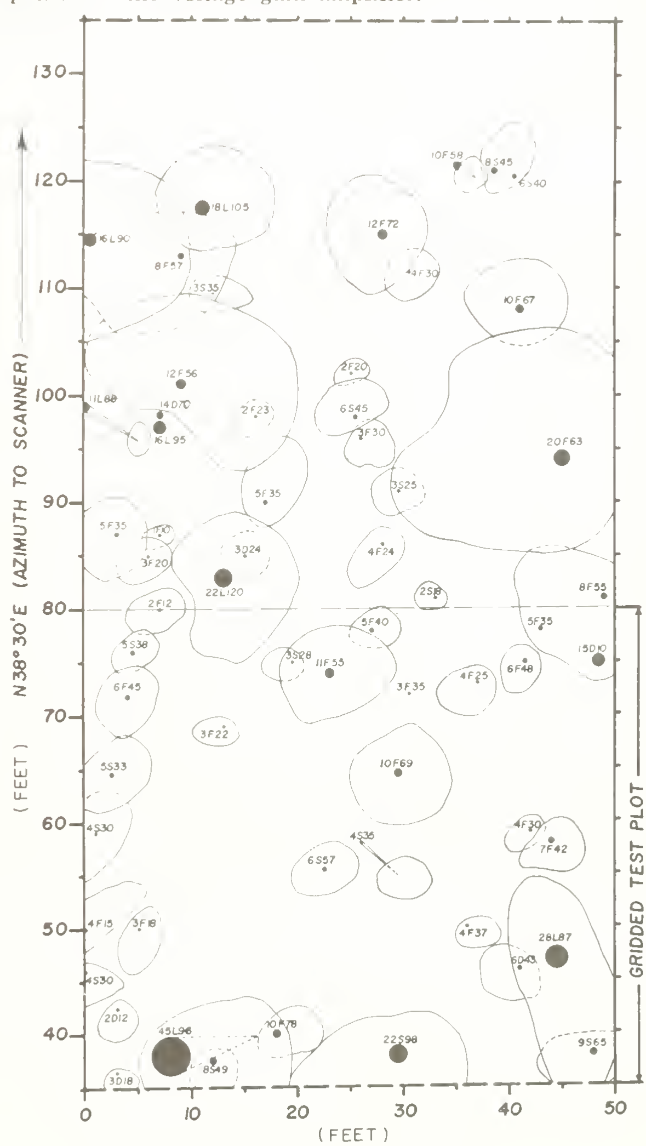


Figure 22. — Plan view of individual tree boles and crowns within the 45° test area.

Discussion of Tests at 45° Plot

This plot was prepared to observe the exact nature of the timber canopy obscuration. A gridded plot was laid out (45 feet by 50 feet) to encompass "several representative tree crowns." A plan view was made of all tree crowns and boles which would obscure any portion of the test plot (fig. 22). For this purpose it was necessary to include trees up to 65 feet in front of the gridded area.

The 45° plot grid locations are referred to by the abscissa and ordinate, respectively, of figure 22, and have the dimensions of feet from the extreme southwest corner of the test area.

Radiation measurements (i.e., scanner signal voltage) were made from a 1.07-square-foot target placed successively at each 1-square-foot grid increment throughout the 45- by 50-foot plot. Figure 23 shows a signal voltage profile of the 45° area. Signals were recorded by 0.1-volt increments. The only system calibration available is that which was extrapolated to 45° from the 50° plot. For the qualitative nature of this report the 50° calibration curves are adequate for the 45° data. For precise extrapolation to 45°, multiply the abscissa of the 50° calibration curves by 1.33 (fig. 21*A*).

In addition, a limited number of larger fire arrays was investigated to determine the

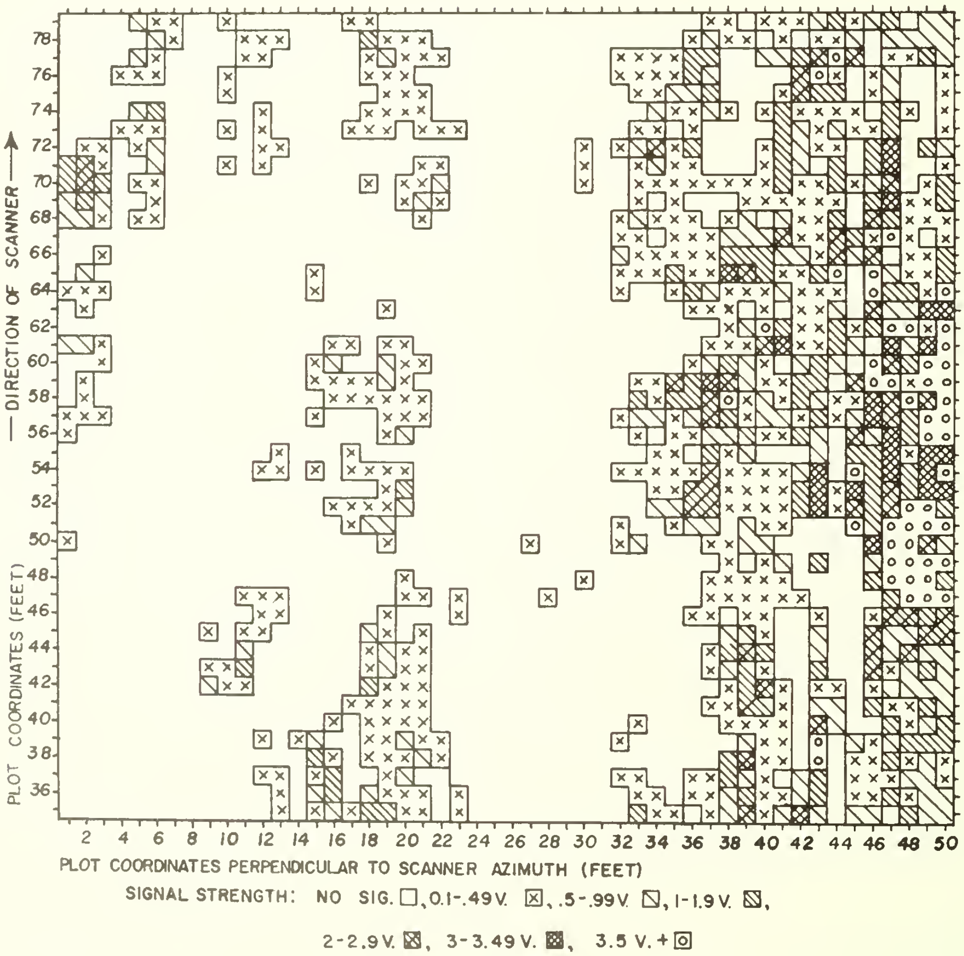


Figure 23. — Signal voltage profile of 45° test area, from 1-square-foot charcoal sources.

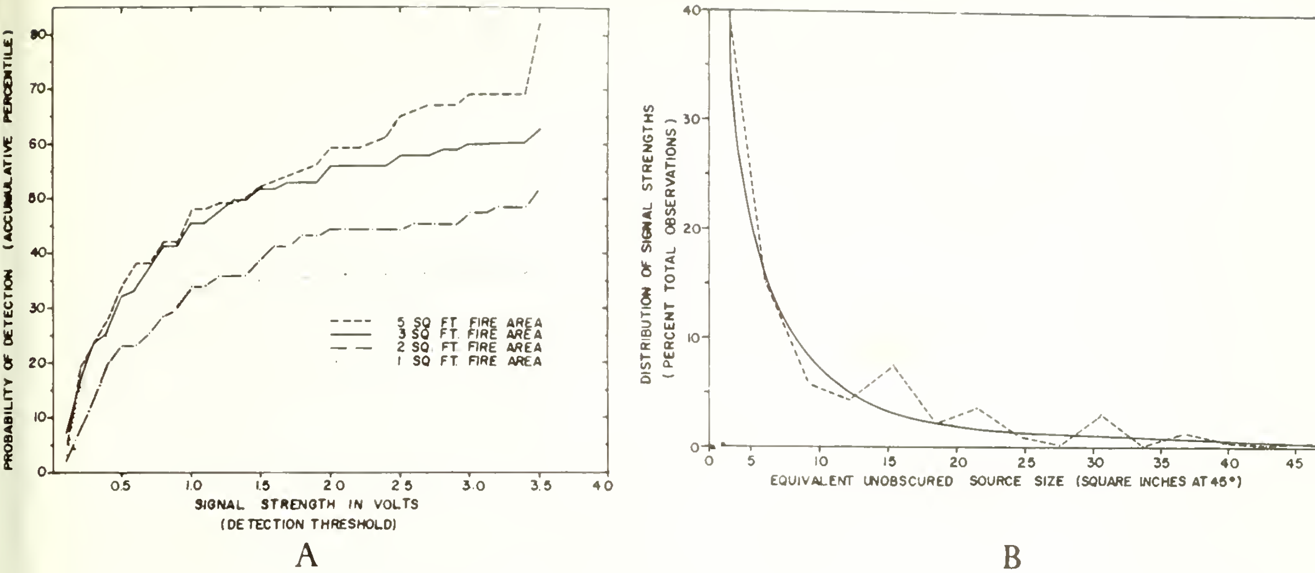


Figure 24 — *A*, Accumulative percent of total observations versus signal strengths for 1-, 2-, 3-, and 5-square-foot targets; *B*, frequency of occurrence of equivalent unobserved source sizes (1-square-foot targets at 45°).

effect that increased fire area has on detection probability. The accumulative percentage of signal strengths to total samples (i.e., percent detection versus detection voltage threshold) is shown in figure 24*A* for four sizes of fires: 1, 2, 3, and 5 square feet of fire area. The 1-, 2-, and 3-square-foot sources were buckets placed close together; the 5-square-foot source was the standard 5-bucket array on a 3-foot-radius circle.

Comparison of figures 24*A* and 21*A* will indicate the denseness of canopy obscurations: e.g., about 60 percent of the observations of 5-square-foot targets had unobscured areas smaller than 12 briquettes (0.25-square-foot) or were more than 95-percent obscured. The relative differences of the 1- to 2-square-foot, 2- to 3-square-foot, and 3- to 5-square-foot target curves suggest a measure of obscuration sizes and distribution. (The large number of very small signals indicates the desirability of improving scanner system sensitivity.) Note also that, relative to the calibration curve (fig. 21*A*), the 1-square-foot target (2.5 v.) does not increase its detection probability after showing through the canopy an emissive area of approximately 15 square inches (i.e., equivalent to about five briquettes). Figure 24*B* indicates the frequency of occurrence of equivalent unobscured canopy "hole" sizes (from all four fire sizes).

The large number of small signals indicates that the open transmission paths are generally very small. Photographs of the timber canopy support this observation (fig. 25). These high contrast photographs depict the nature of the timber canopy obscurations. The camera was tilted up 45°. The scanner is located near the center of each frame. The numbers in parentheses are ordinate and abscissa, respectively, of plot locations evenly spaced throughout the area. Figure 26 provides more detail of the canopy obscuration. These plot locations were selected as representative of the full range of observed signal strengths. The smaller details of the canopy obscurations correlate more closely with signal strength (see also fig. 23). The observations demonstrate the existence and significance of a large number of transmission paths of small cross sections associated with the small signals.

These observations establish the existence of a large number of relatively small signals near detection threshold levels. Cursory comparison of figures 21 through 26 shows the qualitative dependence of detection probability on (1) the canopy "hole" size and fre-

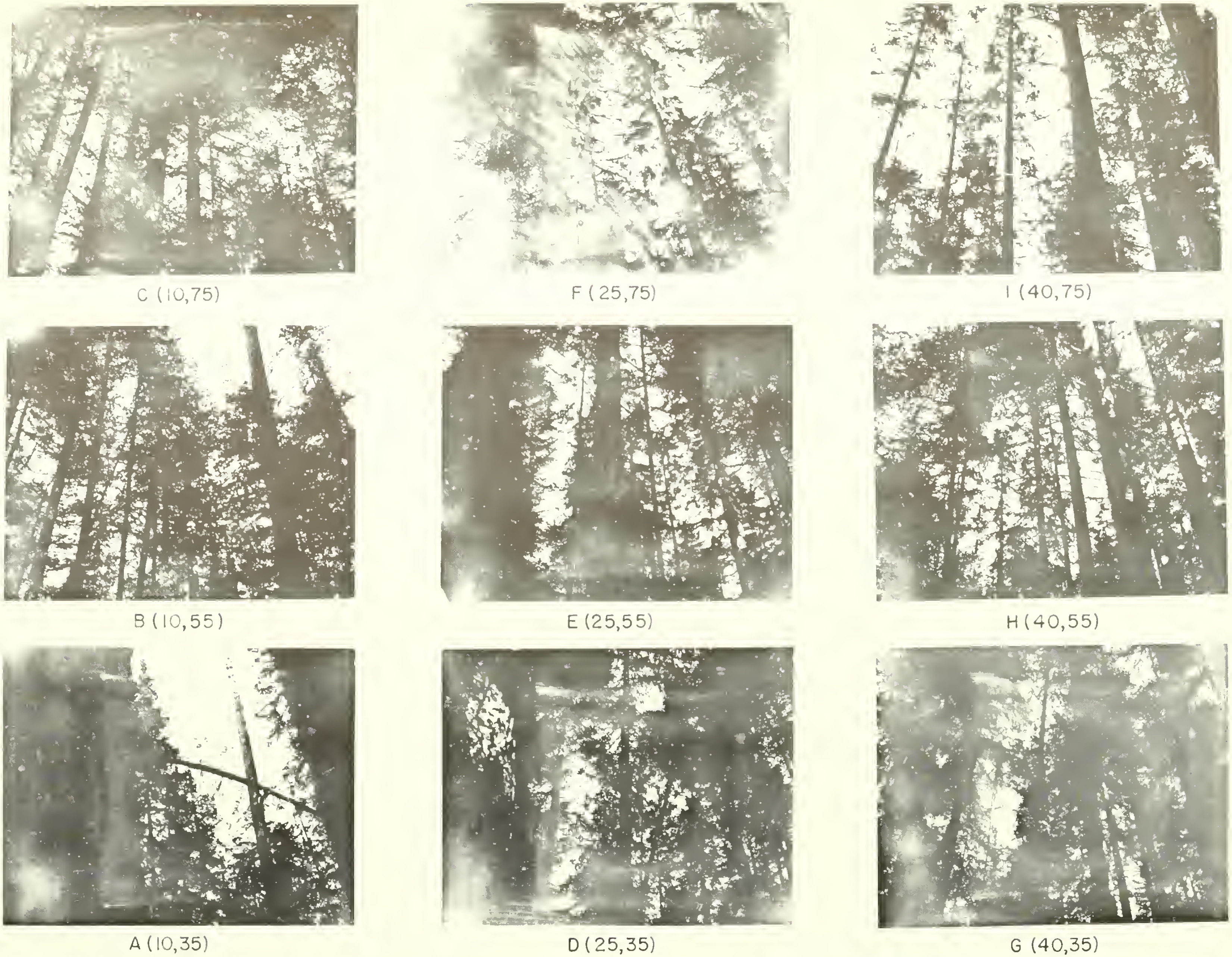


Figure 25. — Photograph of general canopy character of 45° plot from evenly spaced plot locations. Numbers in parentheses refer to plot location abscissa and ordinate associated with figures 22 and 23.

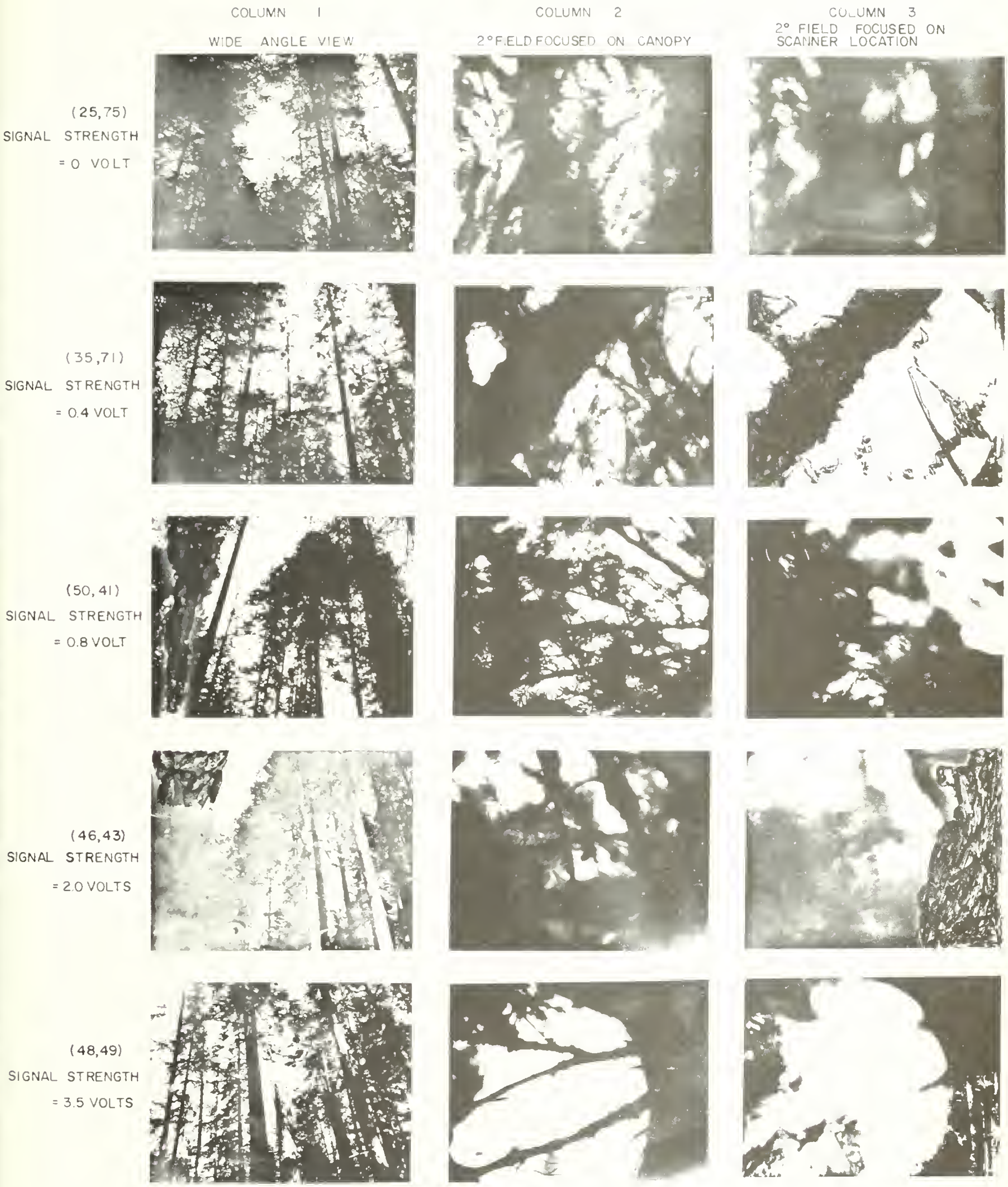


Figure 26. — Photograph of selected plot locations showing canopy characteristics associated with several values of signal strength.

quency of occurrence, and (2) the dispersion of trees throughout the timber stand.

It is inferred from these examinations that (1) a significant number of detections was accomplished with canopy obscurations as great as 90 to 95 percent, (2) the smaller transmission holes are distributed at about 1-foot intervals, and (3) the sizes of the large obscured areas and relatively unobscured areas roughly span a small (1 to 3) number of individual tree crowns.

A detection probability (i.e., percent positive observations) was calculated for the respective 1-, 2-, 3-, and 5-square-foot sources for 45° plot as follows:

Fire size	Percent detection
(Square feet)	(Percent)
1	37
2	51
3	63
5	82

The signal profile of figure 23, demonstrates the inhomogeneous distribution of positive detection reports. The question arises: 'Is the test plot (45 by 50 feet) large enough to be considered representative of the timber stand? Starting arbitrarily at the center of the plot, several square areas of increasing size were considered. In each of these areas the percentage of positive signals was noted and graphed. Percent detection has not yet stabilized when the limits of the plot edge are reached (fig. 27). Consideration of tree-shape factors (i.e., projected crown height/width ratio) and distribution of trees indicates that the plot should be approximately twice as deep (90 to 100 feet) and that the present width (50 feet) is sufficient for representative sampling.

Detection Predictions at 45° For Spot Fire Models

The detailed signal-obscuration profile of the 45° plot (fig. 23) provided the opportunity to examine the probability of detecting different model spot fires. By superimposing a template of a model fire on the signal profile of figure 23, detection was predicted by observing signals falling within the model.

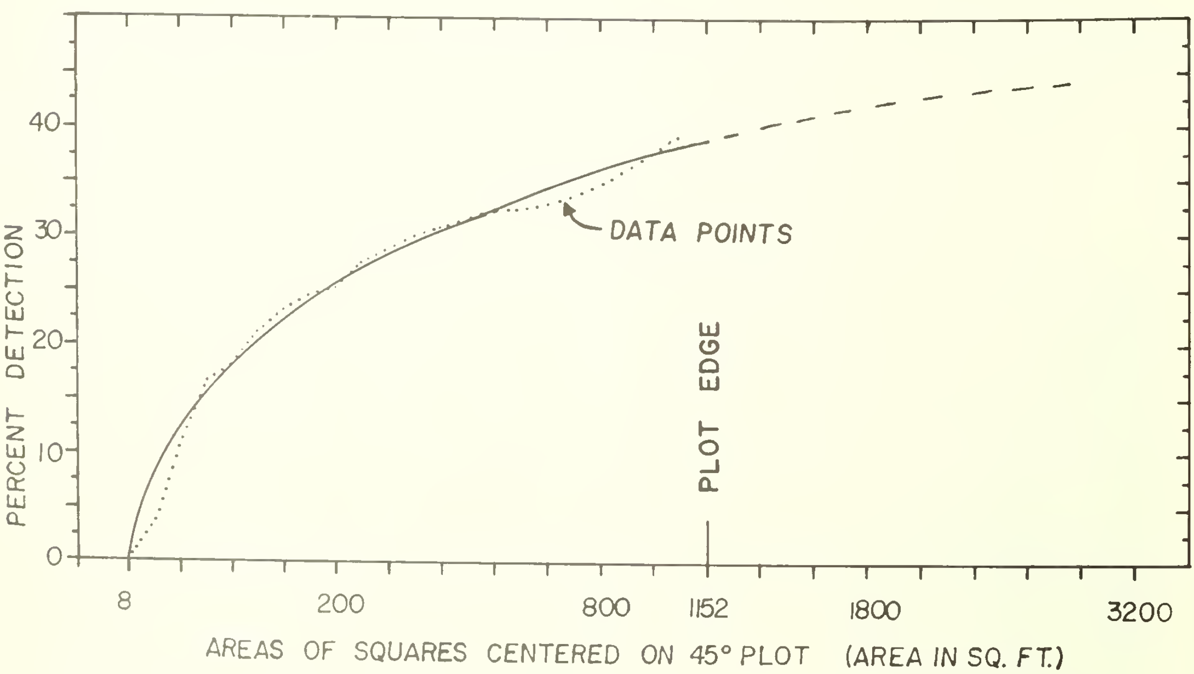


Figure 27. — Measured percent of positive detections as a function of increasing test plot size.

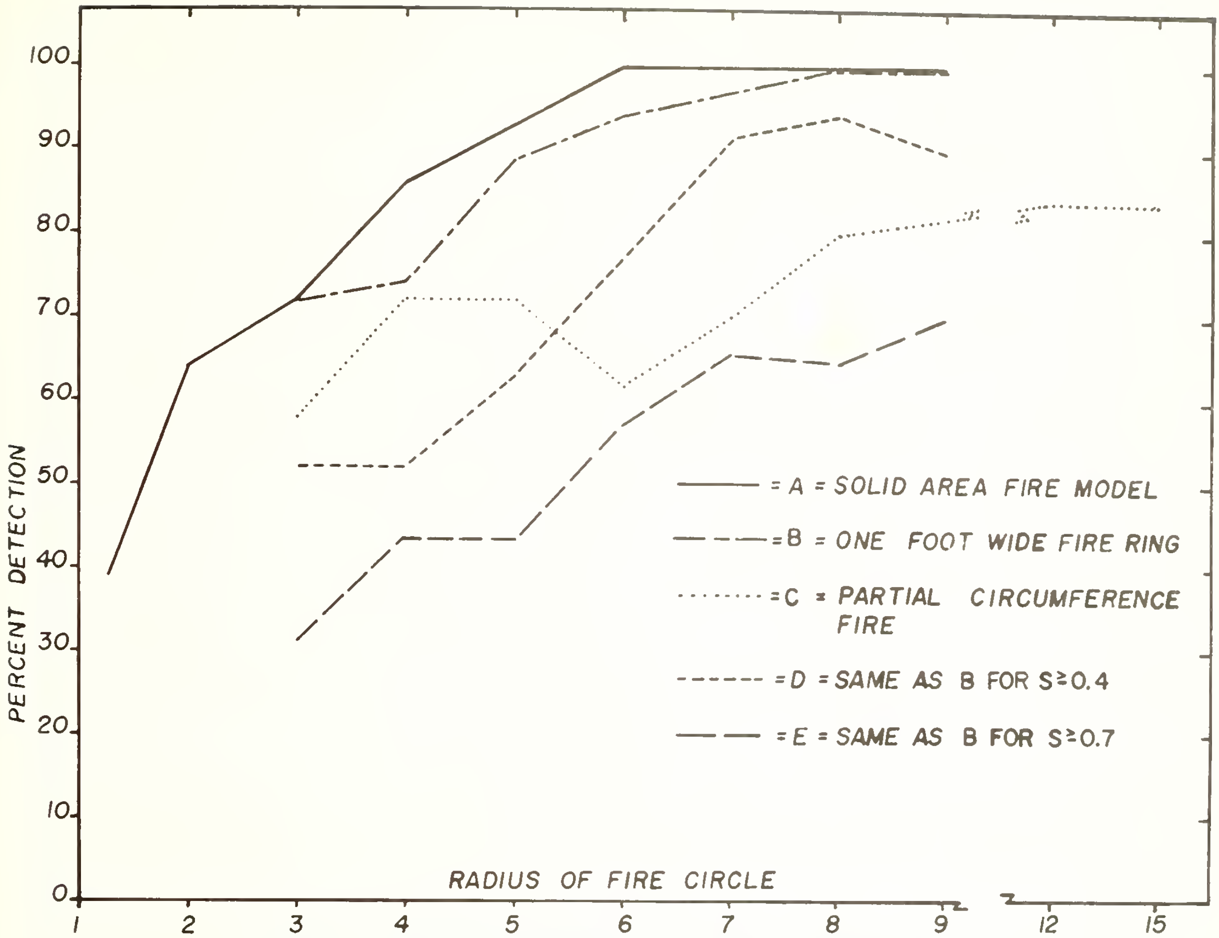


Figure 28. — Percent detection at 45° determined for three fire models as a function of model size and signal threshold.

Three fire model configurations were considered: (A) A solid burning circular area; (B) a 1-foot-wide circular burning ring; and (C) five 1-square-foot burning areas randomly spaced around a circle. The fire radius was varied for each model. Detection probability at 80 random plot locations for each configuration was evaluated as a function of "fire" radius. Positive detection was recorded when a positive scanner signal fell within the "burning" fire area. Results of this analysis are plotted in figure 28, curves A, B, and C. Also examined was the effect of increased detection signal threshold on the detection probability for the circular-ring fire (fig. 28, curves D and E). Qualitatively, these higher thresholds decreased the detection probability, as was expected.

The probability of detection does not increase significantly for fires larger than 9 feet in radius (fig. 28, curve C (the five-fire array)). This may indicate that 9 feet is the normal radius of influence of any tree or group of trees. This correlates nicely with inferences of the same effect observed from the flight data.

The distance to the nearest positive signal from each fire center was recorded (histogram, fig. 29). In no case was the fire center more than 5 feet from at least one positive signal. This indicates that a spot fire started anywhere under this canopy would become observable sometime before it had grown to a 5-foot radius.

Evaluation of the sum of signal intensities within each modeled burning area is usually a more reliable prediction of detection probability. These sums should then be examined with varying signal intensity detection thresh-

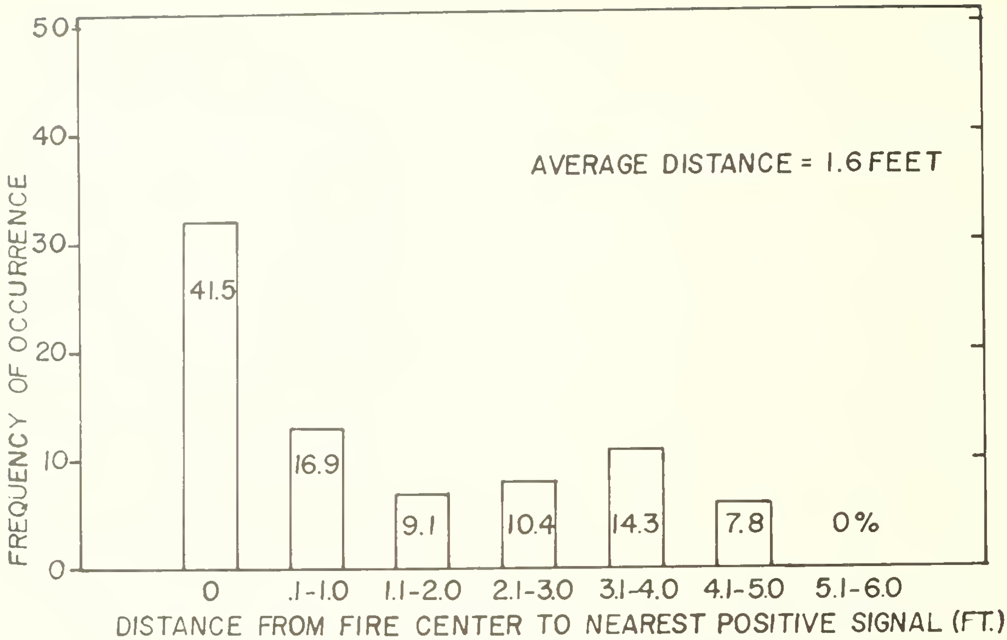


Figure 29. — Frequency distribution of distances from random locations to nearest positive detection.

olds. This evaluation will be one of the goals for experiment redesign. Accurate techniques for calibration and test area enlargement are required if the sampling is to be more representative of the timber stand.

Detection probability for the models is inherently low. The larger "burning" area of the models may have subtended several small transmission paths that would have added up to a positive detection report; however, these paths individually could have attenuated the 1-square-foot targets' transmitted intensity below the .1-volt detection threshold resulting in a negative detection prediction.

A rough evaluation was made to investigate the significance of integrating over several minute transmission paths. Although the radiation intensity from a single small transmission path may be below the level of detection threshold, the total radiation from several such paths may be great enough to give positive detection. While taking samples for fire model A (solid circular fire), each positive detection signal strength that fell within an individual "burning" area was recorded. Eighty random samples were taken of each fire size. The frequency of occurrence of signal strengths versus fire size is plotted in figure 30.

Several observations are worth noting. In each case, fewer than 1 percent of the signals were in the 2.5- to 3-volt interval. The percentage of signals stronger than 3 volts increases slowly with fire size. The distribution of small and intermediate signals tends to gather into fewer signal strength increments as fire size increases. And the mean signal strength of this group tends to larger values with larger fire size. From these observations we may conclude: (1) The total radiation from the smaller transmission paths (individually below system threshold) accounts for the dependence of detection probability on detection signal threshold, and (2) the smaller holes may be spatially distributed in a more homogeneous manner than the larger transmission paths.

Lack of adequate calibration and timber cruise measurements forces us to defer the rigorous statistical correlation of these parameters until more reliable data are produced.

Appendix V includes a brief discussion of theoretical approaches to timber canopy obscuration.

Detection Probability Beyond 45°

Measurements were made at 16 different angles beyond 45° vertical angle. The target

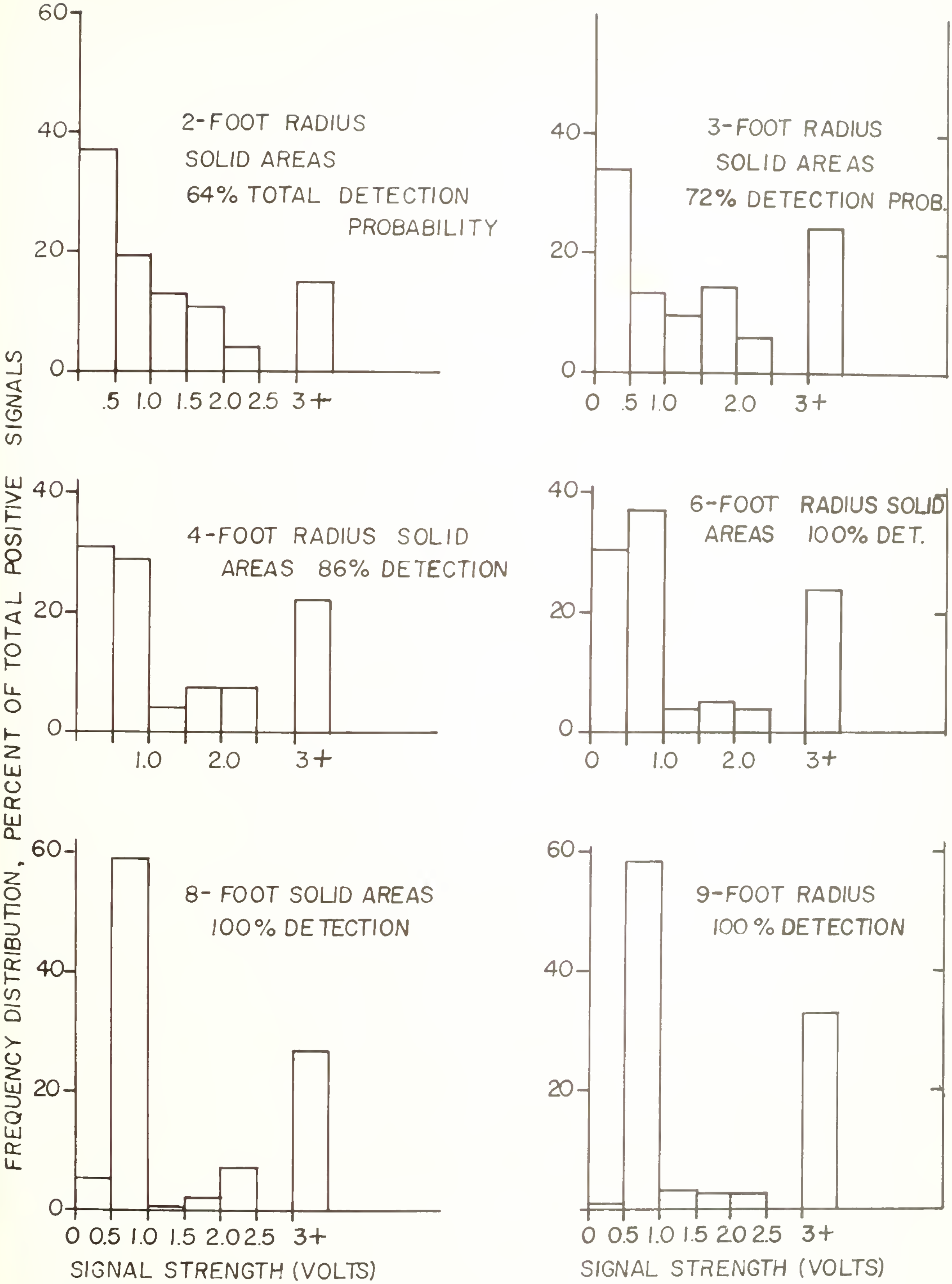


Figure 30. — Frequency distribution of signal strengths versus size of the solid fire model A.

array of five buckets on the 3-foot radius was used exclusively. A 1/16-square-foot signal bucket was used on each run for scanner orientation and calibration. Measurements of detection and signal strength were made at 50 random points along 100-foot lines at each scanner angle. Some of the gross variations may be explained by slope of terrain, species composition, and stand character, but it was not possible to normalize these data to obtain a smooth detection versus angle curve.

The angular dependence results are presented (fig. 31) as raw data; i.e., no attempt was made to normalize the individual points to average stand characteristics. At present we can only acknowledge that the points are very ragged.

After the detection data were taken, extensive timber cruise measurements were made on five representative lines. Stand density data were recorded adjacent to and in front of the five plots that showed the largest differences in percent detection. No correlations have been found between percent detection and any of the following: bole diameters, number of trees per acre, tree heights, basal area, crown weights, or arbitrary visual estimates of crown density. Two significant correlations were: (1) The greater the amount of larch or Douglas-fir present, the greater was percent detection, and (2) conversely, concentrations of Engelmann spruce, alpine fir, and grand fir tended to lower the detection probability.

The most prominent observable factors about the test lines were:

1. The 50° line had 10° favorable slope.
2. Measurements on the 61° line were

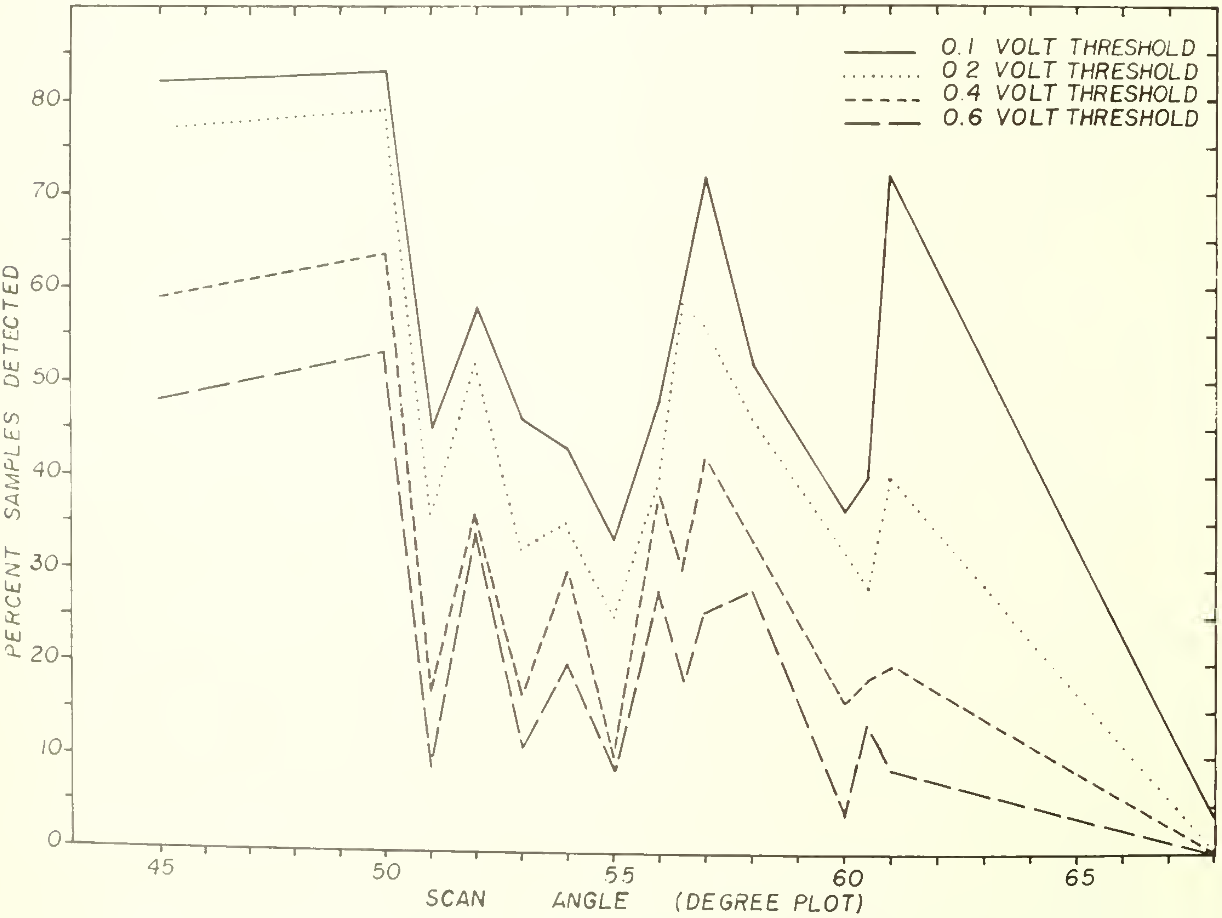


Figure 31. — Percent detection versus aspect angle for several detection signal thresholds.

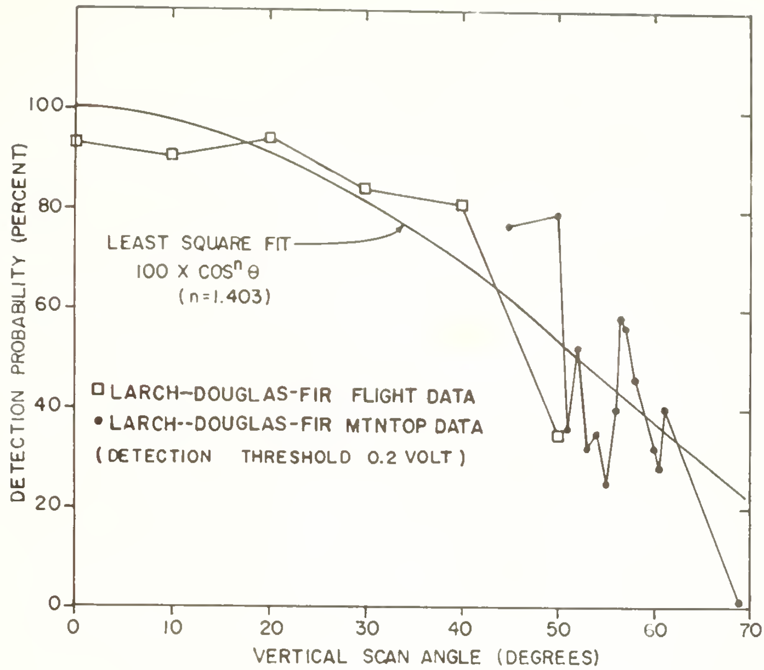


Figure 32.—Phase II, larch—Douglas-fir flight data to 50° extended past 60° by the mountaintop test data.

unique in that they were taken on a very windy night. Also, the timber was largely intolerant species (i.e., "easy site").

3. The 60° line was a short distance from the creek and had a dense understory of Pacific yew (*Taxus brevifolia* Nutt.) brush. Measurements made after this brush was removed increased detection from 10 to 36 percent.

4. Lines 60°, 60½°, and 61° were within a short distance of one another, progressing from wet ground near the creek toward a dry slope occupied by intolerant species.

However, foresters predicted that variation of detection probability would depend more on changes in angle around the 60° - 61° area than on differences in timber type. This is evidently not true. Most of the statistical ambiguities in the detection probability — timber cruise correlation can be attributed to inadequate sample size for the measurements.

In spite of the odd character of figure 31,

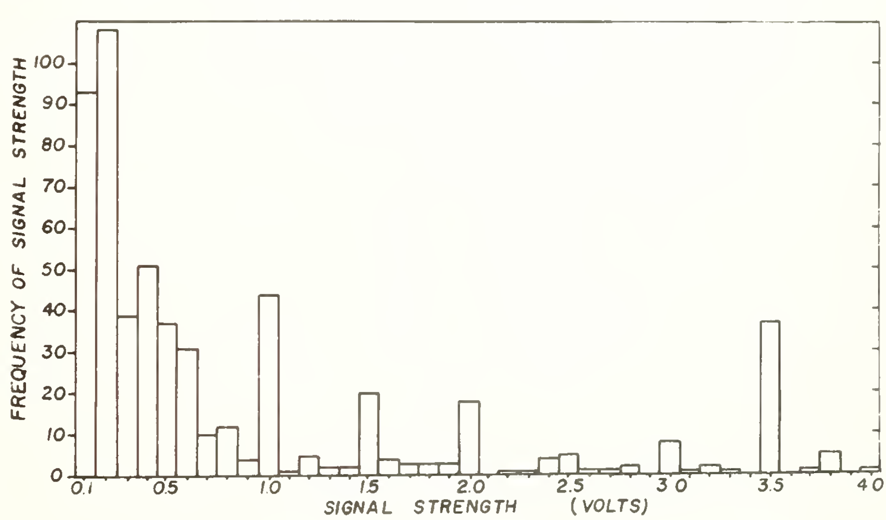


Figure 33.—Frequency of occurrence for all 5-square-foot target arrays, 45° to 69°, by signal strength.

there is no reason to expect that these measurements do not qualitatively describe the existing physical conditions.

To interpolate the detection probability versus aspect angle data between the one-look method of the flight program and the mountaintop test series, a detection criteria relationship between the two must be established. Targets observed on the flight imagery were detected when the target intensity exceeded the maximum background intensity. The criteria that mountaintop target signals must exceed the peak background signal (described in Appendix IV) established 0.2-volt as the appropriate detection threshold. When used as an extrapolation of the flight data (fig. 32), the mountaintop data look a little better.

Pursuant to geometric considerations discussed in Appendix IV, the best fit ($\cos^n\theta$) curve was adjusted to the data and statistically tested. The best fit, n = 1.40, gave an R.M.S. standard error of measurements of 13.3-percent error and an expected ±2.6-percent error at the 95-percent confidence level.

The frequency of occurrence of signal strengths for all data on the 3-foot-radius five fire arrays is shown in figure 33. It is interesting to note the test observer's personal preference for integral and half-integral voltage values. The relation between percent detection and mean signal strength at each of the test plots was examined with the Spearman Rank-Order (Rho) correlation coefficient, *r*. The resultant corrected correlation was $r = +.98$, or approximately a 1-to-1 relation between the two sets of measurements. This correlation is logical and has been assumed in the past; however, it had not been previously justified by rigorous argument.

The accumulative percent detection for successively larger detection signal thresholds is presented in table 4 for all data on 3-foot-radius fires, and in these angular increments: 45°, 50° to 54°, 55° to 59°, and 60° and greater. This was an attempt to smooth out the detection probability versus angle data and to examine the effects of higher detection threshold. The smoothing effect directly resulted from fewer but larger angle classes

Table 4. — **Percent detection for various signal level thresholds, at aspect angles 45° to 60°**

Detection signal threshold (Volts)	Aspect angle increment			
	45°	50° - 54°	55° - 59°	+60°
	Percent			
0.0	100	100	100	100
.1	82	55	53	40
.2	76	46	42	26
.3	60	35	34	16
.4	55	32	30	13
.5	49	25	26	9
1.0	43	24	21	6
1.5	28	12	11	1.5
2.0	23	9	7	1
2.5	22	6	4	
3.0	16	5.8	3	
3.5	14	5	2	

encompassing a greater number of measurement samples per class.

It appears, then, that about 300 to 500 individual measurements are necessary to establish a reliable detection probability in a given timber type at a given aspect angle.

Summary of Mountaintop Test Series

The original objectives of the mountaintop test have not yet been met. This test was planned as the first of a series of possibly two or three tests. The first effort was successful in that it yielded information about the relative value of several obscuration parameters.

Among the deficiencies are:

1. Sampling of percent detection versus angle was poor and inadequate. It is evident now that representative sampling will require test plots three to five times larger than those used. Up to 500 data samples per plot will be necessary.

2. The timber cruise measurements were inadequate for correlation with signal obscuration data.

3. Human bias in the recording of the data was obvious.

4. The limited dynamic range and nonlinearity of the electronic amplifiers introduced uncertainties into the data.

5. Calibration techniques were inadequate for reducing data to reliable absolute units.

The positive results of the test include:

1. The unique instrumentation requirements, logistics problems, and site preparation are now familiar.

2. The general trend of percent detection versus angle is established.

3. The cause and importance of the large number of very small signals have been identified.

The usefulness of five separate buckets in the standard test array has been questioned and discussed at length. The use of five separate sources in one target array does introduce N times the minimum acceptable number of unknowns in any detection probability equation; e.g., five separate measurements of a single bucket "should" more precisely measure detection probability. With a five-bucket array, one does not know which bucket is obscured and which is producing a positive detection signal.

Results of the first mountaintop effort should be regarded as inconclusive. However, these results will be reviewed continually as criteria for experimental design for the continuation of the program.

CONCLUSION

SUMMARY OF PHASES I, II, AND III

During the 3 years of the development and field evaluation of an infrared detection system, many limiting factors have been identified, equipment has been produced to overcome some of the limitations, and some data have been generated on which feasibility can be judged. Except in situations where the patrol area is small and well defined, the usefulness of daytime patrol is limited. The probability of detecting small fire targets as a function of flight pathwidth in four representative timber types is qualitatively defined. For detection purposes the four species tested are in two classes as follows: (1) "easy" detection class, including larch—Douglas-fir, lodgepole pine, and ponderosa pine; and (2) "difficult" detection class, Engelmann spruce.

Operational feasibility of an infrared fire patrol system ultimately is judged on its capability for detection under various measurable conditions of forest and terrain. Instrumentation used to measure any phenomenon must have sufficient sensitivity. A state-of-the-art system is necessary in order that the effects of silva and topology on detection can be determined. The scanning system now in use is not adequate for this purpose. More sophisticated discrimination techniques are needed if the low-intensity signals from timber-obscured targets at angles beyond 50° are to be detected reliably.

Comparison of high altitude imagery with aerial photographs appears to give accurate description of fire location. The Convair T-29 aircraft, equipped with the Doppler radar navigation system, has the capability to follow patrol corridors accurately during nighttime detection flights. The moving window display provides immediate readout of information with high resolution.

The research capability developed during this period undoubtedly will prove to be the most significant contribution toward the operational development of the airborne infrared detection system. The project now has a staff experienced in infrared techniques and qualified to develop and test a superior system.

PLANS FOR THE FUTURE

Design criteria based on detection criteria discussed in Appendixes III and IV have been written for the construction of an infrared receiver and electronic video system to meet the specific requirements of the Fire Scan research program. This system will include a seven-channel tape recorder. A taped video record of detection experiments will allow signal strengths, background temperature difference, and background frequency characteristics to be examined in the laboratory. These are needed to adequately quantify the system's capability.

The 1965 flight program will evaluate this state-of-the-art scanning system. Prior to the test program, the Convair T-29 aircraft will undergo an IRAN inspection and the Doppler system will be inspected and repaired. Experiment design and acquiring adequate instrumentation will be emphasized.

APPENDIX

APPENDIX I

DESCRIPTION OF TEST AREA

Lodgepole Pine Test Area

1. *Test area designation and location.* — The area, within a very dense lodgepole pine stand, is located on the east side of Gold Creek approximately 6¼ miles north of State Highway 20. This area is on the Missoula Ranger District, Lolo National Forest. Legal description is S½SW¼ sec. 6, N½NW¼ sec. 7, T. 14 N., R. 16 W., PMM.

2. *Elevation and topography.*—The area, situated on a bench with low ridges and minor draws, has an elevation of 4,200 feet m.s.l. A marsh is on the east side toward the northern extremity. No slopes on the area exceed 20 percent.

3. *Timber type and size class.* — Timber consists of a typical stand of stagnated lodgepole pine (*Pinus contorta* Dougl.). Some young ponderosa pine (*Pinus ponderosa* Laws.) sawtimber grows on the northeastern portion of the area. The larch (*Larix occidentalis* Nutt.) — Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco) timber type borders the south and east edges of the test area. Density of the lodgepole pine is fairly uniform throughout. Basal area on the plots ranges from 0 in small openings within the stand to 227 square feet per acre.

4. *Direction of flight paths.* — Flights over the area are due north and south; true azimuths, 0° to 180°.

5. *Cruise summary.* — Number of plots in area — 50; acreage of test area — 34.44 acres (1,000 feet by 1,500 feet); prism basal area factor — 20.

Ponderosa Pine Test Area

1. *Test area designation and location.* — The area, within a medium density ponderosa

Table 5. — **Cruise information from lodgepole pine test area**

Timber measurements	Test area: Lodgepole pine	Test area: Ponderosa pine	Test area: Average or total
Trees per acre	156	5.2	161.2
Net volume per acre (b.f.)[1]	8,730	320	9,050
Average basal area per tree (sq. ft.)	.57	1.02	.795
Average d.b.h. (inches), weighted	10	14	10.1
Average tree height (feet), weighted	62	53	61.7
Average lower crown limit, both species in mixed stand[1] (feet)	—	—	28
Average crown thickness (feet), both species	—	—	44
Cumulative stem density, d.b.h. X trees in each diameter class (inches)	—	—	2,662
Crown cover density (percent) as estimated by aerial photos over test fire areas	—	—	80

[1]*Scribner log rule was used for all merchantable volumes. Cruise includes all merchantable trees 8 inches d.b.h. and larger (by 2-inch classes).*

pine stand, is located on a bench south of the Big Blackfoot River, approximately 1 mile west of State Highway 20. The NE¼ sec. 35, T. 14 N., R. 15 W., PMM, encompasses the area. This area is on the Lubrecht Experimental Forest, University of Montana.

2. *Elevation and topography.* — Elevation of the area is 3,650 feet m.s.l. Terrain is slightly rolling, with no slopes more than 10 percent.

3. *Timber type and size class.* — Timber on the area is a stand of residual ponderosa pine. Patches of stagnated pole stands are scattered throughout the area. Average height of dominant and codominant trees in the area of young, thrifty, mature timber is 58 feet, while 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 (slope with a north aspect) where it becomes intermingled with Douglas-fir. As the slope with a north aspect increases in gradient to 30 percent, the pine decreases to scattered clumps in a predominantly Douglas-fir stand. Basal area for plots ranged from 0 to 190 square feet per acre; the less dense plots were on the north side of the area. Average basal area for the overall test area was 73 square feet per acre.

4. *Direction of flight paths.* — Flight paths run due east and west; true azimuths, 90° and 270°.

5. *Cruise summary.* — Number of plots in test area — 70; acreage within area — 34.44 acres; prism basal area factor — 10.

Larch — Douglas-Fir Test Area

1. *Test area designation and location.* — The area, located within a medium density

Table 6. — Cruise information from ponderosa pine test area

Timber measurements	Test area: Ponderosa pine	Larch - Douglas-fir	Average or total
Trees per acre	67	0.1	67.1
Net volume per acre (b.f.)[1]	5,316	13	5,330
Average basal area per tree (sq. ft.)	1.14	1.06	1.13
Average d.b.h. (inches), weighted	14.5	14	14.5
Average tree height (feet), weighted	58	60	58.1
Average lower crown limit, both species in mixed stand (feet)	—	—	18
Average crown thickness (feet), 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 d.b.h. and larger (by 2-inch classes).*

larch—Douglas-fir stand, is approximately 1¼ miles east of State Highway 31, and 1½ miles north of Pierce Lake. This area is on the Condon Ranger District, Flathead National Forest. An approximate legal description is: NE¼ or SW¼ sec. 10, T. 19 N., R. 16 W., PMM.

2. *Elevation and topography.* — Elevation of the area is 4,500 feet m.s.l. Terrain is moderately rolling slopes.

3. *Timber type and size class.* — Timber on the area is old-growth Douglas-fir and larch. The sparse reproduction is predominantly Douglas-fir, an average of 40 feet high and almost 100-percent total crown height. Density of the timber (stems per acre) is uniform over the entire area, varying only in species composition. Basal area for the 50 plots ranged from 20 square feet to 260 square feet; average overall basal area was 149 square feet per acre.

4. *Direction of flight paths.* — Flight paths run north and south; true azimuths, 0° and 180°.

5. *Cruise summary.* — Number of plots on test area — 50; acreage of timber within area — 34.44 acres; prism basal area factor — 20.

Table 7. — **Cruise information from the larch - Douglas-fir test area**

Timber measurements	Test area				
	Douglas-fir	Lodgepole pine	Engelmann spruce - alpine fir	Larch	Average or total
Trees per acre	71.1	14.9	11.0	23.8	120.8
Net volume per acre (b.f.)[1]	8,168	1,316	1,800	5,639	16,923
Average basal area per tree (sq. ft.)	1.20	.69	1.25	1.73	1.21
Average d.b.h. (inches), weighted	15	11	15	17	14.9
Average tree height (feet), weighted	75	77	80	97	82
Average lower crown limit, all species in mixed stand (feet)	—	—	—	—	35
Average crown thickness (feet), 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 d.b.h. and larger (by 2-inch classes).*

Engelmann Spruce — Alpine Fir Test Area

1. *Test area designation and location.* — The area, within a heavy density Engelmann spruce—alpine fir stand, is located on a plateau about 2 miles southeast of Skookum Butte Lookout. This area is on the Powell Ranger District, Clearwater National Forest. Legal description of the area is the SW¼ sec. 7, T. 38 N., R. 22 W., BM.

2. *Elevation and topography.* — Elevation of the area is 5,800 feet m.s.l. Terrain is slightly rolling with no slopes more than 10 percent.

3. *Timber type and size class.* — Timber on the area consists of a stand of overmature Engelmann spruce with scattered grand fir and alpine fir in association. The average height of dominant and codominant trees in the area is 98 feet. Basal areas for the plots ranged from 120 to 360 square feet per acre, while the average basal area for the entire test area was 225 square feet per acre.

4. *Direction of flight paths.* — Flight paths run north and south; true azimuths, 0° and 180°.

5. *Cruise summary.* — Number of plots in test area — 50; acreage within area — 34.44 acres; prism basal area factor — 20.

Table 8. — Cruise information from the Engelmann spruce - alpine fir test area

Timber measurements	Test area				
	Larch - Douglas-fir	Grand fir	Alpine fir	Engelmann spruce	Average or total
Trees per acre	0.7	6.3	20.7	133.0	160
Net volume per acre (b.f.)[1]	63	1,621	3,841	35,864	41,208
Average basal area per tree (sq. ft.)	1.48	1.74	1.47	1.71	1.6
Average d.b.h. (inches), weighted	16.5	18	16.5	18	17.5
Average tree height (feet), weighted	48	83	82	88	86
Average lower crown limit (feet), all species in mixed stand	—	—	—	—	23
Average crown thickness (feet), 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 d.b.h. and larger (by 2-inch classes).*

APPENDIX II

CRITERIA FOR SPECTRAL RESPONSIVITY

Since the advent of solid state semiconductor technology, new devices have been developed that provide capabilities for measurement, at high speed and low intensity levels, of the low energy electromagnetic radiation associated with infrared (IR) wavelengths.

A review of typical sources of radiation and infrared detector responsivities is necessary to establish criteria for system design pertinent to our special applications.

Of immediate interest to the Forest Service is the application of techniques of infrared remote sensing to forest fire surveillance. Here three possible sources of infrared radiation exist — the radiant emission of the fire itself, the emission from terrain background, and the interference of illumination from sources such as the sun.

The spectral radiant emission of real world emitters is measured by their deviation from a theoretically defined ideal black body radiation source. The emissive powers at several black body source temperatures are shown in figure 34. Glowing, burning fuels associated with applications in forest fire surveillance closely approximate the ideal black body radiation curves. In the 3- to 6-micron region, typical terrain background emitters may fall 15- to 20-percent below the theoretical curves, but generally stay within 90 percent of the emission expected from a true black body.[10] Also shown is the spectral irradiance of the sun[11] and rough indications of the transparent atmospheric windows.

[10] *Fredrickson, W. R., N. Ginsburg, and R. Paulson. Infrared spectral emissivity of terrain. Final Rep. Syracuse Univ. Res. Inst., ASTIA Doc. No. AD 155552, WADC - TR - 58 - 2229. 153 pp., illus. 1958.*

[11] *U.S. Air Force. Handbook of geophysics. Rev. ed. New York: Macmillan. 656 pp., illus. 1961.*

To facilitate system design, first the optimum spectral wavelength region is selected, and it in turn is dependent on the nature of the phenomenon to be observed.

Fire surveillance requires not only that burning fuels be detected, but also that their location relative to observable terrain background features be determined. Small spot fires are most easily detected in the spectral region where the fires are most intense (2 to 7 microns, fig. 34). Similarly, terrain background detail is best acquired near the peak of the ambient black body curve (5 to 20 microns).[12] Very little information is available concerning the reflectance of solar radiation from terrain in the intermediate and far infrared regions. The solar spectral irradiance for zero atmospheric absorption (fig. 34) can be used as an upper bound for the expected interference from sunlight. Both terrain reflectance and atmospheric absorption attenuate the reflected sunlight intensity. A spectral wavelength region should be selected as far from the solar irradiance peak as practicable; in this application, this must be to the longer wavelength side. Also very significant, the spectral bandpass must overlap an atmospheric transmission window.

In general, the following qualitative deductions can be made:

1. Thermal emissive temperatures of terrain background can best be measured in the 8- to 14-micron atmospheric window; however, significant information can be acquired in the 3- to 4.2-micron and 4.5- to 5.3-micron windows.
2. Glowing fuel beds can be detected best against a terrain background in the 2- to 2.6-micron, 3- to 4.2-micron, and 4.5- to 5.3-micron windows.
3. For daytime fire detection, the 2- to 2.6-micron band, and possibly the lower part

[12] *U.S. Air Force Cambridge Res. Lab. (Max Nagel, ed.). Background measurements during the infrared measuring program, 1956. Geophysics Res. Dir., ORD Res. Note 46, AFCRL - TN - 60 - 692.*

of the 3- to 4.2-micron band, must be rejected because of reflected solar irradiance.

Considering the above deductions, the use of the 3- to 4.2-micron and preferably the 4.5- to 5.3-micron bands is justified. The Fire Scan program has confirmed these observations in practice; hence, further rigorous theoretical treatment is not now necessary.

A cursory examination of sensitivity parameters of available infrared detectors shows that photoconductive and photovoltaic indium antimonide (InSb) detectors have the most outstanding characteristics in the spectral range of interest to this test. These devices are photoelectric transducers, which supply the electric signal to the electronic video chain. Within their proper dynamic range, the electrical output signal is proportional to the infrared radiant intensity measured in the focal plane of appropriate optical collectors.

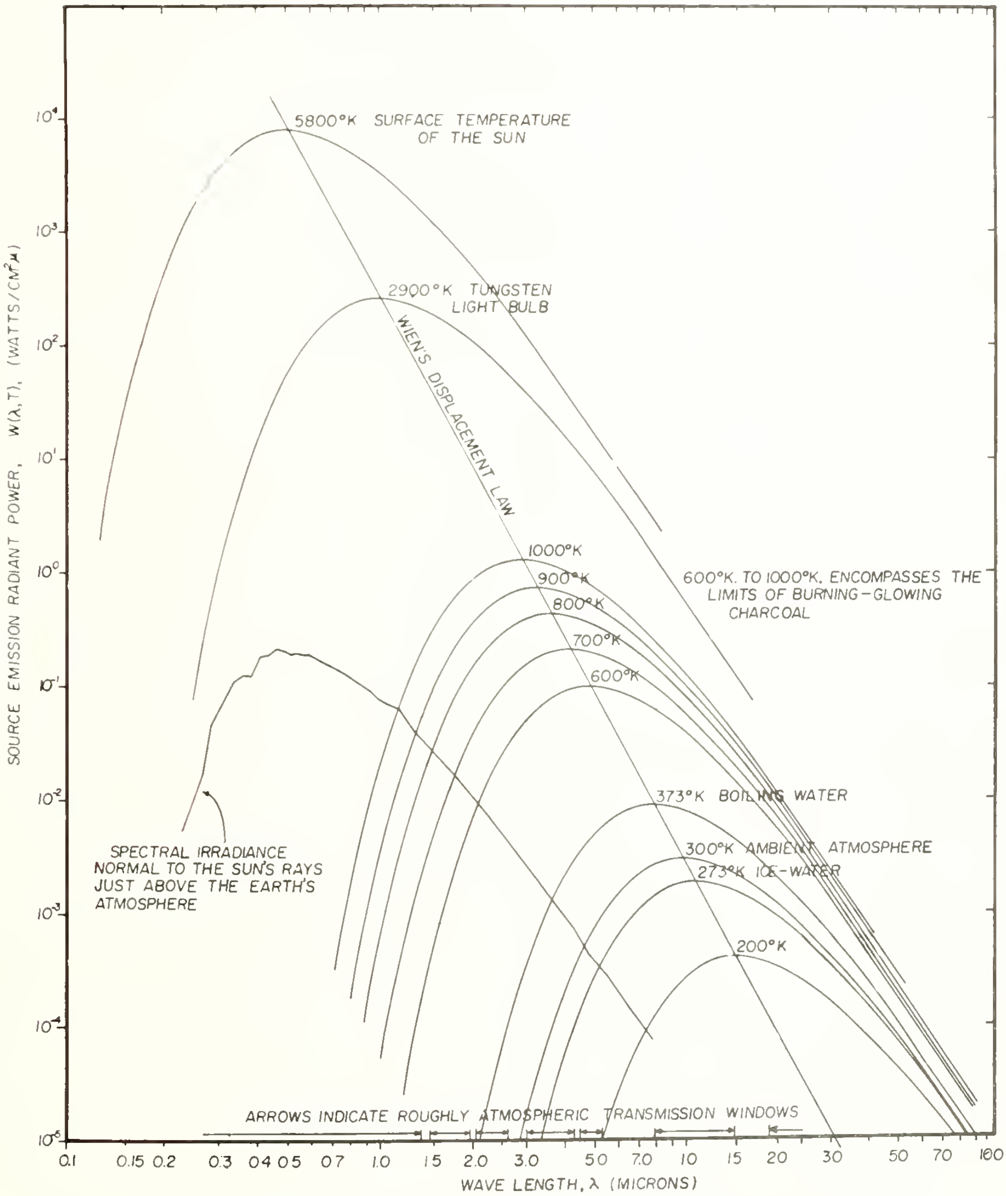


Figure 34. — Absolute spectral emissive powers for black bodies at various temperatures.

APPENDIX III

SENSITIVITY OF SCANNING SYSTEM

Remote sensing devices usually collect radiation with modified Newtonian or Cassigrainian telescopic systems. The detectors measure the total radiation falling on them at some point in the optical image plane. To compare the large number of individual points over an extended terrain object plane and thus provide the relative spatial information, an optical-mechanical scanning mechanism must be provided. This is accomplished by placing a spinning, flat mirror in front of the collector objective. On an aircraft platform, the infrared optical receiver is oriented so that the spinning mirror looks down and scans abeam of the aircraft from one side to the other. The velocity of the aircraft allows TV-like scanning of the two-dimensional object plane (see fig. 35, Appendix IV, scanning instrumentation and geometry).

The radiant power, E, reaching the detector is the product of the power density, $\frac{1}{\pi} W(\lambda,T)$, from the source; the solid angle, ω, subtended by the source from the receiver; and the area, A, of the optical collector objective:

$$E = \frac{1}{\pi} W(\lambda,T) \cdot A \cdot \omega$$

For easy calculation, the Stephan-Boltzman equation is used to estimate $W(\lambda,T)$ for total output power of the source. Then, the power, E, is modified by some constant, k, which is the fraction of the total power that is included by the system spectral sensitivity. Calculation of k is made by numerical integration over empirical measurements of the system spectral response (fig. 39, Appendix V).

The Stephan-Boltzman law states:

$$W = \varepsilon\sigma T^4$$

Where ε is the emissivity of the source, σ is the constant of proportionality, $\sigma = 5.67$ watts cm.$^{-2}$deg^{-4}, and T is the absolute temperature in degrees Kelvin. Then E becomes,

$$E = \frac{k}{\pi} A\omega\varepsilon\sigma T^4.$$

The term for temperature resolution in the limit of small temperature differences:

$$\Delta E = \frac{4k}{\pi} A\omega\varepsilon\sigma T^3 \, \Delta T.$$

Solving for ΔT,

$$\Delta T = \frac{\pi \Delta E}{4A\omega\varepsilon k\sigma T^3} \qquad \text{Eqn. 1}$$

The infrared detector detectivities, D^*, are defined by

$$D^* = \frac{S/N}{J} \sqrt{a\Delta f} \qquad \text{Eqn. 2}$$

where S/N is the signal to noise voltage ratio measured for a specific detector irradiated by power, J; a is the detector area; and Δf is the electrical frequency bandwidth used in the detectivity measurement.

By definition:

$$E = J, \text{ when } S/N = 1 \qquad \text{Eqn. 3}$$

Combining equations 1, 2, and 3 now redefines ΔT as the noise equivalent temperature (NET):

$$NET = \Delta T = \frac{\pi \sqrt{a\Delta f}}{4D^*A\,\omega\varepsilon k\sigma\,T^3} \qquad \text{Eqn. 4}$$

This equation is further refined by examining $\sqrt{a\Delta f}$ in terms of system parameters.

The area of the detector, a, defines the field of view or resolution element from optical principles as:

$$a = F^2\,\omega$$

where F is the focal length of the objective, which has area A.

Further, Δf is the rate at which the terrain field is covered, divided by the optical resolution element:

$$\Delta f = \frac{2\pi\ V/H\ \text{(steradians/sec.)}}{\omega\ \text{steradians}}$$

Then equation 4 becomes:

$$NET = \frac{F\left(\frac{\pi^3}{8} \cdot \frac{V}{H}\right)^{1/2}}{D^* k \, \varepsilon \sigma \, T^3 A \, \omega}$$

where:

F = focal length of collection optics.

V/H = velocity to height (altitude) ratio, to be specified by performance requirements (V/H of .2 or .4 steradian/sec. is typical).

D^* = broad band detectivity of detector; typically, 2×10^{10} watts^{-1}cm.sec.$^{-1/2}$.

$\varepsilon(\lambda)$ = spectral emissivity of background.

k = percent total spectral power of the source accepted by system, for parameters of figure 39, Appendix V; $k = 0.071$ when atmospheric spectral windows are accounted for.

σ = Stephan-Boltzman constant, 5.67×10^{-12} watts cm.$^{-2}$deg.$^{-4}$.

T = background average temperature, $°K$.

A = area of optical collector objective.

ω = optical system resolution, steradians.

Typical NET's are of the order of 1°K. to 2°K. for ambient terrain background with systems using the 3- to 6-micron spectral range.

APPENDIX IV

CRITERIA FOR DETECTION

The electrical signal (video) processing chain in infrared line scanners generally is not d.c. coupled. Hence, an absolute radiometric background intensity reference level is not maintained. However, the background radiation intensity does fluctuate about some local mean value. This mean intensity level shifts relative to the clamped output d.c. signal level over large terrain distances, but does not significantly change over small distances. A system's response to these gross changes is fixed by its scanning speed and low frequency cutoff. For the remainder of this section we shall assume the video system has sufficiently wide bandwidth to establish a short-term d.c. signal level associated with the local mean background radiant intensity.

This kind of equipment is sufficiently sensitive to map terrain background. Accurate detection of hot targets against a terrain background depends upon radiometric criteria.

Define the following terms:

T_0, T_1, T_2, T_3	Temperatures ($^\circ K.$) of local mean background, coolest point and warmest point in background, and hot target, respectively.
$\omega = \delta^2$	Instantaneous field of view.
A	Area of target.
K	Target signal to background signal ratio (explicitly defined below).
$N(\lambda,T)$	Spectral radiance (watts/steradian cm.^{2} micron).
$W(\lambda,T) = \pi N(\lambda,T)$	Spectral radiant emittance (watts/cm.^{2} micron).
θ	Aspect angle (see fig. 35).
r	Slant range.
h	Altitude.
D	Total scan width.
$R(\lambda)$	Responsivity of scanning system (volts/watt, i.e., watts incident on unit square aperture of scanner).
S	Scanner output signal (volts).
a	Area of scanner aperture.

The signal from the system is related to source radiation by:

$$S(T) = a\omega \int_0^\infty R(\lambda)\, N(\lambda,T)\, d\lambda.$$

Since $R(\lambda)$ is not an analytic function, this calculation is made by numerical methods, e.g.:

$$S(T_i) = \sum_j a\omega R(\lambda_j)\, N(\lambda_j,T_i)\ \Delta\lambda_j.$$

Consider a target much smaller than the instantaneous field of view with no obstruction or attentuation in the optical path. Figure 36 is a typical scanner video output signal. S_0 is the clamped d.c. signal bias. Define S_1 and S_2 as signal levels from the coldest and warmest (T_1 and T_2) spots, respectively, in the neighborhood of the momentary field of view and S_3 as the signal from a particular field that contains a hot target to be detected. Let $(S-S_0)$ be the dynamic signal that is proportional to the variation of radiant intensity about the local mean radiant intensity,

$$\omega[N(\lambda,T) - N(\lambda,T_0)]\ \Delta\lambda.$$

Unless complex signal discrimination is used, in order for a small target to be "detectable" the signal from the spot, ω, containing the target must be greater by some factor, K, than the signal from the warmest spot in the background. From figure 36 this becomes:

$$S_3 - S_0 \geq K(S_2 - S_0). \qquad \text{Eqn. 5}$$

For targets much smaller than ω, the worst case, as shown in figure 36, occurs when the target is situated in the coolest spot in the background.

S_3 then becomes:

$$S_3 = \int_{\lambda=0}^{\infty} a\, R(\lambda) \left[\frac{A \cos\theta}{r^2} N(\lambda,T_3) + \left(\omega - \frac{A}{r^2}\right) N(\lambda,T_1) \right] d\lambda.$$

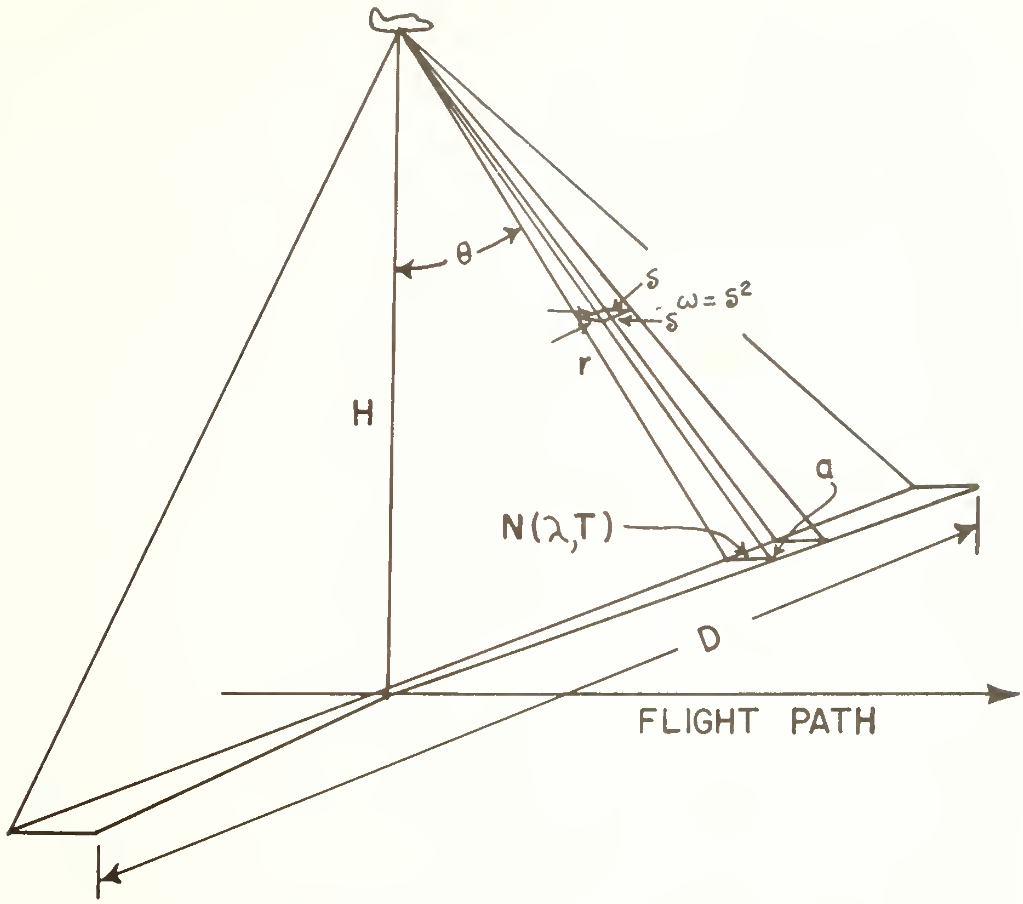


Figure 35. — Aircraft scanning geometry.

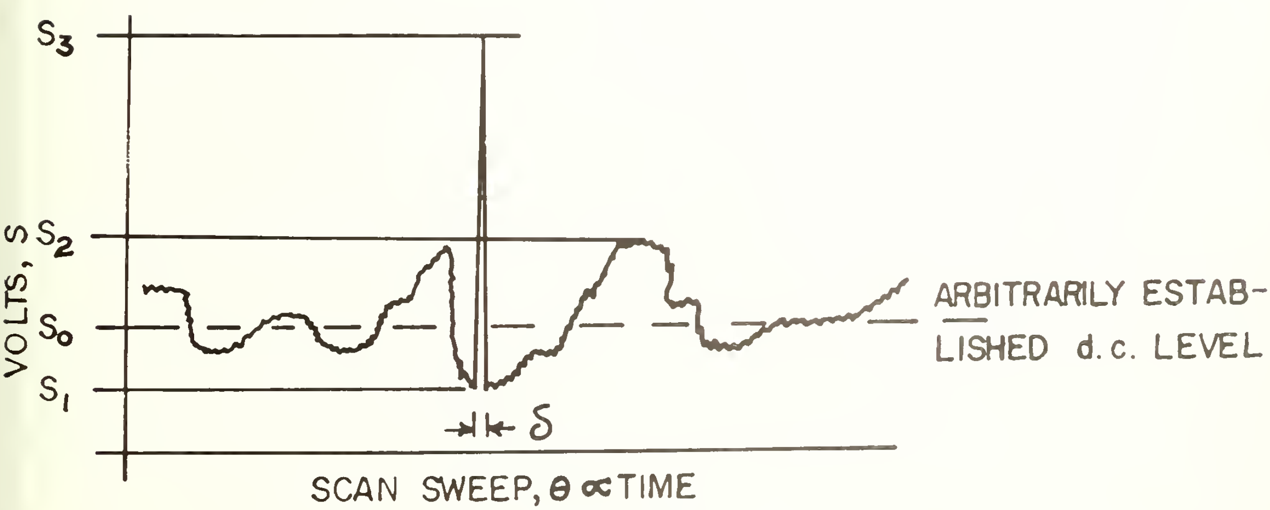


Figure 36. — Typical video signal oscilloscope trace.

Since T varies with θ, S_0 is determined by:

$$S_0 = \frac{a\omega}{\theta_2 - \theta_1} \int_{\lambda=0}^{\infty} R(\lambda) \int_{\theta_1}^{\theta_2} N(\lambda,T)\, d\theta d\lambda.$$

where θ_1 and θ_2 are defined such that:

$$(\theta_2 - \theta_1) \geq \frac{1}{f} \frac{d\theta}{dt}$$

where f is low frequency limit of system band-pass, and $\frac{d\theta}{dt}$ is the scanning speed. To be more precise, S_0 is determined by the preset system d.c. bias. This calculation determines the associated T_0 or $S(T_0)$ in the neighborhood of $\theta_1 < \theta < \theta_2$.

Define S_T as the signal from target alone and assume

$$\omega >> A/r^2.$$

Then:

$$S_3 = S_T + S_1.$$

Criteria for detection then becomes:

$$S_T \geq K(S_2 - S_0) + (S_0 + S_1) \qquad \text{Eqn. 6}$$

S_0, by definition, is the mean signal level, approximately one-half way between S_1 and S_2 (fig. 36).

Hence:

$$S_2 - S_0 \approx S_0 - S_1 \approx \frac{S_2 - S_1}{2}.$$

Thus, we can define a new K' greater than 1 such that Eqn. 6 becomes:

$$S_T \geq K'\left(\frac{S_2 - S_1}{2}\right) + \left(\frac{S_2 - S_1}{2}\right)$$

or

$$S_T \geq (K' + 1)\left(\frac{S_2 - S_1}{2}\right) \qquad \text{Eqn. 7}$$

$$S_T = a\,R(\lambda)\, \frac{A \operatorname{Cos}\theta}{r^2} N(\lambda,T_3) \geq (K'+1) \frac{a\,R(\lambda)}{2} \omega[N(\lambda,T_2) - N(\lambda,T_1)]$$

$$\frac{A \operatorname{Cos}\theta\, N(\lambda,T_3)}{r^2} \geq (K'+1) \frac{\omega}{2} [N(\lambda,T_2) - N(\lambda,T_1)]$$

$$\frac{A}{r^2} \geq \frac{(K'+1)}{\operatorname{Cos}\theta} \frac{\omega}{2} \left(\frac{N(\lambda,T_2) - N(\lambda,T_1)}{N(\lambda,T_3)}\right) \text{Eqn. 8}$$

A note should be made here about instrumentation. The system readout has been assumed to be a signal display (fig. 36) presented by a C.R.T. Large or very intense target sources give adequate signatures for detection. The marginal sources are the ones of concern and are usually much smaller than the instantaneous field, ω.

Electronic detection by pulse-height discrimination (P.H.D.) is much more precise than visual interpretation. The upper trace of figure 37 shows the capability of a typical narrow-band, pulse-height discriminator to distinguish a low amplitude "spike" target signal from large variations in the background intensity as is shown in the lower trace of the same figure. Since the small targets are the major problem, we suppose that the P.H.D. should be narrow banded about the field sampling frequency, f, such that:

$$f = \frac{1}{\delta} \frac{d\theta}{dt}$$

With the narrow-band provision, the lower limit on S_T could be decreased since the ter-

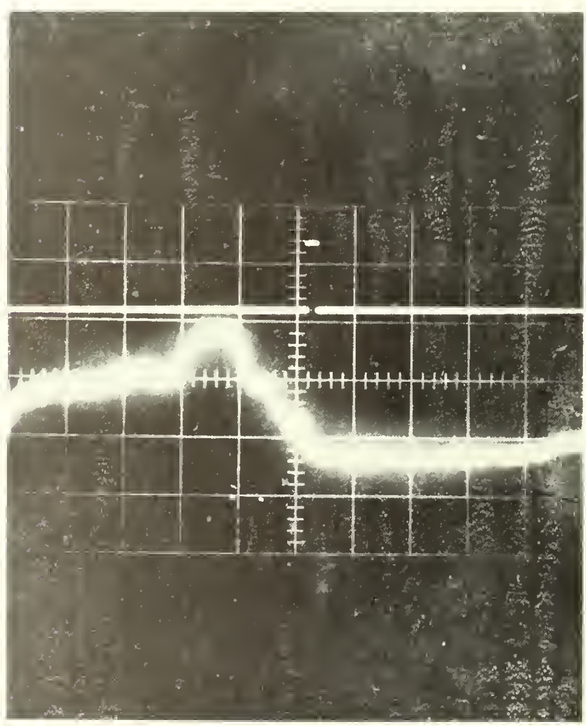


Figure 37. — Pulse-height discrimination circuit separating low amplitude, high frequency signal from background.

rain background features are generally much larger than the instantaneous field, δ^2. Detection of smaller values of S_T would, however, involve a significant increase in the false alarm rate. If a certain false alarm rate is not objectionable, the absolute lower limit of S_T is determined by the system noise level, n_s.

$$S_T \geq n_s$$

and

$$\frac{a\, A \cos\theta\, N(\lambda,T_3)\, \Delta\lambda}{2\delta^2} \geq NET.$$

Note it is meaningless to talk in terms of K in this narrow-band limit since S_0, S_1, S_2, etc., are not established.

Referring again to Eqn. 8:

$$\frac{A}{r^2} \geq \frac{(K'+1)}{\cos\theta}\, \frac{\omega}{2}\left(\frac{N(\lambda,T_2) - N(\lambda,T_1)}{N(\lambda,T_3)}\right) \quad \text{Eqn. 8}$$

Let us assume that with appropriate instrumentation (P.H.D., etc.) we can reliably let $K' = 1$. Also, let $\theta = 0$, $T_3 = 800°K.$, $\omega = 10^{-6}$ steradians, and assume spectral bandwidth of 4.5 microns to 5.5 microns. Note that $h = r \cos\theta$, $W(\lambda,T) = \pi N(\lambda,T)$, and $\Delta W = (W(\lambda,T_2) - W(\lambda,T_1))$.

Then Eqn. 8 reduces to:

$$\frac{A}{h^2} \geq 10^{-6}\left(\frac{\Delta W}{0.33\ (\text{watts/cm.}^2)}\right) = 3 \times 10^{-6}\, \Delta W. \quad \text{Eqn. 9}$$

Figure 38 shows a plot of A/h^2 against $\Delta T = T_2 - T_1$ for background temperatures (T_1 and T_2) around 300° K. ambient. It assumes (1) the detection criteria of equation 7; (2) that optical transmission losses do not bury any signals in the system noise; and (3) there is no target obscuration and you are looking straight down into the bucket.

The angular dependence of A/h^2,

$$\left(\text{i.e., } \frac{A}{h^2} \propto \frac{1}{\cos^3\theta}, \text{ where } r = h/\cos\theta\right)$$

is a consequence of inverse square law and the Lambertian angular dependence on target radiant intensity. It is assumed here that the major terrain features are larger than the instantaneous field of view; hence, the terrain background signal is not attenuated by either of these features by the same factor as the small fire targets. When the target becomes larger than the instantaneous field of view, the angular dependence of detection criteria disappears and A/h^2 is independent of θ.

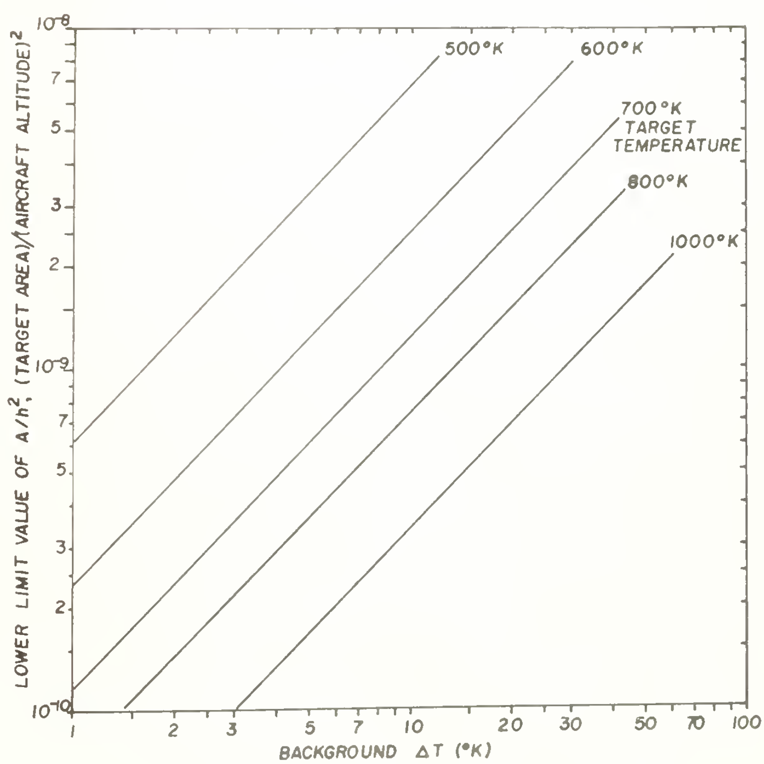


Figure 38.—Lower limit values of (target area)/(aircraft altitude)² ratio as function of peak-to-peak background temperature variation for several target temperatures, assuming detection criteria of Eqn. 7 in the text.

APPENDIX V

ATTENUATION OF RADIATION

The radiation that reaches an airborne infrared scanner from a small incipient spot fire must traverse several attenuating media before it reaches the infrared detector. These media are of three basic types: (1) The geometric obscuration by tree boles, timber canopy, understory, and brush; (2) the atmospheric path consisting of molecular absorption mainly by H_2O and CO_2 and scattering by haze (smog, fog, smoke); and (3) the transmission character of the infrared receiver optics. The latter two media are spectrally dependent; we are discussing them in reverse order.

Infrared Receiver Transmission

The scanning mode is most easily accomplished by a rotating 45° mirror (high speed, nodding optical systems have prohibitive inertia).

The objective element also should be a mirror. Mirror objectives have only one optical surface to figure, have adequate resolution over small fields, and have no chromatic aberrations. However, these mirror objectives usually require at least one secondary folding mirror. Infrared lenses in general have good resolution over a larger field, but have very high reflection and transmission losses. Correction of chromatic aberration requires at least two elements; this requires the figuring of at least four optical surfaces. The relatively large apertures required make lenses both economically and technically prohibitive for the present application.

Mirrors are not perfect reflectors. A typical aluminized mirror has a reflectivity, $R =$ .92 at 4 microns; silver and gold have higher reflectivities but are not as durable as an aluminized mirror. Hence, we can consider the optical transmission, T_{op}, of an aluminized mirror collecting system as:

1. A three-surface system:
   $T_{op} = (.92)^3 = .78$

2. A four-surface system:
   $T_{op} = (.92)^4 = .716$

The sensitivity of the infrared receiver is also governed by the spectral response of the detector and the spectral bandpass of the optical filter, if one is used. These are not conducive to analytic representation and, hence, must be handled by graphic or numerical integration. Typical detector and filter spectral curves are shown in figure 39.

Atmospheric absorption is a major concern in fire detection. The scattering effects are easily described. Smog and smoke particles associated with forest fires are much smaller than the Rayleigh limit for 3-micron radiation; so they are negligible in the present application. Indeed, very good terrain imagery has been obtained through smoke palls 2,000 feet deep. However, water condensate associated with clouds and fog renders them totally opaque. Therefore, we may consider the "scattering" transmission either:

$$T_{scat} = \begin{cases} 1, & \text{(smoke, smog)} \\ 0, & \text{(fog, clouds).} \end{cases}$$

Transmission of the Atmosphere

The problem of molecular absorption is more complex. The spectral region of interest (3- to 6-micron) contains significant H_2O and CO_2 absorption bands. Figure 40[13] shows typical atmosphere transmission. Figures 41 and 42 (U.S. Air Force)[14] show, respectively, H_2O and CO_2 transmissions. Since H_2O and CO_2 concentrations vary independently in the real world, they are handled analytically by separate absorption coefficients. CO_2 concentration is sufficiently stable in time that we consider only its variation with altitude (fig. 43). H_2O concentrations can be meas-

[13] *Yates, H. W. and J. H. Taylor. Infrared transmission of the atmosphere. U.S. Naval Res. Lab. Rpt. 5453. 1960.*

[14] *U.S. Air Force.* Op. cit.

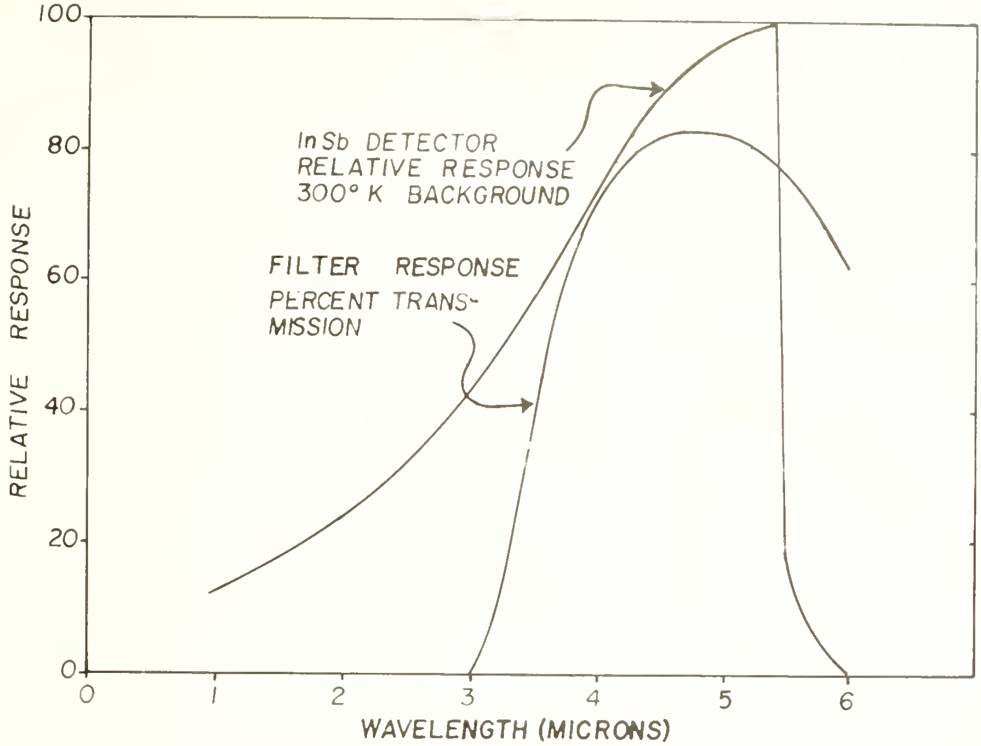


Figure 39. — Spectral characteristics of a typical detector and filter.

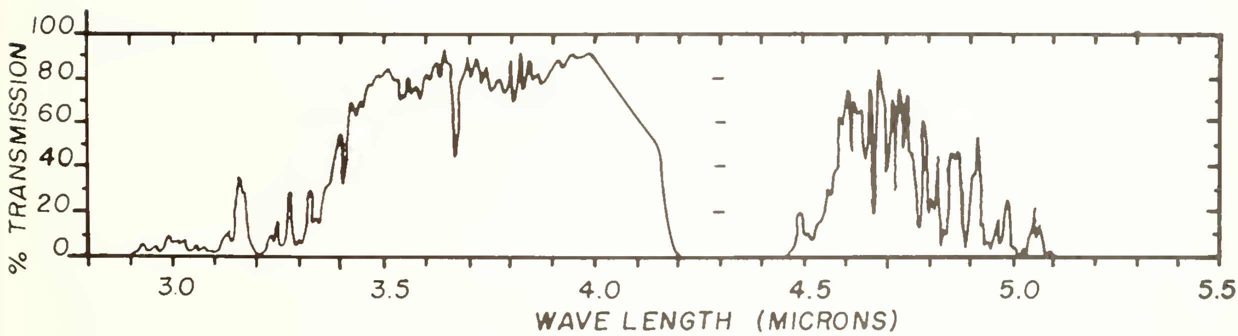


Figure 40. — Typical atmospheric transmission curve; 16.25 km. sea level path, 68.7° F., 53-percent relative humidity, 15.1 cm. H_2O in path.

ured by the relative humidity and dry bulb temperatures (fig. 44), and percent transmission estimated from figure 45. A cursory look at figures 44 and 45 proves that major changes in the minimum detectable signal level can be attributed to realistic variations of relative humidity.

Atmospheric transmission, particularly high H_2O concentration, is obviously one of the major parameters of significance to fire detection probabilities, and its effects should not be neglected.

Whenever possible, the practical procedure would be to use a known source, N_0 (λ,T) for system calibration.

If we have a linear system:

$$S = \frac{S_0}{N_0(\lambda,T)\ \Delta\lambda}\ N(\lambda,T)\ \Delta\lambda$$

Good practice requires calibration for several source intensities spread over the full dynamic range of the system.

Timber Canopy Obscurations

From the mountaintop test procedures described elsewhere in this report, qualitative conclusions were established concerning canopy obscuration factors. These may be separated into two types: first, the larger obscurations (almost always large tree boles), which

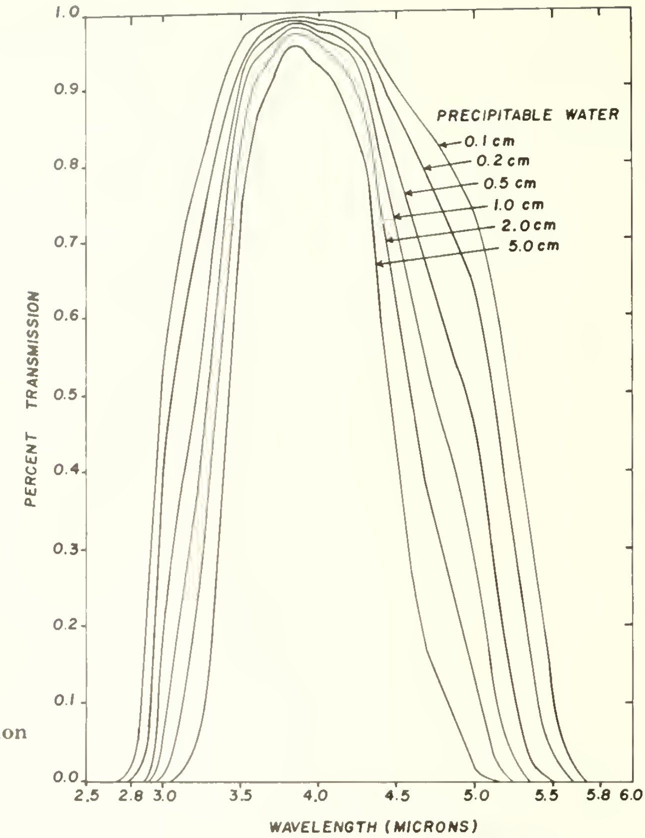


Figure 41.—Spectral transmission of water for various optical paths.

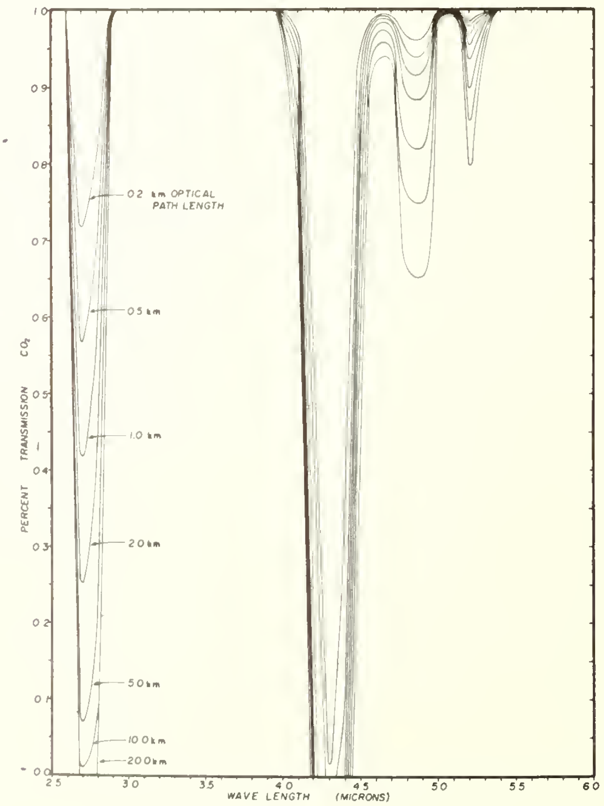


Figure 42.—Spectral transmission of CO_2 for various optical paths.

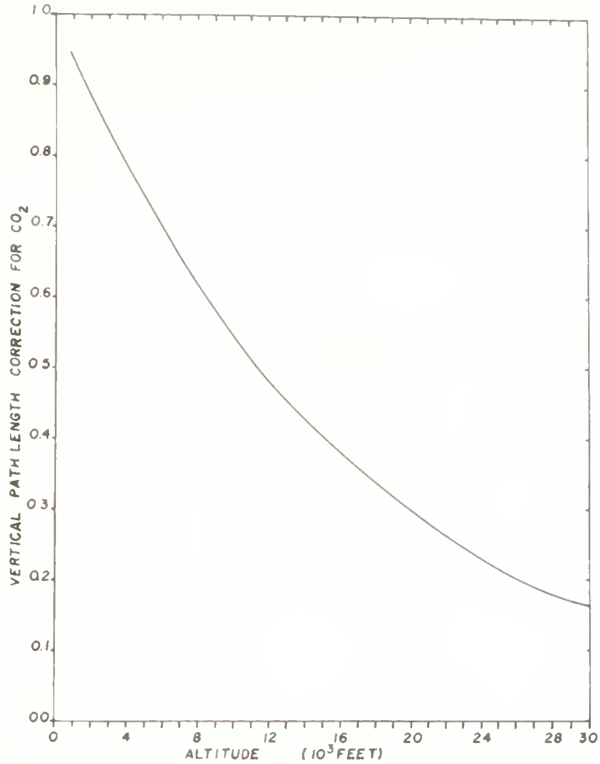


Figure 43.—Variation in atmospheric CO concentration with altitude normalized to sea level.

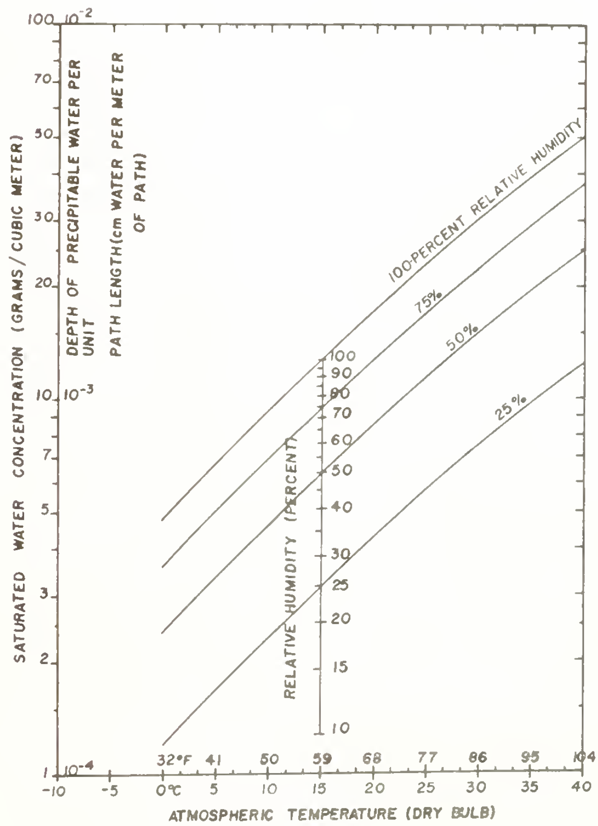


Figure 44.—Precipitable H O concentration as a function of atmospheric temperature and relative humidity.

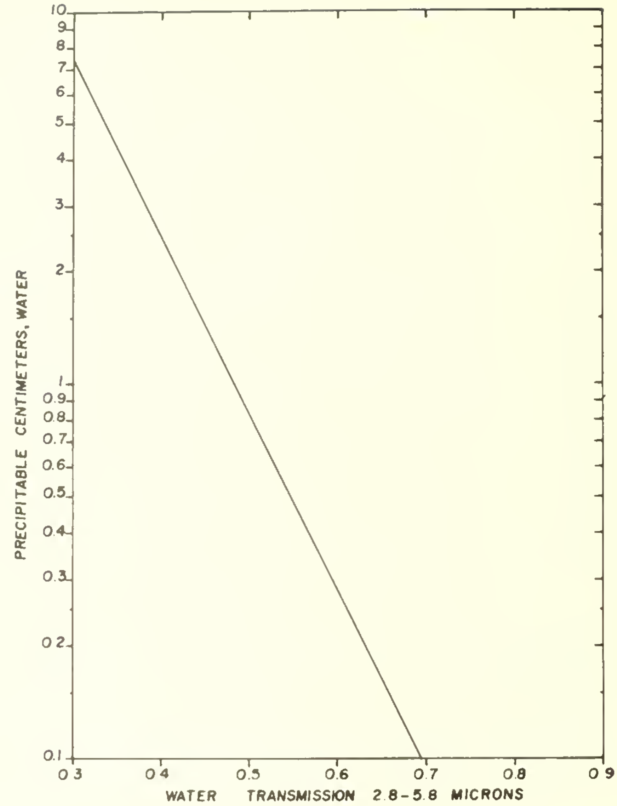


Figure 45.—Percent transmission of water in the 2.8-5.8-micron band versus concentration of precipitable water.

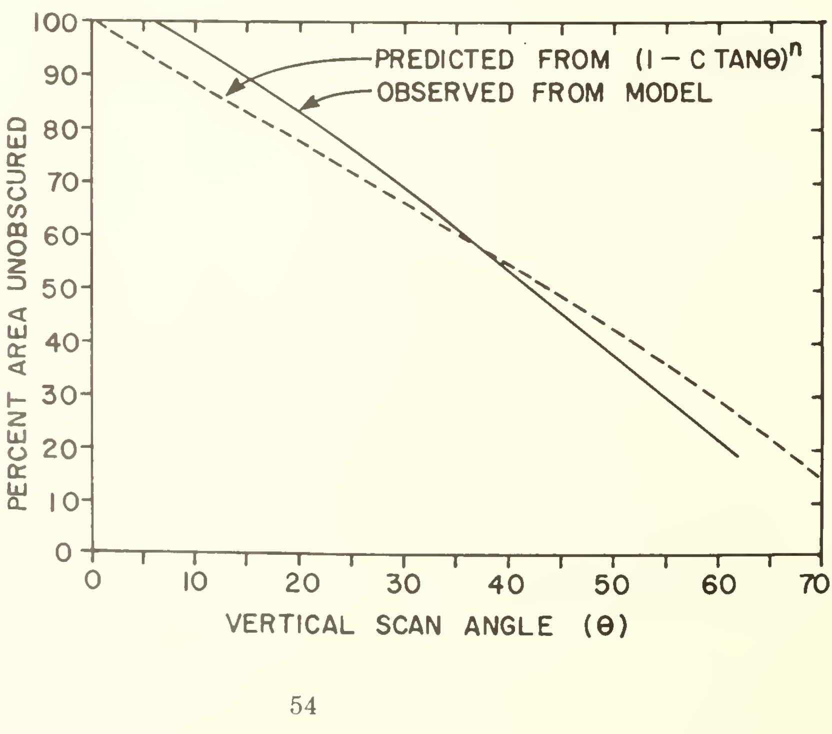


Figure 46.—Observed and predicted obscurations from a tree bole model.

totally obscured the targets; and, second, the small needle and limb obscurations, which only partially attenuated the target radiation.

A conifer tree bole can be approximated by an inverted parabaloid of revolution whose vertical cross sectional area is two-thirds its base diameter, *d* times its height *h*. The projected ground area obscured from an aspect angle, θ, is then:

$$\frac{2}{3} dh \operatorname{Tan} \theta$$

The percent unobscured area, $\emptyset_B$, for a random stand of such tree boles becomes:

$$\emptyset_B = \left(1 - \frac{2/3\, dh \operatorname{Tan} \theta}{43{,}500}\right)^n$$

where *d* and *h* are measurements in feet, and *n* is the number of trees per acre. We tested this bole obscuration by constructing a model of a random tree stand and correlating actual measurements on the model with the formula prediction; results are plotted in figure 46. The model had equivalent timber cruise parameters of 328 square feet per acre basal area, (d.b.h.) of 1-foot and 82.2-foot tree heights.

A similar effort to relate obscuration to timber cruise parameters for the canopy overstory is contemplated. Since correlation of this type of attenuation with present timber measurements is lacking, a test to check any theory is unavailable. However, by the nature and distribution of signal strengths from the mountaintop tests, the following theoretical attenuation model is contemplated for the tree crowns:

$$\emptyset_c = \emptyset_o e^{-\delta x}$$

where δ is related to crown characteristics and x is the optical path length, i.e.:

$$x = \frac{h}{\operatorname{Cos} \theta}$$

where h = crown depth, and θ = aspect angle as before. Further field measurements should provide data for correlation checks on these proposed relations.

The ultimate objective of these considerations is to provide field management personnel with a measure of the usefulness of remote sensing equipment in particular forested areas.

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3. ABSTRACT

The first 3 years of Project Fire Scan's airborne infrared fire detection program are reported. The program objective is the evaluation of systems and techniques for the detection of incipient forest fires. Qualitative correlations are presented of probability of detection versus scanner aspect angle, timber type, and fire target size. Aircraft patrol navigation requirements are briefly examined. A capability is demonstrated for precise observations of timber canopy obscurations from a fixed, ground platform. Appendixes include theoretical discussions of system spectral response, scanner sensitivity, source background radiometric detection criteria, and the several mechanisms of radiation attenuation.

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CONTENTS

INTRODUCTION

Prescribed fire has been used in the forests of the Intermountain West since 1910.[1] It is employed for site preparation for planting or seeding, hazard reduction, livestock range and wildlife habitat improvement, cover type conversion, and insect or disease control. The major advantage of fire for all these objectives is its low cost relative to mechanical or chemical treatments.

The use of fire is increasing rapidly as management of both private and public lands intensifies. In 1964, in Montana and northern Idaho alone, more than 25,000 acres of forest land were broadcast burned under controlled conditions. This was more than double the acreage burned in that area during 1959.

Prescribed burning is defined by the Society of American Foresters as:

> Skillful application of fire to natural fuels under conditions of weather, fuel moisture, soil moisture, etc., that will allow confinement of the fire to a predetermined area and at the same time will produce the intensity of heat and rate of spread required to accomplish certain planned benefits to one or more objectives of silviculture, wildlife management, grazing, hazard reduction, etc.[2]

Foresters new to the field require guidelines for prescribed burning. Men who have planned and administered controlled burns in the past are best current sources of such information. For this reason, 62 fire specialists from private, State, and Federal organizations were interviewed during the spring of 1965. The respondents had participated in a total of over 700 seasons of prescribed burning, mostly in the forests of the Intermountain West. The study area included the States of Idaho, Montana, Utah, western Wyoming, eastern Washington, and portions of Nevada.

The standard interview consisted of an introduction and explanation, a directed question-and-answer session, and planning hypothetical fires on topographic models. Each participant answered nearly 100 questions in the following subject areas: (1) preparations for burning, (2) scheduling the fire, and (3) ignition, control, and mopup. He designed firing plans for three hypothetical burning blocks.

Probably no opinion expressed in the following pages is the best ultimate answer to the problems of beneficial use of fire in the Intermountain West. The diversity of environmental conditions in such an area precludes any single solution. Many promising approaches to these problems have not yet been explored. In the past, prescribed burning has been done very conservatively. Until a more comprehensive background is established, it will be difficult to evaluate objectively the costs, results, or optimum procedures for prescribed fires.

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[1] *LeBarron, R. K. Silvicultural possibilities of fire in northeastern Washington. J. Forest. 55: 627-630. 1957.*

[2] *Society of American Foresters. Forestry terminology. Washington, D.C. 102 pp. 1958.*

INTERVIEW RESULTS

PREPARATIONS FOR BURNING

Prescribed fires require careful planning. The objective of a particular burn is the first consideration, and determines the procedures to be followed. Safety and effectiveness depend to a large extent upon block size, burn layout, and fireline placement. These and allied matters are discussed in the interview questions that relate to fire preparations.

Burning Objectives

Why burn? As mentioned previously, fire has a number of uses in the Intermountain West, including site preparation, hazard reduction, range improvement, and disease or insect control. Currently, the most important combined purpose of prescribed burning is to prepare sites for regeneration and reduce fire hazards in recently harvested stands of timber.

Each respondent was asked to describe a well-prepared seedbed or planting site after a burn. Nearly everyone felt that the fire should consume the duff mantle to the extent of exposing mineral soil on 50 percent or more of the area burned. Estimates on the minimum diameter of the roundwood that should remain after a fire ranged from 4 to 12 inches. Sixty-five percent of the respondents felt that a successful fire would consume all material up to about 6 inches in diameter.

Fine fuels, such as conifer needles and small twigs, create a high wildfire hazard on recently harvested blocks of forest land. Any prescribed fire, however light, that can be made to pass over such a block, effectively removes the danger caused by these fuels.

Burning to control diseases and insects or to improve livestock and wildlife range requires a variety of fire intensities. The organism or vegetative type to be treated determines the fire intensity needed. Fires used to control *Ribes* populations, for example, must be intense enough to kill existing wood stems and to stimulate germination of dormant seeds. However, the results of burning for the above management purposes are not yet as predictable as they are for site preparation and hazard reduction.

Broadcast Burning Versus Pile Burning

Depending upon terrain and silvicultural objectives, logging slash and noncommercial stems may be broadcast burned where felled, or piled before ignition.

Manpower or bulldozers are commonly used to concentrate fuels in piles or windrows in the Intermountain West. Hand labor is often employed for piling debris in thinned stands, recreation areas, and right-of-way clearings. Dozers are currently used to pile or windrow slash in some partially cut blocks and in clearcut blocks, diseased or insect-infested stands, and brushfields being converted to timber production. Bunching slash with bulldozers usually scarifies the site between the piles: mineral soil thus exposed provides a seedbed favorable to natural regeneration.

All of the men interviewed were experienced in burning piled fuels. Each respondent was asked to define the situations in which piled rather than broadcast fuels have been burned, and to give the reasons for this choice.

The pattern of responses showed that pile burning is more widely practiced in the southern and eastern reaches of the study area than in the northern and western: broadcast burning is not common in the ponderosa pine — Douglas-fir and lodgepole pine — spruce types of Utah, Wyoming, southern Idaho, and Montana east of the Continental Divide. Timber is usually harvested in small, clearcut blocks in these areas, and there has also been partial cutting in several stands. Pile burning is frequently preferable to broadcast burning for such treatments. In addition, there has been less experience with broadcast fire in these areas than in the northwestern part of the region studied. A large cadre of forest workers familiar with techniques of broadcast burning would be essential to any sizeable program in the southern and eastern portions of the study area.

Pile burning is also more appropriate than broadcast burning under certain topographic conditions that may occur throughout the study area. At high elevations, where there is a rapid transition from summer to winter, piled logging debris can be burned after snow falls — a time when scattered fuels will not support fire. At low, dry elevations, stands of timber are often not dense and may provide insufficient fuel for broadcast burning.

Mechanical procedures for piling slash are beyond the scope of this study. Two principles are worthy of note, however: (1) If slopes exceed 30 to 35 percent, machines are slow to complete the job, and broadcast burning of such blocks should be considered; (2) operators should make every effort to prevent including soil in piles of slash. Soil mixed with slash makes burning more difficult and increases the chance of holdover fires.

Several respondents expressed the opinion that any fuel worth the cost of piling was also worth covering. In some cases, specialty paper products or asphalt emulsions have been placed on the tops of piles to protect them from precipitation prior to burning. Usually only a small portion of the pile is covered. This spot remains dry enough to support combustion after rain or snow has dampened the surrounding forest.

As indicated, bare mineral soil can be exposed on any desired portion of a machine-piled area, and piles can be burned at times when unpiled slash will not support combustion. Certain disadvantages are also inherent in pile burning; for example, the costs of machine piling and burning are higher than those of broadcast burning in similar blocks, even on slopes of less than 30 percent. Most of the respondents who were experienced in burning heavy fuels of the white pine and ponderosa pine—Douglas-fir types contended that piling is economically justified only on blocks adjacent to high-hazard fuels or to other ownerships.

Some other disadvantages of piling and burning were emphasized during the interviews. Once ignited, a pile or windrow may burn for a day or more. Unless adjacent fuels are wet, the likelihood of fire escaping is increased by the extended burning time. Also, piles and windrows occupy sizable portions of clearcut blocks. A few men had noted changes in soil structure associated with extreme durations and intensities of pile fires.

Windrows are gaining in favor over dozer piles because crawler tractors can be used more efficiently and ignition crews can concentrate their efforts on fewer separate piles. Most respondents felt that windrows should follow slope contours. Contour windrowing reduces the amount of tractor sidehill maneuvering, and subsequent plowing and planting operations are not hindered by having to cross burned windrows that may contain large, unburned logs. A few others maintained that windrows should extend up and down the slope. Men who argued for the latter method listed two reasons for their stand: (1) Tractors working across the slope may do less damage to watershed characteristics than if the tracks and scraping occur parallel to the slope, and (2) ignition can be controlled more efficiently and by fewer men when windrows are burned from either the bottom or top of the slope.

Harvest operations on many forest properties are extending to higher elevations and steeper slopes than in the past. This fact must be considered in planning slash treatments. Broadcast burning may be practiced more extensively in difficult topography than heretofore, due to limitations in tractor use.

Block Size

A burning block is an area planned for complete ignition within one daily work period. It has defensible outer boundaries and may be subdivided by internal firebreaks. Areas that are piled by machine or hand prior to burning are not included in this discussion, since they need not be completely ignited on any one day.

How big should a burning block be? Answers to this question are complicated by the many variables associated with block size — silvicultural practices, topographic boundaries, protection of adjacent timber resources, watershed and wildlife considerations, aesthetic values, and manpower and equipment available for the operation.

For the present we will consider size only in terms of efficiency of ignition and subsequent control. Assuming that an area to be broadcast burned has well-located boundaries, and that all portions of the block are accessible, what are the minimum and maximum areas that can be burned easily and economically?

Nearly all of the men interviewed stated that blocks of less than 20 acres are inefficient and costly to burn. About half of these men felt that 40 acres should be the minimum size for broadcast burning.

There was less agreement on the maximum size for a burning block. Seventy-two percent of the respondents chose maximum block sizes of between 100 and 400 acres; most respondents favored 300 acres. Eighteen percent of the men gave figures of between 500 to 1,000 acres. At the other extreme, 10 percent indicated that the largest block should be between 40 and 100 acres. Men with experience in the white pine type favored slightly larger blocks than those who burned in the other forest types. An optimum block size of 100 to 200 acres was mentioned frequently.

Arguments against burning small blocks were based on the following: A fire less than 40 acres in size has a long perimeter proportionate to its area. Control problems are multiplied as the boundary between a burn and the adjacent forest is lengthened. It is difficult to manipulate the flame front and convection column on small fires in order to protect block edges. Finally, many small blocks are much more costly to patrol after burning than a similar acreage concentrated in a few larger blocks.

Manpower and control needs determine the upper limits of burn size. Blocks larger than 200 acres often require larger crews than are locally available, and importation of men and heavy equipment is expensive.

For tactical reasons an individual block should be burned as one fire with one convection column. Using present procedures and devices, it is extremely difficult to ignite large, sprawling blocks when and where necessary to make the fire behave as a unit.

Layout of Burn

Ideally, a prescribed fire should be held within its firelines. The two most common causes of escaped fires are improper block layout and unexpected winds. Winds will be discussed in a later section on burning weather. Here we are concerned with the principles of block design that insure rapid ignition and successful control of prescribed fires.

The respondents agreed that if the burning was the sole consideration in the block layout, a well-planned area would look something like this: a gently sloping circular mound completely surrounded by roads, with no steep, forested inclines directly adjacent to it. Or it might be a large patch on the face of a mountain, with its upper boundary slightly over the crest and straight edges up and down the slope; this block should narrow slightly toward the lower line.

Fire is a much safer and a more effective tool when block boundaries are located to permit burning under severe fuel and weather conditions. What, then, are the criteria for boundary location? The idealized blocks described above have most of the qualities desired by the prescribed burner. Two fire behavior characteristics are accommodated: (1) A fire normally spreads uphill, perhaps fanning slightly outward, and (2) the rate of spread tends to diminish after reaching the crest of a ridge. These characteristics also conform to the pattern a wildfire might trace under similar topographic conditions.

The nearly circular shape for a block simply illustrates another important planning principle — the greatest area is burned per chain of fireline. Circular blocks are obviously impractical in most situations, but if fireline length can be reduced without creating other hazards, there is proportionately less line to guard and patrol per acre burned. Since straight firelines are also important to the control job, the idealized square block thus becomes the best compromise between area and length of outside line. Carrying this principle a bit further, the larger the block, the greater the area that can be burned per chain of fireline.

The straighter the line, of course, the shorter the length to be defended. Any deviation from a straight upslope line tends to place fire beneath some portion of the line and endanger adjacent stands. Many fire escapes have resulted from so-called doglegs in the fireline.

Topographic features are an essential consideration in the location of a fireline. A straight block edge that transects spur ridges or draws can be as hazardous as a crooked fireline. Radiation across steep, V-shaped canyons has been known to precondition fuels facing prescribed fires until they can be easily ignited by firebrands. In the judgment of the men interviewed, it is better to include the whole of such topographic features in the cutting block or to completely exclude the threatening slope than it is to risk firing an outside stand.

Real situations are compromises between the need to conform to natural stand boundaries when laying out a timber sale, the location of logging roads, the seeding characteristics of the species to be regenerated, watershed requirements, and mountain topography unrelated to the orderly plans of man.

Fireline Construction

Once an area has been selected for burning, fireline specifications must be written. How wide should the fuel break be? How much mineral soil should be exposed? Answers to these questions are always qualified by the nature of fuels, adjacent hazards, and topography.

A fireline width of one dozer blade, or 12 to 14 feet, was considered minimal by the great majority of those interviewed. Fifteen percent of the men preferred to have 20 or more feet cleared between slash and adjacent fuels. The maximum recommended width was 1 chain.

In the Intermountain West, bulldozers used for fireline construction usually have straight blades. This means that fuels are removed from a 12-foot or wider line. However, mineral soil need not be exposed more than a few feet in width. When slash does not abut the standing timber, a narrow, hand-built line can be sufficient.

The purpose of a 12-foot-wide break in heavy fuels is to prevent radiant heat and sparks from igniting fuels outside the burning block. The narrower line of mineral soil is necessary to prevent the fire from creeping through the duff into adjacent fuels.

The respondents voiced some special cautions regarding fireline construction: First, there is a tendency for bulldozer operators to dip their blades through the duff layer into mineral soil. Inorganic soil is thus included in the duff and slash deposited inside the fireline. This mixed berm tends to burn for many days after the main fire is extinguished, creating a hazard in dry weather. As stressed in the discussion of pile burning, soil and fuel should not be intermingled.

Second, wide firelines in slash can defeat their own purpose. The fuels that are moved to construct the line must be deposited somewhere. If pushed outside the block, they present a possible control problem; spot fires that frequently occur near the block edges are difficult to extinguish in slash. On the other hand, if excessive concentrations of slash are deposited within the line, they can also be a threat to adjacent stands when burned. If firelines are widened from one to several dozer-blade widths, displaced slash can accumulate to great height along the line. To avoid this, slash from firelines should be mechanically distributed well within the block boundary. In heavy fuel it is sometimes necessary for bulldozers to push the excess slash 50 or more feet into the burn area.

Third, nearly all respondents insisted that slash should not be tolerated outside the firelines. Many cutting contracts specify that boundary trees be felled toward the block center. Treetops that do fall outside the fireline should be skidded back inside.

Logging roads frequently constitute outer firelines. It is well to plan for the disposal of slash from right-of-way cuttings inside the burning block. Care should also be taken in constructing jammer roads so that logs are not partially buried in the berm.

Some respondents recommended building all outer firelines as access roads for four-wheel-drive vehicles. They mentioned four advantages of such roads: (1) Truck-mounted ignition devices can be employed, (2) fire retardants can be more easily applied along firelines, (3) emergency use of tankers is facilitated, and (4) postfire patrol is more efficient.

Firelines, even those a chain or more wide, may not contain a fire that is poorly designed or executed. Uncontrolled convection currents containing sparks and larger firebrands are the immediate cause of most fire escapes. Firelines merely interrupt the spread of the ground fire. Fire retardants, including water, applied along particularly hazardous line segments immediately before and during burning, aid fire control efforts. While continuous firelines are essential around a burning block, control of the fire depends to a greater extent upon intelligent block design and timing of ignition.

Laydown of Snags and Noncommercial Trees

Blocks of merchantable timber contain many trees that are too small, of poor quality, or too badly decayed to be harvested economically. Such noncommercial trees, if left standing, are an obvious wildfire hazard as well as a source of infection from disease and insects. Unless they are felled during clearcut logging, a separate operation is required to drop them to the ground. Snags outside the fireline contribute to the hazard of fire escapes. Their dry and punky parts or shaggy bark can harbor intercepted sparks. For this reason, snags adjacent to burn blocks are often felled. Two questions in the interview related to the treatment of snags and noncommercial trees: What stems are dropped within the block? How far outside the line should snags be felled?

Almost all respondents felt it was necessary to lay down noncommercial trees within the block before burning. They gave three reasons for their opinion: (1) Laydown contributes to the fuels already available and tends to make them uniform and easier to ignite, (2) fires are restricted to the ground, do not crown within the burn, and reduce the mopup effort, and (3) burned blocks recover their aesthetic qualities sooner if no snags remain after the fire.

Just which trees are felled prior to burning depends upon the method of laydown. Trees and snags may be sawed, pushed over with bulldozers, or uprooted by a heavy cable stretched between crawler tractors. The first two methods are selective, the third nonselective.

Cabling must be done under moist soil conditions to ensure uprooting of residual trees. Unless the trees are both killed and laid close to the ground, they remain green and contribute little to the fire.

All respondents agreed that any snags within a clearcut block should be cut. However, the minimum size recommended for felling standing live trees ranged from 1 to 6 inches in diameter. A good compromise is that all residual trees over 4 inches in diameter at breast height be felled. On the other hand, if site preparation or type conversion is the goal, smaller trees and brush may need to be cut to provide a continuous fuel bed. If mistletoe control is called for, all trees that survive a fire should be felled. A few men felt that laydown was necessary only within a few chains of the block boundary.

Outside the fireline, shaggy-barked or rotten-topped snags should be felled whenever they occur within 1 chain of the line, or when they are not screened by green vegetation in surrounding stands. Laydown should follow the harvest operation as closely as possible; burning is more consistent and effective when both slash and laydown retain their needles. However, old slash without needles can be made more flammable by recently cured laydown.

SCHEDULING THE FIRE

When should burning be done? Prescribed fires in the Intermountain West have been attempted under almost every type of fuel and weather condition, and slash piles have been burned while covered with a mantle of snow. A few prescribed fires have been ignited during a lull in the summer wildfire season.

The purpose of burning determines the time of burning, since a wide range of fire effects can be produced by varying the burning date. The respondents had very little experience in the planning and execution of burns during dry, warm periods, and only a few men had burned prescribed fires in the spring. Opinions presented in this section should be interpreted accordingly.

Age of Fuels

Slash and laydown fuels usually must be cured before they will burn. Curing is indicated by needles that have begun to turn yellow, red, or brown. If trees are allowed to remain on a site too long after cutting, however, the needles and fine twigs will fall to the ground. Within a few years only large stems and branches remain elevated above the duff. Fuels that are either too green or too old are difficult to ignite, burn poorly, and may not generate enough heat to accomplish the desired objectives.

The men interviewed considered 1 to 2 summer months the minimum time required for curing of fresh slash or laydown. The only exception noted was that some dozer piles of lodgepole pine in western Wyoming had been burned successfully within a few days after the live trees were uprooted. Late autumn slash may not be completely cured by next spring. Dry, warm weather is essential to cure green material adequately.

All respondents agreed that broadcast burning is easier and more effective if most of of the needles are still attached to the limbs of slash and laydown. The optimum time for burning is within 1 year of harvest. If more than 3 years elapse after logging, the primary burning objectives are rarely fulfilled. Hazard reduction goals, in particular, are not fully realized if slash remains on a block for much longer than it takes to cure.

More latitude is available in the burning period for piled or windrowed slash. Greater fuel-moisture content can be tolerated in closely arranged fuel elements, although higher heat inputs are required for ignition.

Broadcast burning is of increasing importance in conversion of brushfields and improvement of wildlife habitat. A few brushy sites have been burned in the northern reaches of the study area. Phytocides, especially in oil emulsions, were sprayed on these sites prior to burning. The purpose of spraying was to kill the aerial parts of brush stems, thereby promoting their desiccation and conversion to available fuel.

Nine of the men interviewed had some experience with spraying and subsequent burning of brushfields. They felt that brush should be sprayed in preparation for burning soon after it is in full foliage in the spring, and burned the following autumn. Or, the brush can be sprayed a week or two prior to burning, leaving dead leaves suspended on the branches to enhance the rate of spread.

Season of Burning

Although most prescribed burning in the Intermountain West is scheduled in autumn, fire specialists should consider other seasons as well; this is an important factor. To understand it better, we must know the typical sequence of fire weather in the region. Most of the timbered elevations are covered with snow from early December until sometime in April. Warm, dry weather often follows, and persists until a rainy period occurs in June. At elevations below 6,000 feet there are usually a few days or weeks during May and early June when slash or brush can be broadcast burned. July and August often bring extended periods of hot, dry weather. Sometime during the latter part of August, moist air masses begin to enter the region from the northwest. These cause precipitation that signals the end of the major wildfire season.

Most prescribed fires are scheduled sometime between late August and early November after a specified amount of rain has fallen. Relatively few burns have been conducted in spring and summer. With an increasing acreage needing fire treatment each year, fire specialists are seeking means to extend the prescribed burning period.

When to start autumn burning depends on how much precipitation in August and September is needed before the first match is struck. The answers to this question were distributed as follows:

Minimum precipitation	Responses
(inches)	(percent)
0 - 0.4	36
0.5 - 0.9	26
1.0 - 1.9	32
2.0+	6
Total	100

As indicated above, over half of the group recommended that burning begin before 1 inch of rain had fallen in the early autumn and more than one-third preferred less than one-half inch of rain. A few men were satisfied with one-tenth inch of rain or less.

Fires conducted after only a small amount of rain has fallen are easier to ignite, control, and mop up than those burned later in the autumn. Also, burning under relatively dry conditions results in better site preparation. Fewer hangover fires, more complete control of the convection column, and greater economy are other reasons given for early autumn burning.

North and east aspects and blocks at high elevations should be broadcast burned before those on lower, and south- and west-facing slopes. Piles and windrows of slash should be ignited later in the autumn. When more than a few hundredths of an inch of rain have fallen, slash needs some drying before it can be ignited. As the autumn season progresses and the days become shorter, dew and frost retard diurnal drying, and progressively longer drying periods are required after each rainfall. Ultimately, burning activity ceases as fuels become saturated. The maximum amount of precipitation after which prescribed fires can be scheduled varies with the intervals and drying conditions between storms.

No respondent was able to specify just when the autumn burning season should end. The dates of the last fires are largely dictated by the moisture in the fuel. This topic will be discussed in a later section.

Though the bulk of prescribed burning takes place in autumn, there have been several recent attempts to utilize the spring and summer seasons. The 30 men who favored some spring burning felt that these fires should be scheduled before the usual June rains. They suggested south slopes at low elevations as most appropriate for spring fires. One advantage of burning during this season is that adjacent stands may be too wet to harbor sparks from the fire. The most frequent objection to spring burning was that moist, rotting logs and duff within the burning block might smolder for days or weeks after a fire unless thoroughly mopped up.

Only one prescribed summer fire was discussed during the interviews, though many participants expressed an interest in the potentials of this season. There are a few periods during a typical summer in which fuel and weather conditions are similar to those of early autumn. About half of the respondents prophesied future exploitation of certain summer burning periods.

Time of Day

Within any 24-hour period, fuel and weather conditions vary enough to influence the conduct and control of a prescribed fire. A good planner uses diurnal variation as he does seasonal change in scheduling his fires.

About half of the respondents preferred to burn in the late afternoon, when relative humidity is rising. Reasons given were that the fuels had dried as much as possible, the wind had usually reached its peak velocity and was diminishing, and burning extended into the relatively cool, moist evening when control problems are minimized.

Others were staunch advocates of early morning fires begun as soon as fuels would ignite. These fires were planned to have the block well burned out before the heat of the day. Low wind velocities and daylight working periods were cited as primary advantages of morning fires. Those who favored such timing were working in central Idaho and east of the Continental Divide in Montana, where afternoon winds are strong and persistent.

It is necessary to adjust ignition time as autumn progresses. A morning burner might begin the season by lighting slash at 0600 and end the season by igniting at noon. Similarly, a confirmed afternoon burner might start early season fires at 2000 hours and ignite fires at the end of the season at 1400 hours. Some advocates of morning fires preferred to burn out firelines the evening before they began igniting internal fuels. The men who proposed burning in summer or in early autumn, with little precipitation, recommended that these fires be conducted at night.

Special precautions should be taken for crew safety during night burning hours. Limited visibility requires more elaborate communication arrangements than are necessary for daylight operations. The administrative problem of adjusted workdays is another common difficulty in scheduling prescribed fires, although burning hours should of course be determined by the job and not the clock.

In late evening and early morning ignition, it is important that fuels be sufficiently dry for rapid consumption. If slash lit in the morning is not consumed, a hazardous midafternoon reburn is possible. On the other hand, fine fuels respond quickly to high evening humidities especially after dark. Misjudgment of an hour or two in evening ignition time can result in an incomplete burn and control difficulties the next day.

Variation in topographic aspects and slope positions within a block further complicates timing of ignition. Fuels at the bottom of a moist draw must usually be ignited during a warm part of the day. Upper slopes exposed to sunlight can frequently be burned in the early morning or late evening.

The time of day for burning as well as the time of year merely represent expected fuel and environmental conditions. These conditions are always of primary concern to men who use fire.

Fuel Moisture Content

For the past 30 years, standardized ½-inch fuel sticks have been used as analogs of fuel moisture. Moisture content is measured by weighing the sticks with portable scales. When located in or near prescribed burning blocks, the sticks are a valuable means of approximating the moisture content of slash fuels of comparable size and exposure.

To be significant, fuel moisture estimates must be compared with the results of burning. Unfortunately, there is no widely accepted objective measure of burn success. Despite this limitation, enough prescribed fires have been conducted in the Intermountain West to permit rough assessment of the conditions under which fires escaped control or would not burn well. Through a process of trial and error, experienced burners have concluded that a certain range of moisture content in fuel sticks is likely to represent an acceptable burning condition.

More than three-fourths of the respondents were willing to attempt fires when fuel sticks in the slash block showed between 6- and 15-percent moisture content. A few others would ignite slash when fuel sticks indicated 4- or 5-percent moisture content. Two men would not start fires until the fuel sticks indicated over 16-percent moisture content.

A large proportion of respondents did not install fuel moisture sticks in the forest adjacent to their burning blocks. Of the 14 men who did, 10 wanted the sticks under a forest canopy to indicate a moisture content 2 to 10 percent greater than that of sticks located in the slash. The other four men had found that such a difference rarely existed.

Relative Humidity

The amount of water vapor in the air greatly influences the moisture content of dead organic fuels. Needles and fine twigs respond within an hour to changes in humidity. Larger pieces of slash require days or weeks to adjust to variations in humidity.

Respondents were asked what they felt minimum and maximum relative humidities should be at the start of a broadcast burn. The responses were:

Relative humidity (percent)	10-19	20-29	30-39	40-49	50+
Minimum (percent responses)	27	47	22	3	1
Maximum (percent responses)	- -	3	36	36	25

Seventy-four percent of the men interviewed said they would ignite broadcast slash when the relative humidity was below 30 percent. Only 25 percent of the respondents were willing to begin burning slash when the relative humidity exceeded 50 percent. If we take a consensus, the most acceptable condition for prescribed burning is from 20- to 50-percent relative humidity.

Relative humidity is not static during a fire. A number of experienced burners install hygrothermographs along with rain gages and fuel moisture sticks in clearcut blocks for a week or more prior to burning. They highly recommend this practice to others who schedule prescribed fires. Used in conjunction with spot weather forecasts, hygrothermograph records help predict at what time of day the desired humidity will be reached on a given block.

A few men indicated that sunshine affected both humidity and the flammability of slash fuels. When burning conditions are borderline, the sun's rays can make the difference between a fire that burns continuously and one that merely smolders when ignited.

Sunshine both directly and indirectly increases fuel and air temperatures. The fuels and the soil surface intercept solar rays, are warmed by them, and in turn warm the air. Heating the air reduces relative humidity. When the sun's rays no longer strike the fuel bed, air temperature decreases, causing an increase in relative humidity. This increase and the lack of radiant heat from the sun combine to reduce the flammability of the slash and can have a pronounced effect on goodness-of-burn.

Wind

Prescribed fires are significantly influenced by daily and seasonal changes in the velocity and character of winds. Basically, windspeed determines the rate of spread of a fire. However, there are two kinds of air movement associated with all fires: a roughly horizontal surface wind, and a fire-induced combination of horizontal and vertical convective airflow.

Early and late in a fire, normal surface winds may overpower the effects of rising, heated air, and disperse the convection column. At the peak of energy release from a fire, air may flow from all directions into and upward from the center of combustion, scarcely influenced by surface winds.

Experienced prescribed burners, aware of the different effects of each kind of airflow, consider them when developing burning plans and use them as tools in conducting fires. Winds determine to a large extent the course of control and how much the fuel or duff is reduced. The interview question was asked: How much surface wind is desirable?

Sixteen percent of the respondents preferred to have some wind at the time of ignition because it indicates direction and facilitates planning. These men also believed that broadcast fires and piles would burn more completely with wind. The remaining 84 percent preferred to burn plots when the air was as calm as possible, while recognizing that still days are rare. Some men who practiced east of the Continental Divide complained that relatively high winds almost always existed during their burning seasons. The maximum wind velocity beyond which the group would not burn was:

Maximum velocity (m.p.h.)	5 or less	10 or less	15 or less
Percent responses:	21	65	14

Recent research findings may help clarify the effects of surface wind on rate of spread and goodness-of-burn. In laboratory tests with needle fuels, rate of spread increased with rising windspeed. As rate of spread increased, the intensity of the fire lessened on any given area.[3] These tests suggest that a fast-moving fire consumes less of the available fuel than a stationary fire.

On the other hand, slow rates of spread, characteristic of low or no-wind conditions, often require closely adjoining ignition lines. Many ignition lines are desirable for greater control of the convection column, but they may also require more ignition-crew manpower. Yet managing the convection column by careful addition of areas of fuel is usually easier than trying to overcome the effects of a strong surface wind.

A single, strong convection column is desirable in that it helps overcome the influence of steep slopes and surface winds. If more than one convection column is permitted to develop, they may interact to produce large fire whirls. During the early phases of a fire, every effort should be made to build a single, strong column. Later, when the entire block is ablaze and has begun to burn out, interacting columns cannot always be avoided.

General Weather Conditions

What kind of weather is best for autumn burning? Should it be clear or cloudy — or warm or cool?

Eighty-six percent of the respondents preferred clear skies on the ignition day. Some of these men added such descriptions as "crisp, cool, bluebird weather," and a day "when smoke rises straight up." Three experienced men went to the extent of recommending an unstable atmospheric condition. On the other hand, eleven percent of those queried wanted the skies to be overcast; a few even specified low-hanging clouds and humid weather. There was no clear expression of the air temperatures most favorable for burning.

Clear weather in the autumn usually coincides with high surface barometric pressure. This condition, combined with small differences in pressure aloft, produces only light winds. Also associated with such a system are vertical temperature profiles, which in autumn afternoons tend to permit the development of strong, straight convection columns. At night, inversions in mountain valleys trap moisture and smoke close to the ground. The following morning the sun heats the ground, drying the fuels and clearing the air.

Autumn also brings cold frontal systems that cause periods of higher winds and showers. Clouds may persist for a day or so after a front has passed. Stable air profiles during the latter times dampen convection columns. There are, of course, many varieties of intermediate patterns in the Intermountain West.

If we accept the need for a strong, central convection column, a clear day with low wind is best for burning. The occurrence of inversions explains why early morning ignition is difficult to achieve on many blocks.

There is an obvious need for accurate, localized prediction of weather conditions likely to affect a fire. Specialized fire-weather forecasts are prepared upon request for individual prescribed fires, and can be obtained through U.S. Weather Bureau offices. Most respondents made use of these special forecasts.

IGNITION, CONTROL, AND MOPUP

Ignition and control procedures vary widely depending upon burn objectives, environmental conditions, and available manpower. It is therefore impossible to develop a standardized, step-by-step outline of how to manipulate men and equipment on a prescribed fire. Indeed, experienced men start burns with the expectation that many of their plans will be altered during the course of the fire. Though ignition schedules and control methods should be clearly formulated well in advance, all plans should be flexible in order to meet unexpected changes in weather or fire behavior.

The chapters on prescribed burning in

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[3] *Anderson, H. E., and Rothermel, R. C. Influence of moisture and wind on the characteristics of free-burning fires. Tenth Internatl. Symposium on Combustion. Cambridge, England. 10 pp. 1964.*

Davis' text should be required reading for all who plan fires in the Intermountain West. While outlining several ignition methods, he insists that "The trained judgment of good personnel is an essential that cannot be imparted in any textbook or manual."[5]

The following sections deal with tools and techniques of general application to prescribed burning — not with specific judgments that must be made in the field.

The Plan

Each respondent contributed his ideas on prescribed fire plans. The suggestions are summarized below.

First, an adequate map should be prepared for each burning block. The scale is not critical if all topographic and cultural features are clearly shown. Some men prepare overlays for their maps, upon which they plot the location of skid trails, jammer roads, ignition lines, fire control equipment, and crews. These maps are essential on complex prescribed fires.

An experienced man can sketch a map of proposed ignition lines from a vantage point on or near the block. One imaginative respondent suggested that the planner close his eyes after sketching the map, ignite the fire in his imagination, watch it burn, and then make adjustments in the pattern. Similar techniques are used by chess players and military planners. To repeat, flexibility is essential.

Placement of ignition and control crews should be clearly indicated on the map. Some fire specialists mark crew stations on the ground as well as on the map. Numbered signs, corresponding with numbers on the map, should be placed at key points on the block to designate ignition lines and placement of equipment. These signs are also useful in directing the movement of men and vehicles before and during the fire. The sequence of ignition is usually outlined on the map and in accompanying written plans. Escape routes for men and vehicles should be clearly marked; logging roads may be numbered for this purpose.

[4] *Davis, K. P. Forest fire — control and use. New York: McGraw-Hill. 584 pp. 1959.*
[5] *Ibid, p. 511.*

The plan should provide for dissemination of fire intelligence. This begins with a complete briefing of the entire crew before stations are taken. Ideally, the briefing should take place at the point overlooking the block that will later serve as command post for the fireboss. Key points on the map and ground should be identified and the ignition sequence reviewed. Mopup duties may be tentatively outlined. Above all, emergency lines of retreat must be assigned to each crew.

Portable two-way radios and loudspeakers are good communication tools on prescribed fires. Radios should be assigned to scouts, sector bosses, ignition crew foremen, and operators of heavy equipment. Portable loudspeakers can be used to broadcast instructions from the fireboss. He should also have some direct means of communicating with his headquarters in order to receive special fire-weather forecasts.

Finally, the plan should outline mopup and patrol activities. The investment of men and time in postfire action depends upon how well the block burned, spot fire occurrence during the fire, and subsequent weather conditions. Because not all of these factors can be predicted in advance, planning for mopup and patrol is necessarily sketchy. However, all of the men interviewed advocated patrol after prescribed fires, and about half of them recommended mopup operations around the edges.

Ignition Devices

Proper ignition devices should provide rapid, controlled lighting of lines of fire along predetermined routes. The success of the burn frequently depends upon the speed and efficiency of ignition crews. Crews should be equipped with ignition devices best suited to the fuels and working conditions on different blocks. For this reason, a variety of devices should be on hand.

Ignition devices currently employed include matches, fusees, propane torches, drip torches, and pressurized diesel flamethrowers. Flamethrowers consist of both backpack and truck-mount types. Very pistol flares, thermite grenades, and sausages filled with jelled petroleum products are also useful.

To identify the kinds of devices favored by burners in the various forest types, all interviews included the question: What ignition tools do you prefer for starting prescribed fires?

Though backpack propane torches were mentioned more frequently than any other, no one device was the choice of a clear majority. Truck-mount diesel flamethrowers are gaining in popularity in the white pine type, and there is increasing use of pressurized-tank diesel units in the southern reaches of the study area. The advantages and disadvantages of the various devices are summarized below:

Ignition device	Advantages	Disadvantages
Matches	Always available in quantity	Require fine, dry fuels
	Rapidly dispensed	Localized ignition
		Poor in wind
Fusees	Light in weight, convenient	Require fine fuels
	May be extended on pole	Localized ignition
	Hot, concentrated flame	No residual effect
	Relatively long-burning	
	May be thrown	
Propane torches (backpack)	Very hot flame	Heavy and awkward
	Long burning	Time-consuming refill
	Maintain own pressure	Refill can be hazardous
	Good for piled slash	No residual effect
Diesel flame-throwers (truck-mount)	Long residual flame	Restricted to near roads
	Long burning	Require gasoline pump
	Fast roadside ignition	Require large quantities of fuel
	Wide ignition pattern	
Diesel flame-throwers (back-pack)	Residual flame	Heavy and awkward
	Easy refill	Require pressurizing
Drip torches	Residual flame	Need frequent refills
	Light and portable	
	Fast igniting	
Very flares and thermite grenades	Some residual effect	Relatively costly
	Remote ignition possible	May burn too hot for slash ignition
Jelled petroleum products in sausage casings	May be ignited with fuse	Require presetting
	Good for piled slash	
	Persistent flaming	

Many other fuels and devices have been used to start prescribed fires. Some of these, such as gasoline blow torches, are hazardous to personnel; others, such as diesel-soaked sawdust, require separate ignition action.

Spraying slash or brush with diesel fuel from helicopters or ground-based pumpers prior to ignition has been tried on a small scale. This treatment promotes burning of green, moist, or scattered fuels.

Ignition Patterns

Where a prescribed fire is ignited is often as important to its success as *when* it is started. The system of planning described earlier, wherein the block is burned first in the mind of the planner, works well if the principles of fire behavior in slash are well known and can be visualized in the field.

When large quantities of heavy fuels burn, a buoyant action is imparted to the atmosphere above the fire. Air from all sides moves into this area of reduced pressure. As described earlier, when the upward movement of heated gases is strong enough, it can overcome the effects of light surface winds or adverse slopes.

If a block is ignited in many places simultaneously, the whole fire burns fiercely in place, not affecting or being affected by its surroundings. This extreme case is called a fire storm. If only one line of fire at a time is started in slash fuels, the flames and convection column are greatly influenced by both slope and wind.

All ignition procedures are based on the foregoing characteristics. There are three basic ignition patterns: area, internal, and strip. Each man interviewed was asked which of these patterns he used in his prescribed fires.

None of the respondents used area or simultaneous multiple ignition. Internal or center ignition was practiced primarily by men with experience in the white pine type. Men who burned steep slopes generally preferred to ignite in strips, starting at the top of the block or on the downwind side. Respondents who held to strip burning alone had rarely attempted internal ignition, but men who preferred internal firing patterns often used strip ignition on steep slopes.

Of those who specified internal ignition, the question was asked: On how steep a slope can center firing be effective? The answers ranged from a 10- to a 60-percent slope, with an average of 30 to 35 percent.

Several respondents mentioned an effective combination of strip and internal ignition patterns, in which lines of fire 50 or more feet below the uphill firelines are started prior to ignition of the extreme upper edge. When the internal fire becomes intense enough to draw air from above, the outer perimeter is ignited. Thus the flames at the top sides of blocks on relatively steep slopes can be directed inward. This technique is often faster and safer than a single backing fire from the outside firelines. However, it only applies where peripheral ignition is normally indicated.

Controlling the Fire

Most prescribed fire plans call for ignition crews and holding crews backed up by tankers, water pumps, and sometimes bulldozers. Depending upon the size and potential of the fire, the total manpower needed may range from 6 to 60 workers.

The control needs of each fire should be carefully assessed during the planning period. Potential escape points should be sought out and, if possible, corrected. Each danger spot must be evaluated in terms of the number of men and pieces of equipment required for containing the fire.

Most men felt that crew size should be determined by fire size and potential for trouble. However, about half of the respondents admitted that crew size varied little from the number of men usually assigned to brush disposal activities. In other words, the same sized crew, usually 10 to 12 men, is sent to most of the prescribed fires scheduled by a given administrative unit. Most planners wished for greater flexibility in crew size from block to block.

Blocks are often burned in small patches when larger than normal fires are scheduled. Sometimes portions of a block are burned on successive days. Thus the actual size of the crew frequently determines the manner in which a block is burned. This situation occurs most often on blocks up to 100 acres in size. On really big blocks of 200 to 400 acres, the fireboss routinely asks for assistance from neighboring administrative units, logging crews, or protective associations.

Respondents agreed that most escapes were caused by wind and consequent spotting outside the fireline. When asked how this might be prevented, the almost unanimous response was "through better block layout." Hot fires with strong vertical convection columns also greatly reduce control problems. Regular patrol was recommended to avoid postfire escapes.

The most experienced burners were relaxed in their attitudes toward escapes. Their opinions can be summarized by the statement, "Don't drop the torches once ignition begins!" This means that continuing the ignition pattern minimizes the effects of fires that have spotted over the firelines. Or, in other words, if the ignition crew drops its torches and joins with the control group in fighting an escape, the original fire may lose its drawing action or spread contrary to the firing plan.

It is not necessary here to describe how escapes of prescribed fires should be fought. Most burn planners have had experience in the control of wildfires, and there are many references that explain firefighting methods in great detail.

The majority of control problems can be avoided by intelligent layout, scheduling, and ignition of fires. With reliable weather forecasts available, escapes need rarely occur. If they do, odds are that the cause will be unexpected surface winds. Control crews and equipment are usually assigned to prescribed fires for these emergencies. The men and equipment used to control a fire are a form of insurance; their numbers and cost are the premiums paid.

HYPOTHETICAL FIRES

The final portion of the interview involved the planning, ignition, and control of fires on three hypothetical blocks. Plaster models represented the topographic positions and outlines of the three burn areas. We asked respondents to plan for broadcast burning of the blocks as though the fuels and burning conditions were typical of the forest type of their experience. As each man located firelines, placed equipment, and laid out ignition lines on the models, the interviewer sketched identical details on corresponding topographic maps. A total of about 150 such maps provided the data for this section.

The models are illustrated in figure 1. Areas surrounding the individual burning blocks theoretically support stands similar to those harvested. All noncommercial stems are assumed to be felled, and cut fuels to be one summer season in age.

Figures 2, 3, and 4 each consist of three parts — a photograph of one of the models and two topographic maps. The photograph gives perspective to help interpret the maps. Respondents were informed that the models had considerable vertical scale exaggeration and were asked to assume the steepest slope to be about 60 percent. All other slopes are proportionately less.

The topographic maps and symbols are generalized representations of the plans made by the participants. The maps should not be interpreted as exact reproductions: many details of the ignition lines have been omitted to avoid confusion. When an ignition line parallels an internal road, it usually means that both sides of the road were ignited.

On all of the maps, the numbered ignition lines begin with the tail of the arrow and end with the head. Intermediate arrow points show the direction of travel.

The number and placement of pieces of equipment should also be freely interpreted. Every actual burning block is different. These hypothetical situations are presented to illustrate principles, not details.

Block I

The topographic maps in figure 2 show the two ignition patterns recommended by respondents for the first model. Figure 2B represents the plan favored by three out of four of the men interviewed. It is a straightforward center ignition pattern with successive increments of fuel added from all sides. The domelike topography and locations of logging roads lend themselves well to a center-fired plan.

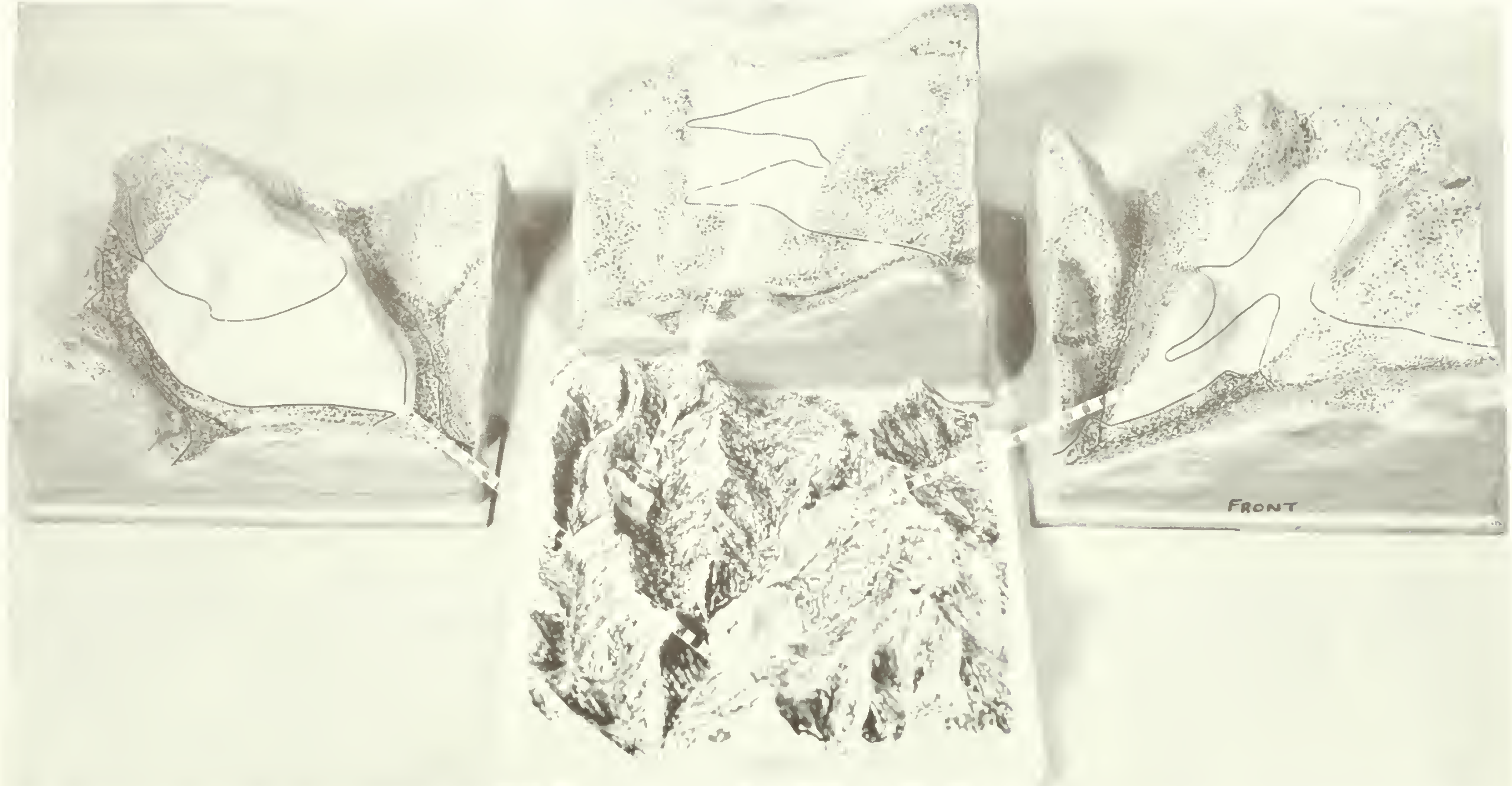
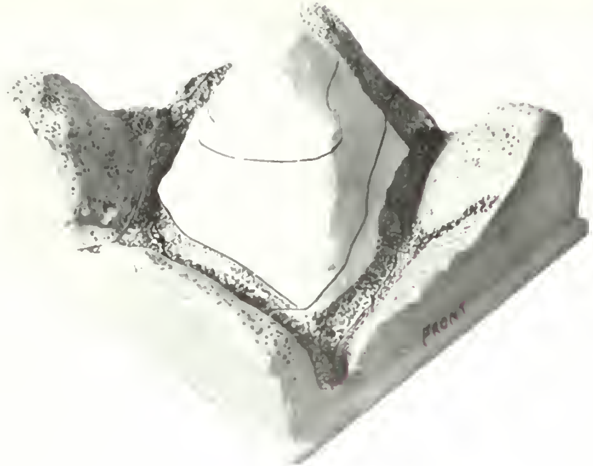


Figure 1. — Topographic models shown to interview subjects. The lower model shows overall terrain features. Each of the upper models contains a hypothetical burning block. Black lines on the blocks represent logging roads.

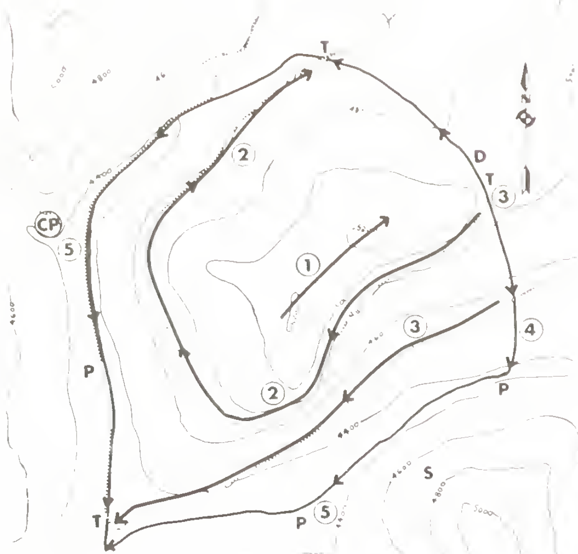


2A

Figure 2. — Block I is about 120 acres in area.

Legend:

⟶	Ignition lines
	Roads
CP	Control point
T	Truck-mounted water tanker
P	Streamside water pump
S	Scout
D	Bulldozer



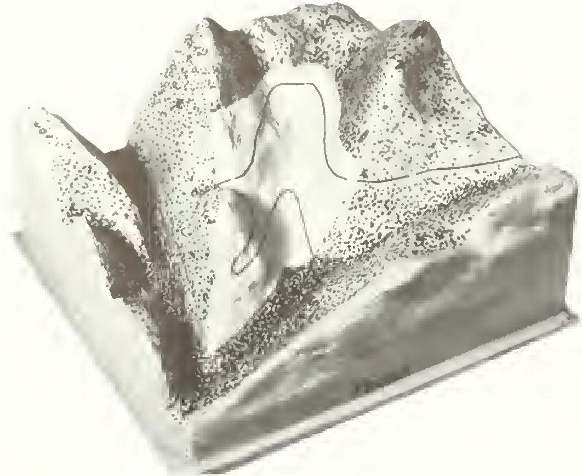
2B

2C

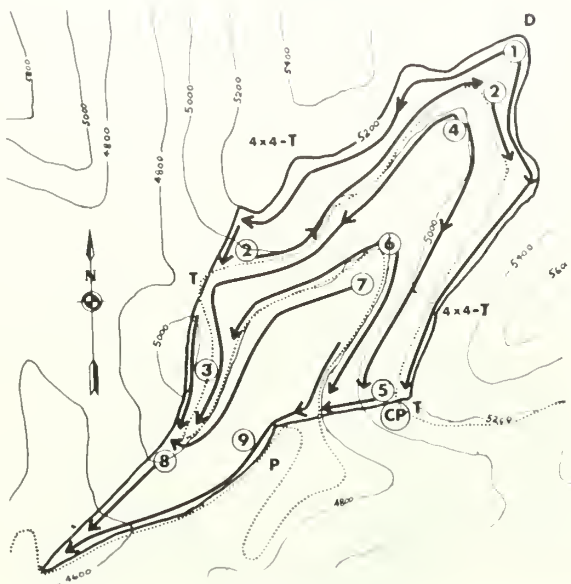
Figure 3. — Block II is about 80 acres in area.

Legend:

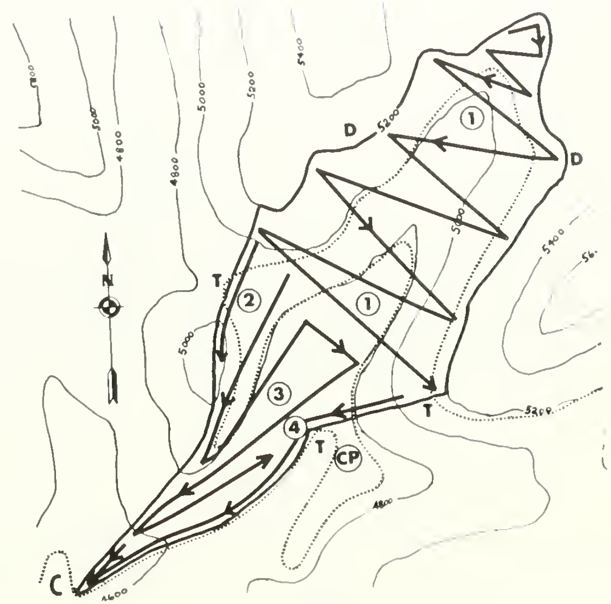
⟶	Ignition lines
········	Roads
CP	Control point
T	Truck-mounted water tanker
P	Streamside water pump
S	Scout
D	Bulldozer



3A



3B

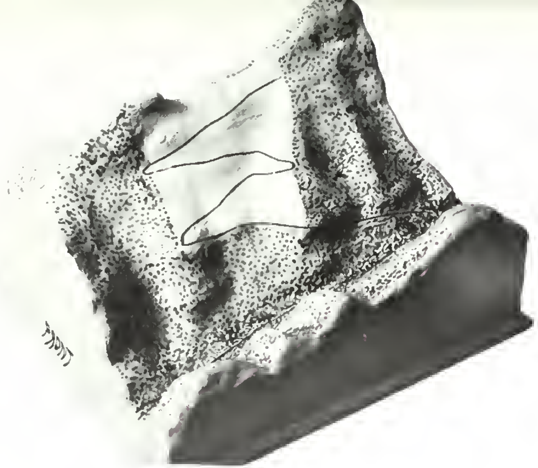


3C

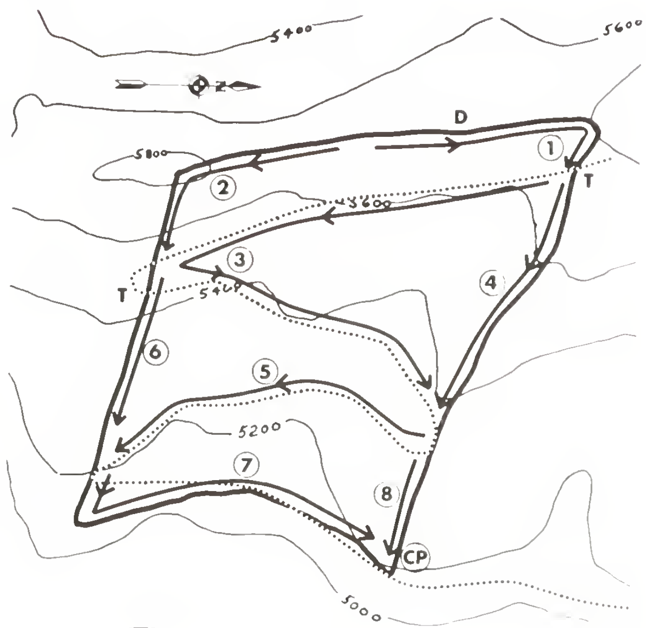
Figure 4. — Block III is about 40 acres in area.

Legend:

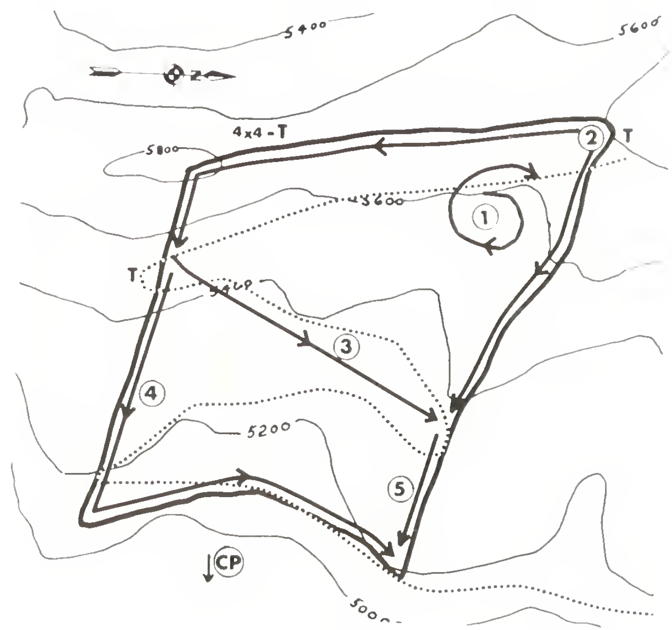
⟶	— Ignition lines
....	— Roads
CP	— Control point
T	— Truck-mounted water tanker
P	— Streamside water pump
S	— Scout
D	— Bulldozer



4A



4B



4C

Ignition lines numbered 4 and 5 and a portion of lines marked 3 on figure 2B coincide with the block boundaries. Two crews are needed to ignite the lines marked 5. These crews proceed simultaneously down-canyon from the northern and southeastern extremities of the block.

Respondents recommending plan 2B specified three tank trucks, one bulldozer, and three water pumps located as shown on the map. Note that the control point, or position of the fireboss, is across a drainage from the burning block. Though low in elevation, it is on a road and has a good view of one side of the block. A scout is located on the opposite hillside to report progress on the south side of the fire. All ignition, control, and equipment crews are equipped with two-way radios for communication with the scout and fireboss.

The relatively wide spacing of ignition lines is based on an assumed continuous mantle of fuels. The time elapsed between ignition of each successive line depends on the rate of spread. The sequence of ignition was planned to maintain a central convection column. Line 2 should therefore be completed before the fuels ignited along line 1 are burned out. Lines 3, 4, and 5 should be ignited while the internal fire is still burning.

Figure 2C illustrates an alternative ignition pattern. The center is ignited first, as before, but each face is fired at a different time. Note that the northeast-facing slope is ignited immediately after the center; then the northwest, southeast, south, and west, in that order. This sequence depends on appropriate moisture, temperature, and relative humidity. Too, the cool aspects must be fired early in the afternoon, and the normally hotter, drier aspects lighted later in the day. The outside edges of the block are ignited as each numbered line reaches the bottom of the hill.

The ignition pattern in figure 2C permits burning of scattered, low-volume fuels, which might be impossible in a pattern such as figure 2B. Fewer pieces of equipment are required for the pattern in 2C, indicating an easier burning job. Also, a different control point is shown on this map to point out that alternative placements were suggested during the interviews. Some firebosses prefer to be at the spot where control difficulty is anticipated; others prefer to roam about the block. About half of the men planning this burn were inclined to move the fireboss to correspond with ignition and control activity.

Block II

This block includes the lower portion of a draw. Particular attention should be given to the saddle on the western edge and to the long stretch of outside fireline with timbered stands above. This example of a complex situation demonstrated some of the special problems faced by burners in the field.

Figures 3B and 3C illustrate the caution with which respondents approached the planning of block ignition. These maps show two methods of burning small segments at the head and uphill sides of the draw. Again, 75 percent of the men favored the burning plan shown in figure 3B. Bulldozers were called for on both plans to fight possible escapes. Many suggested that the outside firelines be prepared as roads suitable for four-wheel-drive tank trucks.

On both patterns, ignition crews were to proceed slowly downhill from the upper reaches of the block. Quite a few respondents wished to burn out the upper strips at night before igniting the lower portion of the block. In any case, several hours would be consumed by the cautious addition of small increments of fuel as burning progressed downhill.

Erratic winds near the saddle might contribute to control problems. Accordingly, the southeast-facing hillside was also planned for slow downhill ignition.

The fact that three different exposures are represented on this block makes timing of ignition very difficult. The pattern shown in figure 3C requires fuels on different faces to be of about the same moisture content. In this pattern, control crews above the block would ignite the outer edges as line 1 was fired.

The fireboss at the control points located on both maps can observe the whole block, although smoke would probably obscure his view of the upper boundary at times when control would be critical. It is essential that control crews on the upper fireline be equipped with radios in order to notify equipment operators and other crews of threatened escapes.

The danger of fire spreading rapidly up the draw rules out a center-ignition pattern. The slow backfires indicated for both plans would undoubtedly make the 80 acres in this block more costly to burn than the 120 acres of the first block.

Block III

The block illustrated in figure 4 has been reasonably well laid out. The west boundary is slightly over the top of a major ridge, and both north and south edges are without serious overhang of uncut fuels. Note that the north boundary follows the top of a spur ridge.

As in the other blocks, three out of four of the respondents recommended the first alternative: a simple ignition pattern shown in figure 4B. Both sides of the internal roads are ignited as burning progresses downhill. The upper strip is ignited along lines 1 and 2, followed by firing of the west edge, which is a short distance over the crest of the ridge. Subsequent ignition follows the road. Note that the north and south boundaries are not ignited until the adjoining central portion of the block is afire. This tends to draw the flames away from adjacent stands. Crew 4 would start ignition as crew 3 rounded the upper switchback.

Figure 4B shows tankers at the intersections of the two upper roads and the fireline, and a bulldozer on the ridgetop. It is rare to find a bulldozer assigned to a burn of this size. The control point on this map is located on the northeast corner of the block to place the fireboss close to operations.

Figure 4C illustrates an internal ignition pattern for this block. After the convection column is well developed, crews start from the northwest corner and ignite both north and west edges of the block. Ignition line 3 serves to reinforce the central column and draw it downhill.

Lines 4 and 5 complete the circuit. Number 4 crew should begin its downhill ignition line when crew 3 is about halfway across the block. Line 5 should be ignited after crew 3 has completed its line. Crews 4 and 5 should reach the northeast corner of the block at the same time.

PLANNING FOR THE FUTURE

The use of fire as a land management tool is expanding rapidly. Each year different applications are conceived, a greater acreage is burned, and new techniques are put into practice. New men must be trained to assume leadership in a growing program of prescribed burning. The problems of burning under less than optimum fuel and weather conditions urgently require solution.

The respondents were asked to comment on the future of prescribed fire in the Intermountain West. Their answers to questions on how new men should be trained and how to meet the challenge of an expanding program of prescribed burning are presented in the following sections.

Training New Men

Almost all respondents recommended training through direct contact with the planning and execution of actual fires. On-the-ground training should include visits to the fires of nearby management centers. A few men suggested that trainees be temporarily assigned to burning operations in different parts of the country. The majority of respondents believed that new men learned more by watching burns than by participating in them.

About half of those questioned felt that wildfire experience is useful in prescribed burning. A few men disagreed. The latter group contended that objectives and methods are different in wildfire situations and that there is little opportunity on wildfires to observe the patterns of fire behavior that interest prescribed burners.

Forest management specialists without experience in fire control are using prescribed burning more frequently than in the past. Silviculturists, wildlife biologists, range managers, and entomologists require additional knowledge if they are to make the best use of fire in their work. While fire control specialists will continue to assume major responsibility for burning programs, they can expect that other groups will become more closely involved in setting objectives and planning for prescribed fires. Seminars and training classes on prescribed burning should have high priority in the future. At these sessions, personnel from the several disciplines concerned with using fire can discuss and coordinate plans for the development of their programs.

A Larger Program

How can we efficiently burn a greater acreage? Forty-eight percent of the respondents recommended burning in summer as well as in autumn. Many periods in July, August, and early September are suitable for prescribed fires. Night burning coupled with aggressive mopup the following day was recommended for this season. Summer fires would burn more completely than equivalent burns in the autumn. No one suggested that fires be ignited during periods of high fire danger, but many felt that meteorological conditions were more appropriate for burning in summer than during other times of the year.

About 13 percent of the respondents were in favor of adding a spring burning season. They realized that not all blocks are suited to spring fires, but felt that some of the autumn load could be transferred.

Eight percent of the men suggested that highly specialized crews conduct burns on several administrative units. Eleven percent urged that larger burning blocks be planned to include the same acreage in fewer prescribed fires.

No single solution is available to forest managers facing an enlarged burning program. However, spreading the workload to seasons other than the autumn is the obvious first step.

SUMMARY

The study reported in this paper summarized the experience and opinions of 62 prescribed fire practitioners. The men participating had accumulated over 700 seasons of prescribed burning in all. Most of this experience was gained in the forests of the Intermountain West. Personnel from State, private, and Federal organizations contributed their knowledge during formal interview sessions.

Preparations for Burning

Most prescribed burning has the dual purpose of hazard reduction and site preparation on blocks from which merchantable timber has been harvested. Sometimes logging slash and noncommercial stems are broadcast burned where felled; on other occasions this fuel is hand- or machine-piled, or windrowed by bulldozers. Piled logging slash is usually burned late in the autumn. Broadcast burns are typically scheduled soon after the summer wildfire season is past.

Broadcast-burning blocks range in size from 10 to 400 acres. Optimum size for economic operations was judged to be between 100 and 200 acres.

Layout of the block in relation to topography and adjacent hazards is important to successful burning. Good layout requires a minimum of fireline for the enclosed area, uphill boundaries slightly over ridgetops, and reasonably straight upslope edges. Acute corners and doglegs in the outer fireline are potential trouble spots. Compromises in block layout and size are often necessary due to management needs and the realities of fire behavior.

Firelines are typically constructed by using bulldozers equipped with straight blades. One or two blade widths are usually enough to contain a prescribed fire. A continuous line of mineral soil should surround a burning block, but if soil is mixed with fuels moved by bulldozers, the mopup and control job is increased. Slash remaining outside the firelines can harbor sparks and interfere with control action.

Most respondents preferred to fell all trees larger than 4 inches in diameter on burning blocks before the fire. Shaggy-barked and rotten snags should be felled within the fireline and for a distance of about 1 chain outside the block. Noncommercial trees and snags, when felled, help create the desired uniform fuel bed.

When to Burn

Slash fuels require 1 or 2 months of warm, dry weather to cure before burning. Broadcast fires are easier to plan and conduct if burned while needles remain on the branches. For most species, this means that fires should be scheduled within 2 years of harvest cutting. Fuels without needles can be successfully burned if they are bunched in piles or windrows.

Sixty-two percent of the men interviewed preferred to have less than 1 inch of rainfall on the block before burning it in autumn. North and east aspects and blocks at high elevations should be burned prior to burning south- and west-facing blocks. Hazard-reduction objectives can be met by burning warm hillsides at lower elevations in the spring. Mopup must be thorough after spring fires.

Both early morning and late afternoon are favored times for burning. As autumn progresses, some blocks must be burned during the hottest part of the day. Burning hours vary for different objectives and fuel conditions. Ignition time should be determined by the job, not by the clock.

Fuel moisture sticks have been placed on blocks to help decide when to burn. The recommended range for burning is from 6- to 15-percent moisture content.

Relative humidity greatly influences moisture content of fine fuels and thereby influences the behavior of prescribed fires. A range of from 10- to 50-percent relative humidity is suitable for starting fires. Hygrothermographs are important tools in predicting daily changes in relative humidity. They should be placed on a block a week or two prior to burning to help estimate the time of diurnal rise in humidity.

Sixty-five percent of the respondents liked to burn plots when wind velocity was 10 miles per hour or less. Most preferred calm air for prescribed burning. A few men liked a steady, low-velocity wind to minimize the possibility of fire whirls. Clear, cool weather, when smoke columns rise straight up to high altitudes, was preferred for prescribed burning. Most respondents made use of special fire weather forecasts prepared by fire-weather specialists at Weather Bureau stations throughout the region.

Burning

Plans for prescribed fires require detailed maps that show topographic and cultural features, placement of men and equipment, and proposed patterns of ignition. Ignition and control crews should be familiar with these plans before the fire. Crews should also be advised of the fire's progress and changes in ignition plans. Mopup and patrol action after the fire are essential to prevent escapes at a later time.

Ignition devices should be selected for speed and flexibility in lighting many kinds of fuels. Burning crews can make use of several kinds on different fires.

Both strip and center ignition patterns are used by crews in the Intermountain area. A strong, central convection column tends to make burns more efficient and to reduce escapes.

The problems of controlling prescribed fires are simplified when: (1) The size of control crews is related to the expected difficulty of burning each block; (2) good block layout reduces the possibility of escapes; and (3) a strong central convection column draws flames toward the center of the burn.

Respondents were asked to plan the ignition sequence and placement of equipment in three hypothetical burning blocks. Six different solutions are presented in the body of this paper.

Future Needs

Training new men in prescribed burning techniques requires both field experience, and formal classes and seminars on the subject. Future programs will necessitate a greater exchange of knowledge between fire control personnel and other specialists who use fire in forest and range management.

Burning during spring and certain summer periods can reduce the backlog of unburned blocks and allow increased acreage to be burned each year.

APPENDIX

SURVEY PARTICIPANTS

Forest Service Personnel

Harold E. Anderson
Robert J. Beaubier
Dave R. Brown
Marvin H. Combs
Frederick F. Cougill, Jr.
Floyd R. Cowles
Frederick A. Dorrell
Ralph R. Dyment
Orville E. Engelby
Vernard L. Erickson
Samuel S. Evans, Jr.
E. Maurice Fickes
Alvin J. Flory
Andy O. Fossum
William J. Fredeking
Lawrence D. Glover
Hubert Hanson
Louis F. Hartig
John L. Hautziner
Theodore R. Hay
Robert J. Henderson
H. Reid Jackson
John W. Johnson
Henry L. Ketchie
Theodore W. Koskella
Henry F. Kottkey
David R. Kyle
Richard E. Leicht
John R. Lyman
Fred H. Mass
Robert J. McCarthy
J. Frank Meneely
Ross P. Middlemist
Dan V. Montgomery
Wayne S. Newcomb
Herbert M. Oertli
Earl W. Parks
Homer W. Parks
Clemens J. Pederson
Neil Peterson
Joseph M. Pomajevich
J. Everett Sanderson
William B. Sendt
Clifford T. Solberg
Ralph Space
Clinton F. Spindler (deceased)
John Sudnikovich
Merrill E. Tester
Gustav A. Verdal
Alfred W. Walter
Hubert B. Ward
Donald V. Williams
Floyd E. Williams
Alvis B. Young
Kenneth I. Young
Ulrich H. Zuberbuhler

State and Private Organizations

Ernest B. Corrick	Anaconda Forest Products
A. B. Curtis	Clearwater Timber Protective Assn.
Richard D. Griffith	St. Regis Paper Company
Ralph Hanson	Blackfoot Forest Protective Assn.
Milton O. Koppang	Clearwater Timber Protective Assn.
Carl Managhan	Montana State Forester's Office
Edwin A. Ring	Idaho State Forester's Office
Herman Schultz	Montana State Forester's Office

INTERVIEW QUESTIONS

1. What were the purposes of the prescribed fires?

   a. Are there differences in procedure of timing depending on purpose?

   b. If so, expand each separately per below:

2. How can the fuels be described? How large are the areas to be burned?

   a. Classify by weight per acre, size classes, species, age, depth, and disposition (scattered or continuous).

   b. Does procedure or timing differ depending on fuels?

   c. If so, expand each separately per below:

3. What fuel preparations are necessary?

   a. Felling noncommercial trees. When?

   b. Spraying brush. How recommended? When?

   c. Time required for curing — maximum, optimum, minimum?

   d. Fireline construction.

      (1) Widths recommended for different topographic conditions: flat, 50 percent, 90 percent, V-shaped canyon, ridgetops.

      (2) Adjacent-stand treatment recommendations. Felling snags what distance? Others?

4. Time of burning.

   a. Are there differences in timing due to exposure, slope, and elevation? If so, expand each separately per below:

   b. Time of year.

   c. Time of day.

   d. Recommended fuel moisture content in burn area.

   e. Difference between stick weight in the open and adjacent forest.

   f. How much precipitation do you feel is necessary before autumn burning?

5. What weather conditions are suggested prior to fire? During fire? If a range of weather conditions is possible, what is acceptable for each of the following?

   a. Wind — maximum, optimum, minimum?

   b. Temperature — maximum, optimum, minimum?

   c. Relative humidity — maximum, optimum, minimum?

   d. Synoptic pattern — optimum, marginal?

6. Do you use special fire-weather forecasts?

7. Ignition procedures:

   a. What devices do you use?

   b. What determines firing pattern — center ignition, strip ignition?

   c. What safety measures are needed?

   d. What time sequence is recommended for each kind of firing?

8. What does a well-prepared site look like? Can a prescribed fire be too hot?

9. Control and mopup:

   a. Why have some of your fires exceeded their bounds?

   b. For each reason, how can it be prevented?

   c. What mopup operations do you plan?

10. How should new men be trained? How are we going to accomplish the larger burning job ahead?

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Project headquarters are also at:

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BIBLIOGRAPHY OF HIGH-TEMPERATURE KILN DRYING OF LUMBER

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MECHANISMS OF FIRE SPREAD RESEARCH PROGRESS REPORT NO. 2

by

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MECHANISMS OF FIRE SPREAD
RESEARCH PROGRESS REPORT NO. 2

Field Study
Under
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by

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MECHANISMS OF FIRE SPREAD RESEARCH PROGRESS REPORT No. 2

(Field Study)

INTRODUCTION

In 1961 the National Science Foundation awarded grants to Washington State University and the Northern Forest Fire Laboratory of the Intermountain Forest and Range Experiment Station to further a joint study of the mechanisms of fire spread in wildland fuels. The combined efforts of the two research groups encompass theoretical modeling, laboratory studies, and field investigations of the spread of flame fronts. Of these, the modeling and laboratory studies received the most attention (Anderson 1964), but some field burning was considered essential. The basic objectives of field experiments were to test measurement techniques and the adaptability of laboratory instrumentation to field operations, and to determine correlations between laboratory and field test fires.

Several major problems are encountered in attempting to study wildfire fronts and the mechanisms of their spread. The difficulty of study increases with the size and intensity of the fire. Most of these difficulties arise because of:

1. The extreme variability of fuel and of environmental factors along the front.

2. The complexities of measuring and recording fire characteristics in a moving front.

3. The need for remoteness for the safety of personnel, expensive recorders, and other instrumentation.

4. The lack of time needed to set up and describe an area prior to the passage of the front.

5. The present methods of sampling fuel are destructive and do not permit measurement of the same fuel which burns. Destructively sampling fuel near the fire introduces a high probability of collecting fuel that is significantly different from the fuel that burns.

Initial burns used prepared wooden cribs on level ground. This held factors of kind and arrangement of fuel constant. From the experience gained by burning cribs, networks of thermocouples and recorders were developed for recording temperatures. New photographic techniques were designed for use in measuring flame depth, rate of spread, and residence time.

The next step was to burn test fires in prepared slash fuel beds designed to produce low-intensity fires in fuel uniform in material but varied in size. The study was conducted at the Priest River Experimental Forest in northern Idaho during the 1962 fire season. Results from these fires are the basis for this report. Previous studies of fire spread in logging slash were used in designing these fuel beds (Fahnestock 1960). Tree crown logging slash was collected from active logging areas and loaded into carefully controlled fuel beds. After 3 months of curing, the beds were instrumented and burned. To date no attempts have been made to study the flame fronts of large fires in detail. Exploratory photographic measurements have been attempted on large prescribed fires.

METHODS

PREPARATION OF FUEL BEDS

George Fahnestock's work (1960) on logging slash was a guide for establishing the experimental plots. The purposes of his study and the present one were different. Fahnestock was interested chiefly in comparing the influences of species, loading, and aging on burning slash. He was evaluating factors that influence the burning of natural beds of logging slash. The study reported here was designed to relate flame front characteristics to a specific fuel bed. To facilitate the comparison of data from the two studies, fuel beds were loaded at the same weights per acre (7.5, 20.0, and 32.5 tons per acre) as Fahnestock had used. We used slash from lodgepole pine and Douglas-fir, two of the nine species that Fahnestock studied. Rather than using 20- by 20-foot plots with center firing as Fahnestock had, the 1962 plots were 6 by 60 feet and fired at one end to represent a moving segment of a fire front.

Slash was collected, and 24 plots were prepared at the Priest River Experimental Forest in May 1962. Lodgepole pine and Douglas-fir slash from full tree crowns was collected on nearby State of Idaho lands in active logging area. The bole and large tree limbs were not included. Only the tree tip (4 feet to 6 feet) was included with the branches. This slash was hauled to an experimental burning area on a flat at the southwest end of the experimental forest.

Whole-branch samples were selected from the fuel for moisture content determination by xylene distillation. The moisture determi-

Figure 1 .— Collecting Douglas-fir slash near the Priest River Experimental Forest.

nations were necessary to calculate the wet weight loading of fuel beds which would yield 7.5, 20.0, and 32.5 tons per acre dry weight.

Boundaries for experimental burning plots were laid out with stakes and strings. Thirty-six 6- by 60-foot plots were staked in 6- by 6- foot increments (10 increments for 60 feet). Some plots were not used because of irregularities or roughness of the ground. Twenty-four plots were assigned fuel loadings by random selection. The plots were replicated four times for the two species and three loadings.

Each deposition of slash filled two 6- by 6-foot squares at a time with a predetermined fraction of the total load placed on a bed (fig. 3). For example, the 7.5-ton beds were loaded at 2.5 tons per layer. One sling load filled a 6- by 12-foot area at 2.5 tons per acre. One complete layer was installed at 6- by 12-foot increments. Then a second layer was added but offset 6 feet so that the placing of layers overlapped the end joints as in brickwork. The third layer was the same as the first. This method of loading provided uniformity both horizontally and vertically. More and thicker layers were used to build the 20.0- and 32.5-tons-per-acre beds.

The plots were located in an enclosed area so that they would not be disturbed by livestock. Weed killers were used to prevent plant growth in the plots. All plots were fully exposed to the elements until July 27. Experimental burning was started at that time and was completed within a week.

FUEL BED SAMPLING

Analyses of the fuel beds included prefire and postfire sampling. Before firing, 12- or 18-foot sections of the fuel beds were destructively sampled to determine the distribution of size classes. Fuel components in sampling sections were carefully measured into five diameter classes: <1/8 inch, 1/8 to

Figure 2. — Priest River Experimental Forest outdoor slash laboratory.

1/4 inch, 1/4 to 1/2 inch, 1/2 to 1 inch, and 1 to 2 inches. These size-class measurements were summarized as percents of the total fuel bed ovendry weight. Ovendry weight computations of large segments of fuel sampling beds also provided a cross-check on the weights of plot loadings.

Percentages of moisture content (dry weight basis) were determined by diameter classes to compute size distributions based on ovendry weight. Additional size-class samples were analyzed for moisture content prior to the first fire and following the third fire of each day. Moisture content in fuel elements up to one-fourth inch in diameter was determined by xylene distillation. The larger fuels were dried in an oven at 103° C.

Residue plots were established following three fires to provide estimates of loss of fuel weight during combustion. All ash residue falling within randomized circular plots was collected and weighed, and moisture contents were measured by xylene distillation. The total ovendry weights of residue on the three fires were computed from these data. The fires chosen for residue sampling were Fire No. 7 (Douglas-fir, 32.5 tons/acre), Fire No. 8 (Douglas-fir, 20.0 tons/acre), and Fire No. 10 (lodgepole pine, 32.5 tons/acre). Heat of combustion of the residue was measured in an oxygen bomb calorimeter.

Figure 3. — Slash was weighed in a sling suspended from a scale and then loaded into the plots.

The heats of combustion of the five diameter classes were recorded. Three separate samples were ignited in the bomb calorimeter to determine an average heat value for each size class. Additional sample pellets were dried in an oven at 103° C. to determine moisture content. Determinations of heat of combustion were corrected to ovendry weight, and all heat contents were expressed as the low heat values.[1]

[1] *The low heat value was calculated by assuming that the fuel was 50 percent carbon, 44 percent oxygen, 6 percent hydrogen, and formed 0.539 pound of water vapor for each pound of dry fuel (Fons et al. 1960). This water vapor reduced the high heat value by 0.539 × 972 B.t.u./lb., or 524 B.t.u./lb., due to the latent heat of vaporization.*

INSTRUMENTATION

Since this was the project's first attempt at quanitative field measurements of flame fronts, the number of individual measurements was limited to allow maximum utilization of manpower and instrumentation. Photographic measurement, visual observation, and electronic instrumentation were used to evaluate each method and to provide correlation checks. Measurements made during the burning included photographic recording of the rate of spread, flame depth, flame height, and flame angle; visual observation of rate of spread, wind angle of attack, and fire behavior; and electronic recording of rate of spread, flame depth, vertical temperatures,

Figure 4. — Separating Douglas-fir slash into size classes.

flame base temperature profile, residence time, convection column velocity, and ground wind velocity.

The four instrumentation stations on each fuel bed were set up over the longitudinal centerline of the bed at the 12-, 24-, 36-, and 48-foot points along its length. Twelve stations were fabricated so that fuel beds were intsrumented three at a time.

The instrumentation stations were designed to be as portable as possible. The main support assembly was fabricated in the shape of an "F" with 3/4-inch and 1-inch iron pipe. The leg of the support assembly stood at the side of the fuel bed and fitted into an iron sleeve molded into a portable concrete base. The arms of the "F" assembly reached out over the fuel bed to the centerline. A horizontal bar attached at a right angle to the end of the lower arm of the "F" was parallel to the centerline of the fuel bed. The whole assembly was raised or lowered to position the horizontal bar 6 inches above the mean fuel surface. The top arm of the "F" was 10 feet above the surface of the bed.

Instrumentation on each support assembly consisted of six chromel-alumel thermocouples mounted on the horizontal bar at 9-inch intervals: six chromel-alumel thermocouples mounted on a steel wire stretched vertically from the lower to the upper arms of the "F" (attached 1, 2, 4, 6, 8, and 10 feet above the

Figure 5. — A lodgepole pine plot being burned. Note the four instrumented stations connected by landlines to the monitoring instruments.

fuel bed); and a Kiel probe at the expected vertical height of the flame.

The thermocouple leads were fed through the support assembly pipes to the thermocouple junction position. The signal leads were extended behind the support assembly to an ice bath where reference junctions were made. Landlines carried the signals from the ice bath to a switching box for selection of the desired station signals. From the switching box, signals were fed to two light beam oscillographic recorders. This arrangement allowed monitoring of all four stations of a fuel bed with two recorders by switching as the flame front progressed (figs. 5 and 6).

All thermocouples were butt-welded 24-gage chromel-alumel cut to equal lengths so the total source resistance sensed by the galvanometers was nearly the same. Measurement of the total source resistance showed the maximum variation in any one channel to be 1.72 ohms. Calculation of the change in sensitivity showed the possible variation in indicated temperature at a full-scale deflection would be 4° F. This would be an error of 0.2 percent at a temperature of 2,000° F. The possible error due to the thermocouple material would be 0.75 percent at 2,000° F. The response time of the light beam galvanometers with the equivalent source resistance was 0.05 second for 63 percent of the input change. The thermocouples were the source of greatest inaccuracies because of their time response and errors due to radiation and conduction losses or gains. Using an average velocity of 12 feet per second and 500° F. as the average temperature encountered, the response time of the thermocouples was calculated to be about 1.75 seconds for 63 percent of a step change in temperature. Because of the lag in time response of the thermocouples, the true maximum or minimum temperature may not be indicated. The indicated temperature was felt to be within ±10 percent of the maximum operating temperature for the thermocouple material used.

A microdifferential pressure transducer was used to measure the dynamic pressure in the convection column above the fire. The pressure from Kiel probes over the fire was routed to the transducer, which measured the differ-

Figure 6. — A closeup of the horizontal bar attached to each instrumented station.

ential pressure (ΔP) between a selected probe and atmospheric pressure. The convection column temperature was taken simultaneously with the dynamic pressure so that the convection column velocity at that point could be computed.

The Kiel probes were at fixed heights of 4, 7, and 10 feet above the fuel beds. Once attached to stations, these probes could not be moved during the fire; consequently, the readings came sporadically as wind allowed the fire to stabilize beneath a probe. A probe on each of the four stands permitted four opportunities to obtain useful data as the fire traveled along the 60-foot fuel bed.

In addition to the instruments at the stations, a directional hot wire anemometer was positioned 5 feet from the edge of the fuel bed, 3 feet above the ground and aligned with the fuel bed to measure the ground wind velocity. A wind speed and direction indicator was positioned similarly to determine wind direction.

A specially modified battery-powered motion picture camera was set up on a tripod at right angles to the length of the fuel bed. An electronic timer and battery-powered motor drove the camera for 6 seconds at 1-minute intervals. High-speed color film (ASA 160) permitted rapid exposure with good resolution.

Three new fuel beds were selected and instrumented each day, alternating between Douglas-fir and lodgepole pine. One bed of each loading (7.5, 20.0, and 32.5 tons per acre) was burned each day. Replicates were chosen at random. Burning always progressed from the heaviest loading to the lightest in sequence, and all plots were burned from south to north.

MEASUREMENTS

Rate of spread. — Rate of spread of the flame front was recorded for later analysis on motion picture film and by temperature traces of evenly spaced thermocouples on oscillograph recorders. The photographic data were taken in 6-second bursts (32 frames per second) at 1-minute intervals. Rate of spread was determined by scaling the distance the fire advanced in 1 minute.

Thermocouples were located at 9-inch intervals at each station. As the fire passed, the temperature rise was recorded by the oscillograph. Rate of spread was then taken from the temperature rise times of the traces as the fire moved from thermocouple to thermocouple. Since stations were spaced 12 feet apart, the rate of spread from station to station was also measured. The rate of spread from the first to last thermocouple at each station provided a third method of measuring rate of spread.

Flame depth. — Flame depth is defined by the distance from the leading edge of the frame front to the rear edge of the solid flaming area. Flame depth was measured directly from the photographic data. The flame depth was also calculated from the thermocouple residence time data using the formula $D = R_s \times T_r$

where

D = flame depth—ft.

R_s = rate of spread—ft./min.

T_r = residence time—min.

Residence time is defined as the length of time the flame is supported at a fixed location. Residence time may be taken from a thermocouple trace between the time of temperature rise to the time the temperature starts to drop.

Combustion rate. — The measured flame depth, rate of spread, and pounds of fuel per square foot were combined to determine rate of combustion of fuel in pounds burned per square foot per minute. We assumed that all the fuel was consumed by the flame front. The following equation describes the combustion rate per unit area:

$$G = \frac{R \times W}{D}$$

where

G = burning rate—lbs./ft.^{2}/min.

R = rate of spread—ft./min.

W = weight of fuel burned per unit area —lb./ft.^{2}

D = depth of flaming zone—ft.

Other studies (Thomas et al. 1961; Fons et al. 1962) show a correlation between flame length over flame depth and burning rate.

The equation used by Thomas was:

$$\frac{L}{D} = f\left(\frac{Q^2}{gD^5}\right)$$

where

L = flame length—ft.

D = flame depth—ft.

Q = volumetric flow of gaseous fuel—ft./min.

g = acceleration due to gravity—ft./min.²

Fons used a similar equation:

$$\frac{L}{D} = f\left(\frac{C^2G^2}{\rho^2 gD}\right) = f\left(\frac{V^2}{gD}\right)$$

where

C = lbs. of gas produced per lb. of fuel

G = burning rate—lbs./min./ft.²

ρ = density of gases—lb./ft.³

g = acceleration due to gravity—ft./min.²

V = combustion gas velocity—ft./min.

In either case, g is present to make the functional relation dimensionless and indicates the process is gravitationally controlled. These relations can be extended to make the function dependent upon G, the unit area burning rate:

$$\frac{L}{D} = f\left(\frac{Q^2}{gD^5}\right) = f\left(\frac{V^2}{gD}\right) = f\left(\frac{G}{\rho(gD)^{1/2}}\right)$$

A later study (Thomas 1963) showed that the relation held for several types of fuel media and included some of Fons' (1960) earlier work. This indicated the probability of any diffusion type flame fitting somewhere along this curve (Thomas 1961, 1963).

Vertical temperature profile. — The vertical thermocouples at each station produced measurements of the temperature gradient from points 6 inches to 10 feet above the fuel surface. The maximum temperature zone was determined for each elevation in each fuel type and loading. The average temperature was then determined at each elevation.

Fuel compactness. — One of the most difficult fuel bed parameters to assess is the compactness[2] of the fuel bed. Tests conducted to determine the influence of compactness on rate of spread (Curry and Fons 1939) showed rate of spread to be proportionate to the square root of λ (volume per surface area).

In order to evaluate compactness, the following items must be determined:

1. Volume of fuel bed. This factor can be obtained easily for prepared fuel beds. For prescribed fires and uncontrolled fires, considerable difficulty arises.

2. Weight of the fuel bed or loading. The statements in 1 above apply to this factor.

3. Fuel size and proportion of total weight. For laboratory fires where only needles are used, no difficulty exists. For tests where slash is used or for other fires mentioned above, destructive sampling is necessary.

4. Density of fuel particles. Values are available for needles and wood and are usable for specific fuel beds of these materials. When the fuel particles can be a combination, the needles become one size class and the twigs and branches are broken into size classes and given an estimated density.

5. Fuel particle surface area-to-volume ratio. Past studies by Curry and Fons (1939) and Fons (1946) provide values for various fuels. Not all fuels are covered, and additional studies are needed. Since the values for the above factors are known, the compactness of each fuel bed can be calculated.

The equation for compactness is:

$$\frac{1}{\lambda} = \frac{\Sigma(\sigma_1 V_1 \text{ - - - } \sigma_n V_n)}{V_T - \Sigma\left(\frac{\%_1 W_T}{\rho_1} \text{ - - - } \frac{\%_n W_T}{\rho_n}\right)}$$

where

$\frac{1}{\lambda}$ = compactness—ft.²/ft.³

σ = surface area-to-volume ratio for size —ft.²/ft.³

V = volume for size class—ft.³

$\% W_T$ = percent of fuel bed weight for size class—lbs.

ρ = density for size class—lb./ft.³

[2]*Fuel bed compactness is defined as the surface area of the fuel divided by the void volume of the fuel bed (ft.²/ft.³). The void volume of the fuel bed is the total geometric volume minus the volume occupied by the fuel.*

WEATHER

All experimental plots were burned in very dry, hot weather during the period July 27 through August 2, 1962. Accumulative drying had been so good that the logging slash was thoroughly seasoned and highly flammable. A condensed record of the weather on the burning days is shown in table 1.

Table 1. — **Weather observations at test fire site**

Date	Hour	Dry bulb	Wet bulb	Humidity	Average wind	Fire number and hour test fire was ignited	
		°F.	°F.	Percent	M.p.h.		
7/27/62	0900	70	60	57			
	1250	87	64	28	4.0	1	1250
	1345	87	64	28	4.5	2	1345
	1440	90	64	24	4.0		
						3	1500
	1620	90	64	24	3.0		
7/28/62	1550	94	64	18	7.0		
	1620	93	64	20	5.0	4	1630
						5	1731
	1800	92	64	21	7.0		
						6	1815
7/30/62	0840	68	57	52	1.5		
	1000	79	61	36	3.0		
	1100	81	61	32	3.0		
						7	1126½
	1200	85	62	27	7.5		
						8	1209
	1255	89	63	23	4.5	9	1254¼
	1725	90	63	21	4.0		
7/31/62	0820	68	58	56	4.0		
	1000	81	61	32	5.0		
	1115	85	63	30	3.5		
	1320	90	63	21	3.0		
						10	1351
	1410	93	63	18	3.5		
						11	1449
	1525	94	63	16	5.0		
						12	1536
	1620	92	62	17	6.5		
8/1/62	1100	83	63	33	4.0		
	1400	90	65	26	5.5		
	1645	91	64	22	2.0		
						13	1700
	1725	92	64	21	4.0		
						14	1735½
	1800	92	64	21	2.0		
						15	1820
	1845	82	64	38	1.0		
8/2/62						16	1031
	1036	71	62	61	2.5		
	1115	70	61	61	0.5		
						17	1133
	1213	78	63	44	6.0		
						18	1258½
	1323	80	64	42	4.0		

EXPERIMENTAL RESULTS

FUEL BED EVALUATIONS

Diameter size class distribution. — The size class distribution indicated that the fine fuel components (fuels one-fourth inch and smaller) comprised 39 percent of the lodgepole pine and 34 percent of the Douglas-fir fuel beds on an ovendry weight basis (table 2). An intraspecies comparison presented a fair degree of uniformity of fuel bed loadings by size class. Interspecies loading differences appeared when the average percent of total fuel bed weight of lodgepole pine was contrasted with that for Douglas-fir. Lodgepole pine fuel beds usually contained a greater percentage of branchwood in the 1/8- to 1/4-inch and 1/4- to 1/2-inch size classes. The other size class where the species' percentage composition differed markedly was from 1 to 2 inches. Twenty-seven percent of the Douglas-fir fuel and 14 percent of the lodgepole pine were this larger branchwood.

Table 2. — Percent of total fuel bed weight (ovendry), by diameter size class and loading, for lodgepole pine and Douglas-fir

Diameter size class (inches)	Lodgepole pine			Douglas-fir			Average percent of total weight by diameter size class	
	Loading (tons per acre)							
	7.5	20.0	32.5	7.5	20.0	32.5	L.P.P.	D.F.
< 1/8	22.33	19.87	26.69	15.97	32.16	32.27	22.93	28.14
1/8 - 1/4	12.64	17.61	18.38	5.14	6.46	3.99	16.21	5.51
1/4 - 1/2	26.94	20.50	20.41	9.03	10.98	9.68	22.62	10.17
1/2 - 1	29.50	23.60	20.66	28.25	31.23	25.60	24.59	29.08
1 - 2	8.59	18.42	13.86	41.61	19.16	28.46	13.62	27.10

Fuel bed loading. — The determinations of ovendry weight of large portions of fuel beds permitted the comparison of the actual fuel bed weights with the theoretical fuel bed weights (table 3). During preparation of fuel beds, concurrent moisture content measurements of the slash determined the weight (ovendry basis) of material needed to achieve loadings equaling 7.5, 20.0, and 32.5 tons per acre. Duplicating these loadings required the placement of 120, 320, and 520 pounds, respectively, on the 6- by 60-foot plots. Success in closely approximating the theoretical pounds of fuel (ovendry basis) required per loading depended largely on moisture fluctuations within the fuel. These results reflect the conditions under which the fuels were collected. Lodgepole pine, which deviated very little from the theoretical loadings, was collected from trees during an active logging operation. Therefore, moisture was relatively uniform throughout the slash. Douglas-fir was collected several weeks after logging, and actual loadings deviated considerably from theoretical loadings.

Table 3. — **Deviations of weights of fuel in beds from theoretical ovendry weight loadings**

Loading (tons/acre)	Theoretical bed weight	Lodgepole pine actual bed wt.	Deviation	Douglas-fir actual bed wt.	Deviation
	Lbs.	Lbs.	± (lbs.)	Lbs.	± (lbs.)
7.5	120	122.4	+ 2.4	181.6	+61.6
20.0	320	336.0	+16.0	266.6	−53.4
32.5	520	522.7	+ 2.7	486.5	−33.5

Moisture content. — Moisture content of fuel was measured before the first fire and after the third fire on each day. Fuel moisture content of the second fire was computed by straight-line interpolation. Almost without exception, fuels in the three larger size classes did not vary in moisture content during an afternoon's burning (table 4). The time lag of the two smaller size classes was short enough to produce diminishing moisture trends in most instances.

Table 4. — **Moisture content of lodgepole pine and Douglas-fir slash by size class**

Fire number	Species	Loading	Moisture content (by size class)				
			<1/8"	1/8-1/4"	1/4-1/2"	1/2-1"	1-2"
		Tons/acre	Percent				
1	Fir	32.5	7.9	8.9	10.8	9.9	12.1
2	Fir	20.0	7.3	8.5	10.8	9.9	12.1
3	Fir	7.5	6.5	8.0	10.8	9.9	12.1
4	Pine	32.5	8.1	8.1	11.8	14.2	14.0
5	Pine	20.0	7.5	7.9	11.8	14.2	14.0
6	Pine	7.5	7.1	7.7	11.8	14.2	14.0
7	Fir	32.5	6.9	7.1	8.0	9.3	9.4
8	Fir	20.0	6.6	6.8	8.0	9.3	9.4
9	Fir	7.5	6.2	6.4	8.0	9.3	9.4
10	Pine	32.5	5.8	6.8	8.5	9.5	10.4
11	Pine	20.0	5.8	6.8	7.8	9.1	10.4
12	Pine	7.5	5.8	6.8	7.4	9.0	10.4
13	Fir	32.5	5.4	6.1	9.8	10.3	11.6
14	Fir	20.0	5.4	6.1	9.8	10.3	11.6
15	Fir	7.5	5.4	6.0	9.8	10.3	11.6
16	Pine	32.5	8.4	7.8	10.3	9.5	10.3
17	Pine	20.0	7.8	7.6	10.3	9.5	10.3
18	Pine	7.5	7.4	7.4	10.3	9.5	10.3

Table 5. — **Heat of combustion of lodgepole pine and Douglas-fir by size class**

Diameter size class (inches)	Heat of combustion[1]	
	Lodgepole pine	Douglas-fir
	B.t.u./lb.	
< 1/8	[2]8713 ± 12.39	8139 ± 22.08
1/8 - 1/4	8704 ± 6.69	8524 ± 16.54
1/4 - 1/2	8519 ± 31.61	8305 ± 17.43
1/2 - 1	8397 ± 49.76	8268 ± 18.70
1 - 2	8455 ± 26.74	8451 ± 18.15

[1]Expressed as low heat value on ovendry basis.
[2]The ± values are standard errors of the mean.

Table 6. — **Heat of combustion of residue and fuel bed weight loss**

Fire	Heat of combustion[1]	Weight of residue	Fuel bed weight loss	Weight loss
	B.t.u./lb.	Lbs.	Lbs.	Pct.
No. 7 Douglas-fir 32.5 T/A	[2]5365 ± 20	51.75	434.75	89
No. 8 Douglas-fir 20.0 T/A	8016 ± 278	45.12	221.48	83
No. 10 Lodgepole pine 32.5 T/A	9041 ± 184	39.37	483.33	92

[1]Expressed as low heat value on ovendry basis.
[2]The ± values are standard errors of the mean.

Heat of combustion. — Heat values by size class were determined for both species (table 5).

The heat of combustion of the residue was determined for three fires and weight loss of fuel beds was computed (table 6).

Fire intensity. — In order to compare fires burned at different times, under different loading conditions, or using different fuel types, some measurement of fire intensity was necessary. Comparing only rates of spread was not sufficient since laboratory studies have shown that two fires in different fuels may have the same rate of spread but different rates of fuel consumption. If fuel consumption rate could be measured in the field, then a means of comparison would be available. Since equipment to do this was not available, other measurements were used.

Byram defined fire intensity as the rate of energy release, or rate of heat release, per unit time per unit length of fire front (Davis et al. 1959). In equation form, fire intensity can be written as:

$$I = HWR$$

where

I = fire intensity in B.t.u. per unit time per unit length of fire front

H = heat yield in B.t.u. per pound of fuel

W = weight of available fuel per unit area

R = rate of spread in unit length per unit time.

Use of this equation can give some numerical concept for comparing individual fires but may be deceptive if no other fire parameter than rate of spread is used. Fons et al. (1962) extended this equation and showed a relation between flame length and fire intensity. This relation can be described mathematically by $L = 0.74(HWR)^{.667}$ where L is flame length. The results of the test field fires were analyzed and plots made for the fuel types (table 7 and fig. 7). For lodgepole pine we found $L = 0.43(HWR)^{0.651}$ and for Douglas-fir $L = 0.26(HWR)^{0.670}$. The heat yield was assumed to equal the heat of combustion for this analysis.

The results were compared with those from Project Fire Model (fig. 7) and showed essentially the same slope for all fires. However, each fuel had a separate curve. If fires in each fuel produced flame lengths of 60 inches, intensities varied from 715 B.t.u./min./in. for Fire Model cribs to 3390 B.t.u./min./in. for Douglas-fir slash. This demonstrated that a single curve did not satisfy fire conditions in all fuels. Thus, more investigation is required before a complete description can be made.

As a relative measure, fire intensity can be useful. The three fires analyzed for residual heat of combustion were used to determine where the test field fires would fall on the intensity scale (table 8).

Before fire intensity can be described numerically, the heat yield of the fuel must be defined. This heat yield is equal to the heat of combustion minus the heat losses resulting from radiation, vaporization of moisture, and incomplete combustion (Davis et al. 1959).

Table 7. — **Fire intensity test data**

Fuel type and loading (tons/acre)		Loading	Heat value	Rate of spread	Rate of spread	Fire intensity	Fire intensity	Flame length
		Lbs./ft.^{2}	B.t.u./lb.	Ft./min.	Ft./sec.	B.t.u./sec./ft.	B.t.u./min./in.	Inches
Douglas-fir:								
32.5	1	1.35	8292	5.15	0.086	963	4815	71.8
	2	1.35	8292	7.20	0.120	1343	6715	76.8
	3	1.35	8292	5.40	0.090	1007	5035	85.1
20.0	1	0.74	8281	5.05	0.084	515	2575	48.8
	2	0.74	8281	4.82	0.080	490	2450	49.7
	3	0.74	8281	3.39	0.056	343	1715	46.5
7.5	1	0.50	8340	2.59	0.043	179	895	31.7
					0.088	367	1835	31.1
	3	0.50	8340	—	—	—	—	30.0
Lodgepole pine:								
32.5	1	1.45	8571	3.53	0.059	607	3035	101.5
	2	1.45	8571	3.40	0.057	708	3540	86.0
	3	1.45	8571	4.80	0.080	994	4970	114.2
20.0	1	0.93	8550	5.90	0.098	779	3895	79.0
	2	0.93	8550	2.70	0.045	358	1790	70.0
	3	0.93	8550	1.79	0.030	238	1190	47.2
7.5	1	0.34	8544	4.70	0.078	226	1130	41.8
	2	0.34	8544	5.22	0.087	253	1265	45.2
	3	0.34	8544	—	—	—	—	45.8

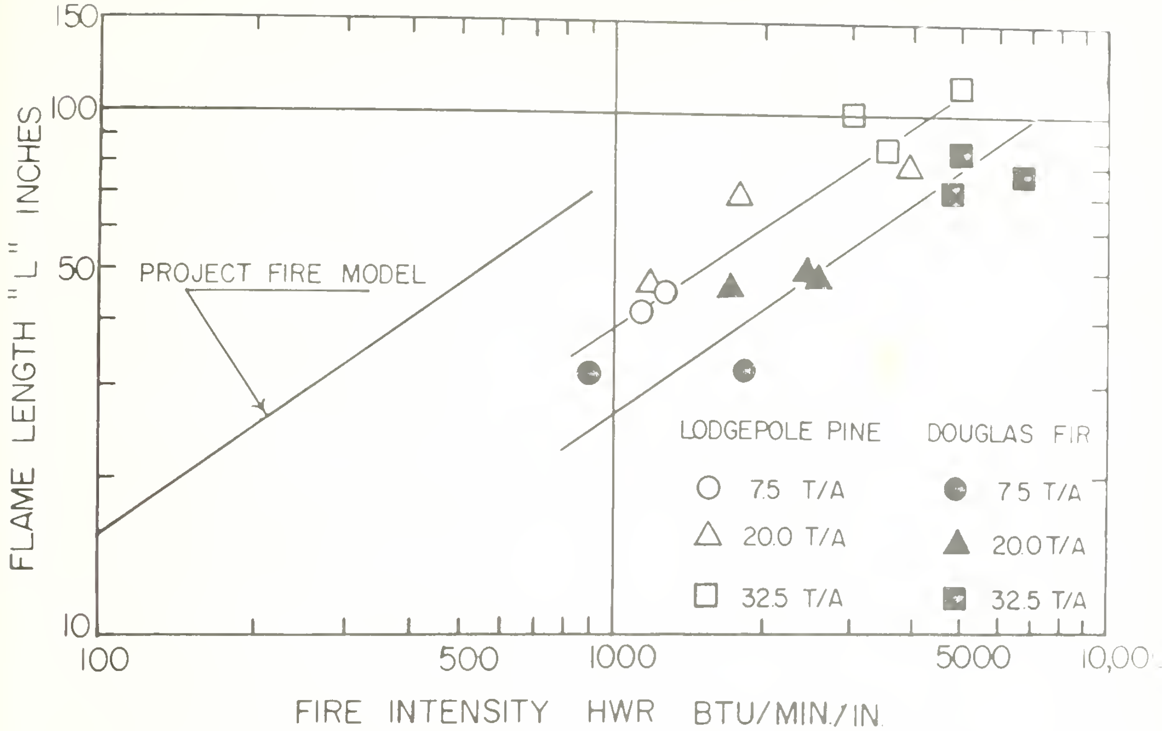

Figure 7. — Flame length as a function of fire intensity for three different fuels in two different fuel beds.

Table 8. — **Fire intensity based on equation I = HWR**

Fire number	Species	Loading	Heat yield (H) [1]	Fuel weight (W)	Rate of spread (R)	Intensity
		Tons/acre	B.t.u./lb.	Lbs./sq. ft.	Ft./sec.	B.t.u./sec./ft.
7	Douglas-fir	32.5	6715	1.35	0.129	1169
8	Douglas-fir	20.0	6680	0.74	0.064	316
10	Lodgepole pine	32.5	7145	1.45	0.059	611

[1]Heat yield is defined as the heat of combustion minus the heat losses due to radiation, vaporization of water, and inefficient combustion. For each fuel, radiational heat loss was established as 800 B.t.u./lb. and latent heat of vaporization loss as 524 B.t.u./lb. Heat losses due to incomplete combustion varied by fire as follows: (1) Fire 7, 570 B.t.u./lb., (2) Fire 8, 1357 B.t.u./lb., and (3) Fire 10, 681 B.t.u./lb. These values represent fuel energy that was not released, rather than actual heat losses.

Byram states that radiation accounts for 10 to 20 percent of the heat of combustion. He feels that a 10-percent loss might be a more realistic figure since some of the radiated heat is returned to the active fire system in preheating unburned fuel. The heat balance developed by Fons et al. (1960) contributed 18.1 percent of the total heat value of the fuel to radiation. In the Priest River analysis the radiational heat loss was arbitrarily set at 800 B.t.u. per pound — slightly less than a 10-percent deduction.

The heat loss due to the vaporization of the water of reaction was accounted for. All measurements of heat of combustion were expressed in terms of the low heat value, which reduces the high heat value by the latent heat of vaporization (524 B.t.u./pound).

The heat loss due to incomplete combustion is not known for forest fires. However, combustion inefficiency must be determined to compute heat yield of a fuel. Sampling residual fuel weight and residual heat of combustion following three fires provided this necessary heat loss data.

Byram reports that a majority of wildfires probably has intensities in the range from 100 to 1,000 B.t.u. per second per foot of fire front (1959). Intensity values of these experimental field fires fall within this proposed wildfire range.

FIRE CHARACTERISTICS

Rate of spread. — Only a few fires showed a uniform rate of spread from beginning to end. Most variations in rate of spread for individual fuel beds could be attributed to changes in wind velocity. Since the photographic measurements of rate of spread at 1-minute intervals did not give uniform rates for the fuel beds, the average for the beds

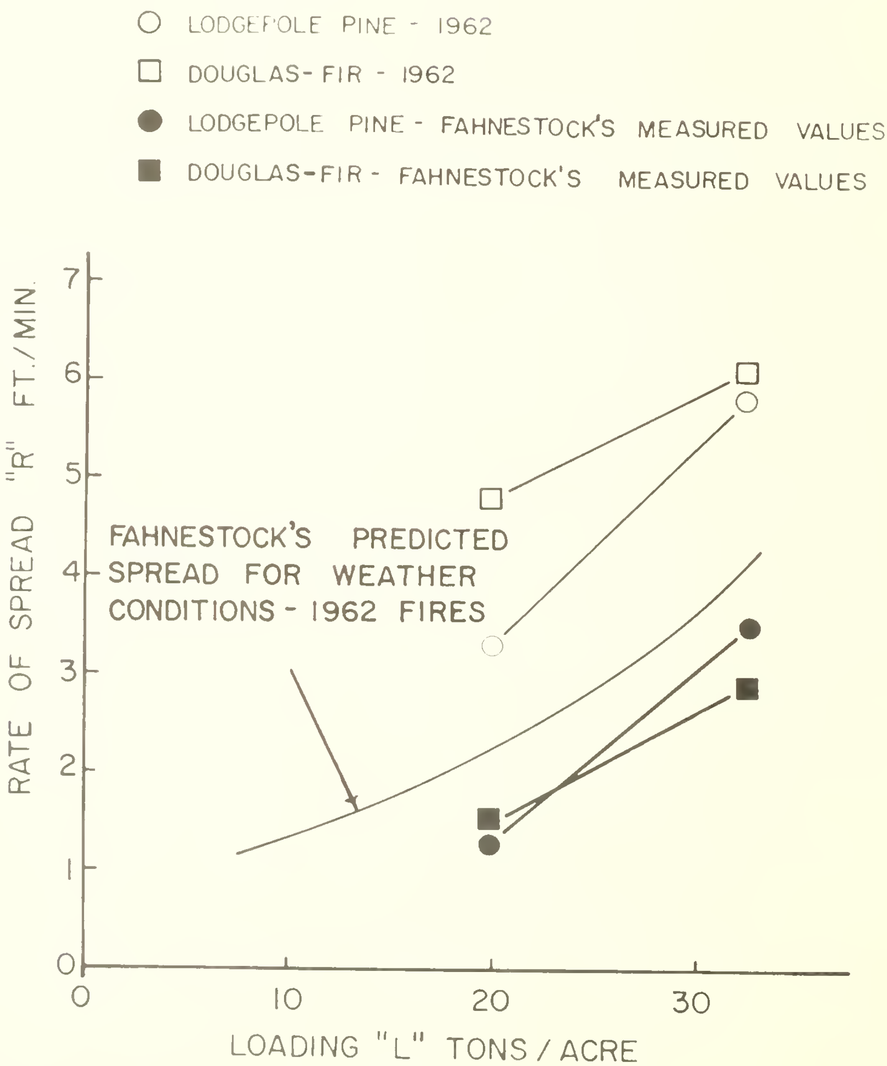

Figure 8. — Influence of loading on rate of spread in fuel beds either end-fired or center-fired.

was used. Average rates of spread for the full length of the plots for each species by loading are shown in figure 8. Most of the 7.5-ton-per-acre beds did not burn for the full length and therefore are not plotted in figure 8. Fahnestock's (1960) results for the same species and loading are presented for comparison. The curves are very similar but his rates of spread were much lower. This can be accounted for by the less severe weather Fahnestock encountered during his experiments. Too, Fahnestock center-fired his plots; this caused an inflow of air to the convection column that further retarded the forward movement of the flame front.

Rates of spread shown by the thermocouples were even more erratic. The thermocouples were apparently too high (6 inches) above the fuels; this allowed them to be alternately in or out of the flame as it moved about in the air currents. Better results probably would have been achieved if the thermocouples had been placed at the fuel surface. By utilizing the longer spans between the first and last couples at a station, or the

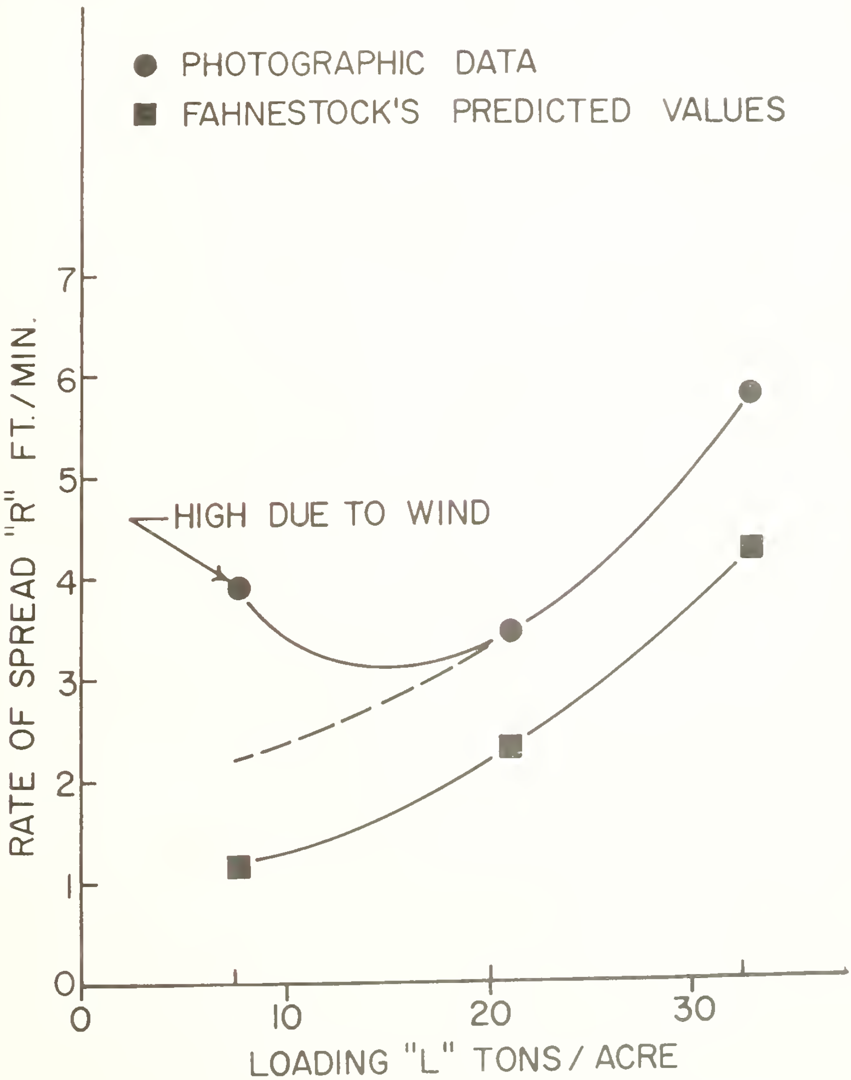

Figure 9. — Influence of loading on rate of spread in lodgepole pine comparing photographic average values with predictions from Fahnestock's equations.

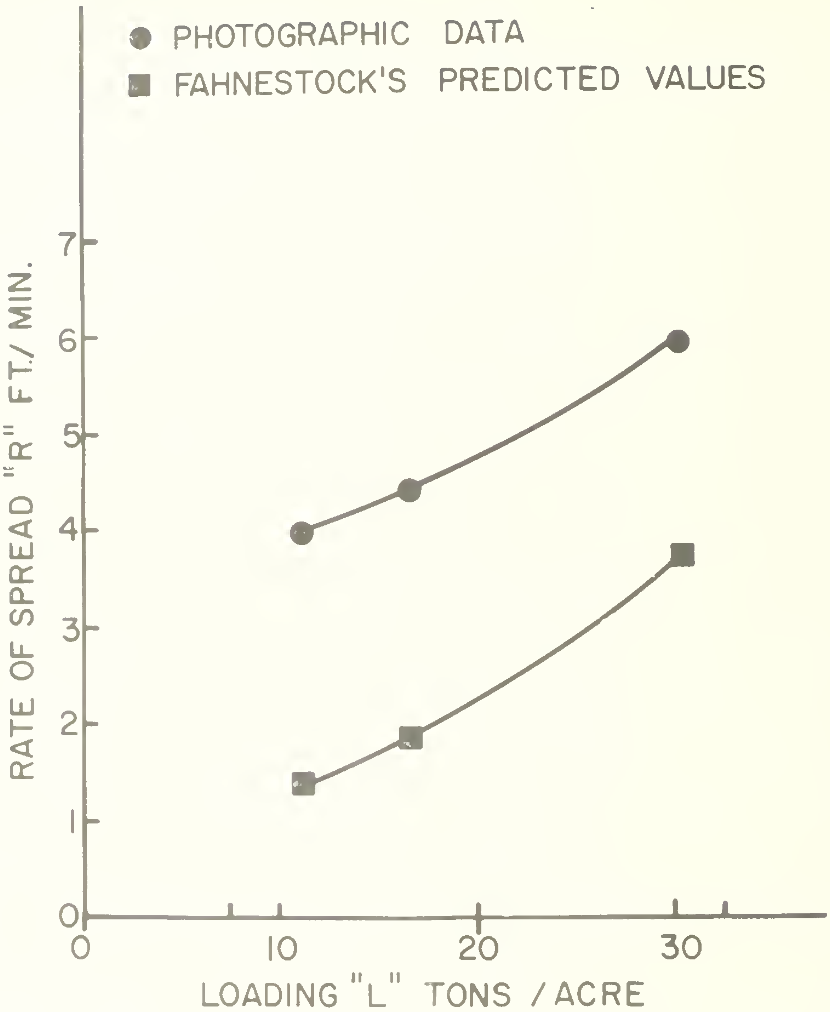

Figure 10. — Influence of loading on rate of spread in Douglas-fir comparing photographic average value with predictions from Fahnestock's equations.

distances between stations, uniform spreads were measured which produced usable results. Figures 9 and 10 show the comparison of the average rates of spread measured by photography with the rate of spread predicted by Fahnestock's equations.

Our experiments indicated that loading influences rate of spread, but that the wind is a stronger influence. The effect of wind upon rate of spread was studied for each species without segregating the data for loading or fuel moisture. An exponential function appears to fit the data the best, and regression analysis of the logarithm of rate of spread against wind velocity gave a separate equation for each fuel type.

$$R_{LP} = 3.48\ e^{.00192U}$$

where

R_{LP} = rate of spread of lodgepole pine fuel beds—ft./min.

U = windspeed—ft./min.

The equation was derived for windspeeds from -400 to $+400$ ft./min.

$$R_{DF} = 2.66\ e^{.00388U}$$

where

R_{DF} = rate of spread of Douglas-fir fuel beds—ft./min.

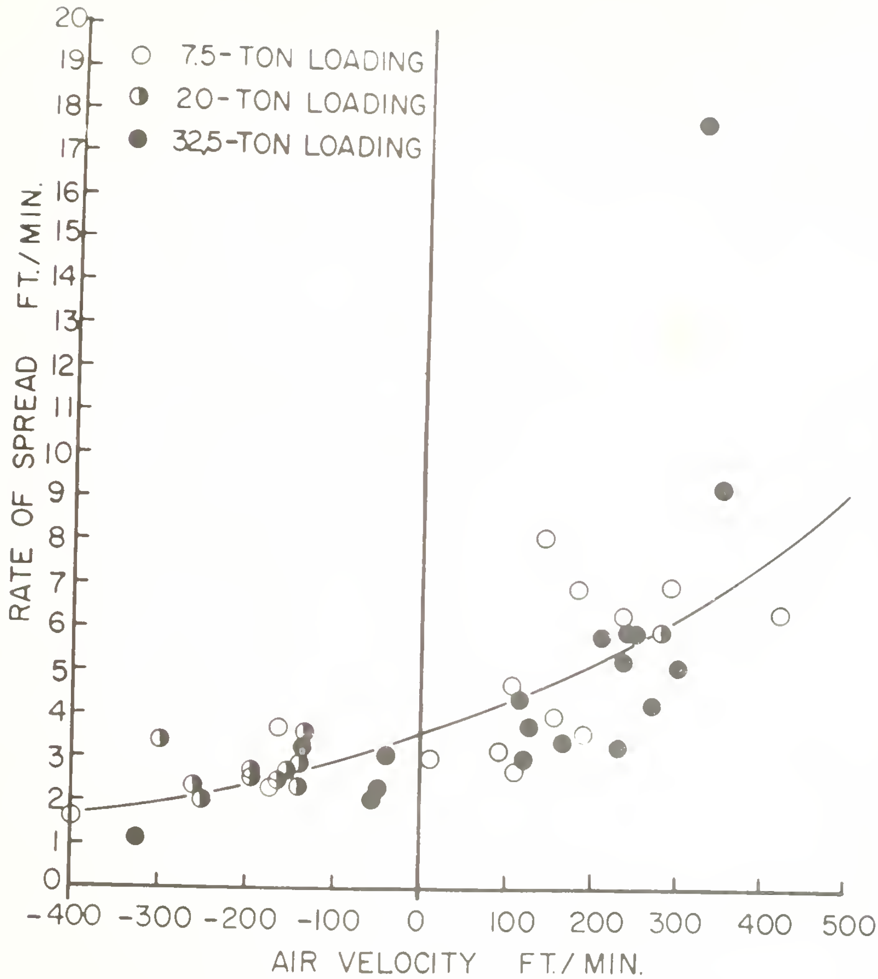

Figure 11. — Wind effects on rate of spread in lodgepole pine fuel beds.

Plots of these equations (figs. 11 and 12) show that the influence of wind largely overshadowed the effects of loading. For example, the three lodgepole pine fuel beds loaded at 32.5 tons per acre had average rates of spread vs. average windspeeds:

R	U
9.1 ft./min.	327 ft./min.
5.3 ft./min.	267 ft./min.
3.5 ft./min.	58 ft./min.

Rate of spread is proportional to loading and windspeed. However, not enough test samples were obtained to describe the relationship accurately. More laboratory work will help establish this, and later fieldwork will indicate the relation between laboratory and field fires.

Flame depth. — Measurements of flame depth by photographic and electronic methods (fig. 13) agreed so poorly that we know one or both techniques need improvement. The most probable causes of error were: placement of thermocouples too high above the fuel bed; misjudgment of flame depth because the flame front was skewed; and parallax effects because of camera angle. Since more photographic measurements were available,

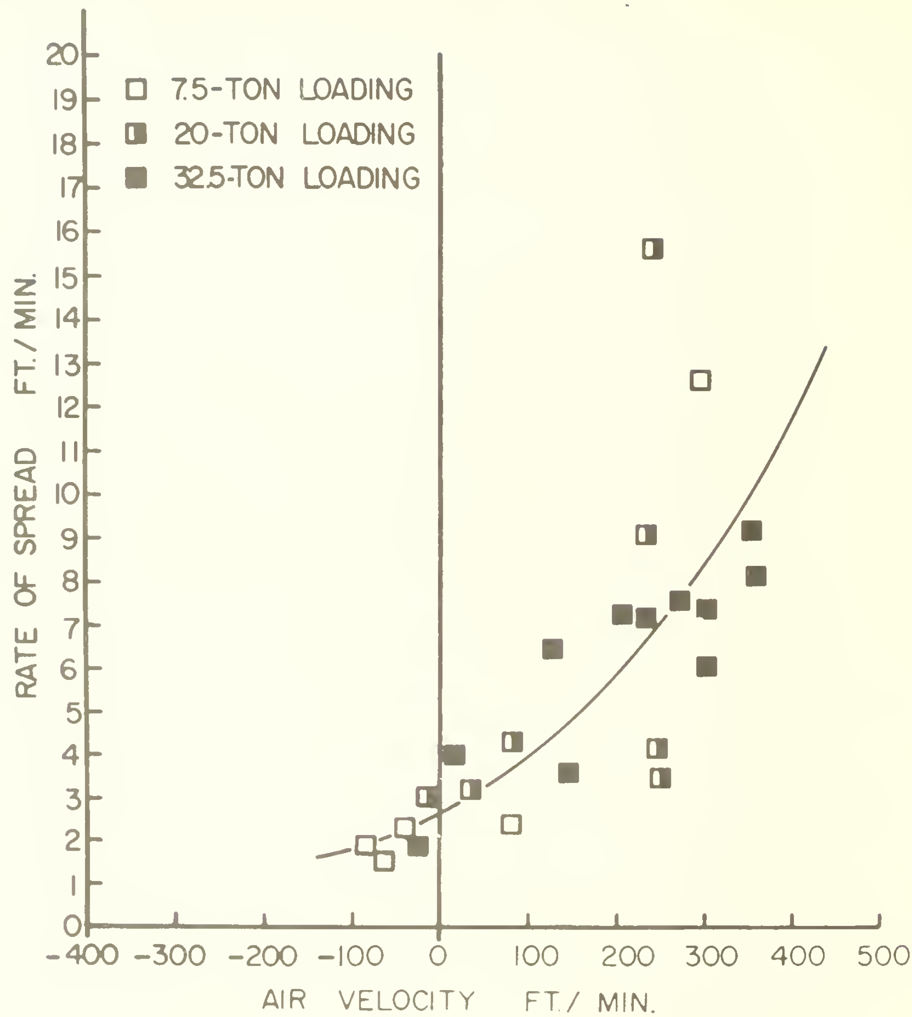

Figure 12. — Wind effects on rate of speed in Douglas-fir fuel beds.

they were used in later calculations of combustion rate.

Combustion rate. — Combustion rates calculated from the equation:

$$G = \frac{R \times W}{D}$$

where

G = unit area burning rate, lb./min./ft.^{2}

R = rate of spread, ft./min.

W = loading, lbs./ft.^{2}

D = flame depth, ft.

are plotted against loading (fig. 14). The effect of loading appears to be the same for both fuels, but characteristics of the fuels cause the burning rates to be different. The primary fuel particle size may be important. The same principles developed by Thomas (1963) and Fons (1962) on diffusion flames should apply to the test fires in the field. The major difference is that the field fires could not be considered symmetrical and probably were offset for this reason. The relation used for determining the diffusion flame characteristics of these fires was:

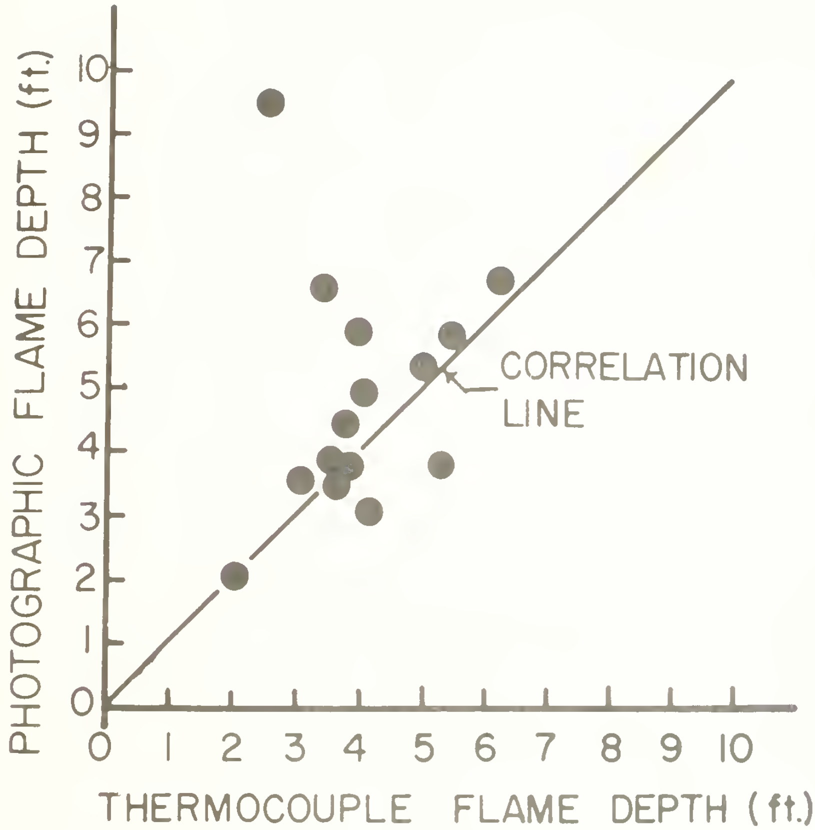

Figure 13. — Correlation between photographic and thermocouple measurement of flame depth.

$$\frac{L}{D} = K\left(\frac{G}{\rho(gD)^{1/2}}\right)^n$$

where

L = flame length, ft.

D = flame depth, ft.

G = unit burning rate, lbs./min./ft.^{2}

ρ = air density, 8.1×10^{-2} lb./ft.^{3}

g = acceleration constant, 1.152×10^5, ft./min.^{2}

and K and n are constants of the function. This analysis shows a family of curves that have nearly the same slope but different intercepts (fig. 15). Variation in the constants is shown in table 9.

Table 9. — **Fire characteristics' constants**

Test	K	n
Douglas-fir	13.7	0.630
Lodgepole pine	21.5	0.627
White pine	26.0	0.630
Ponderosa pine	55.0	0.607
Thomas'	42	0.610

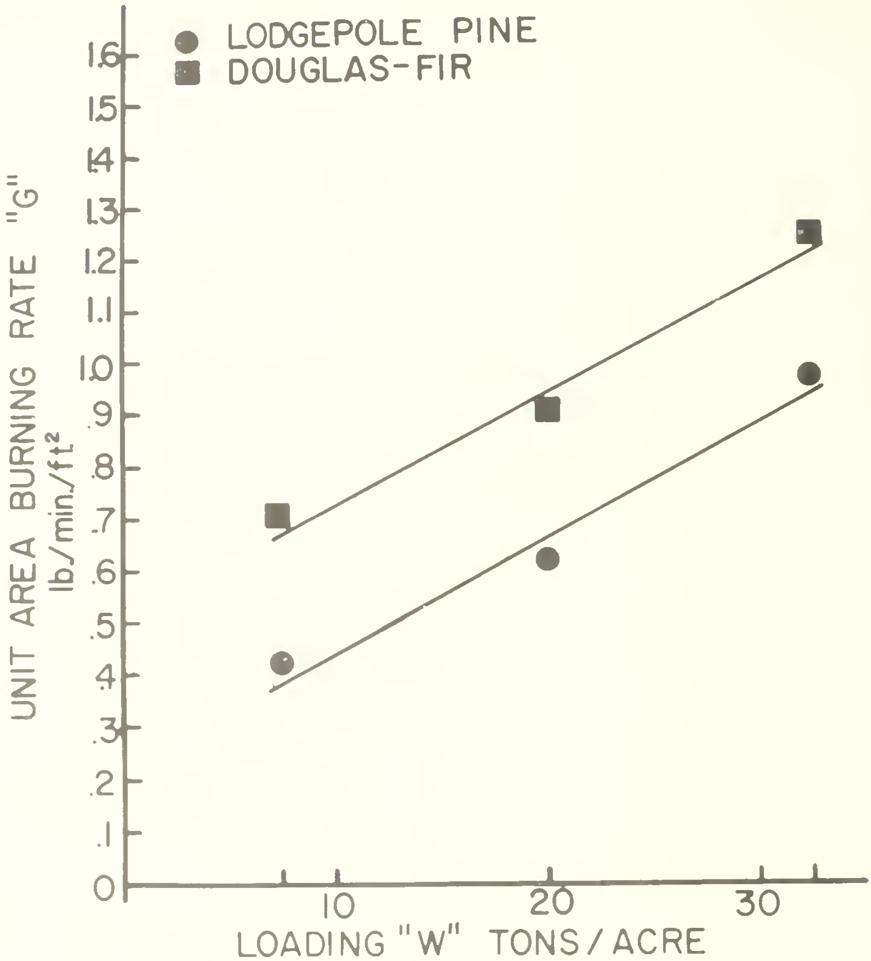

Figure 14. — The influence of loading on unit area burning rate is shown to be nearly linear. Average values for each loading were used.

The presence of a nearly constant exponent indicates the functional relation is essentially the same for laboratory and field tests. The variation in the intercept constant is probably due to inaccurate measurement of flame depth, overestimating G, the effects of wind, and underestimation of flame length. Additional laboratory tests, investigating the effects of wind and a system to measure weight loss, are being analyzed and will be reported later.

Vertical temperature profile. — Each fuel type shows a definite separation according to loading. Apparently the Douglas-fir fires were not as hot as the lodgepole pine fires, and loading seemingly had greater influence upon Douglas-fir. The lodgepole pine fires at 20 tons per acre and above did not increase in intensity very rapidly (figs. 16 and 17). These temperature indications do not agree with the fire intensity or burning rate calculations. This discrepancy points out that temperature measurements alone cannot give reliable conclusions. More must be known of the fire phenomena to allow intelligent use of these measurements.

Convection column velocity. — Analysis showed that only the data taken above the maximum flame height were meaningful. Many data points were taken within the

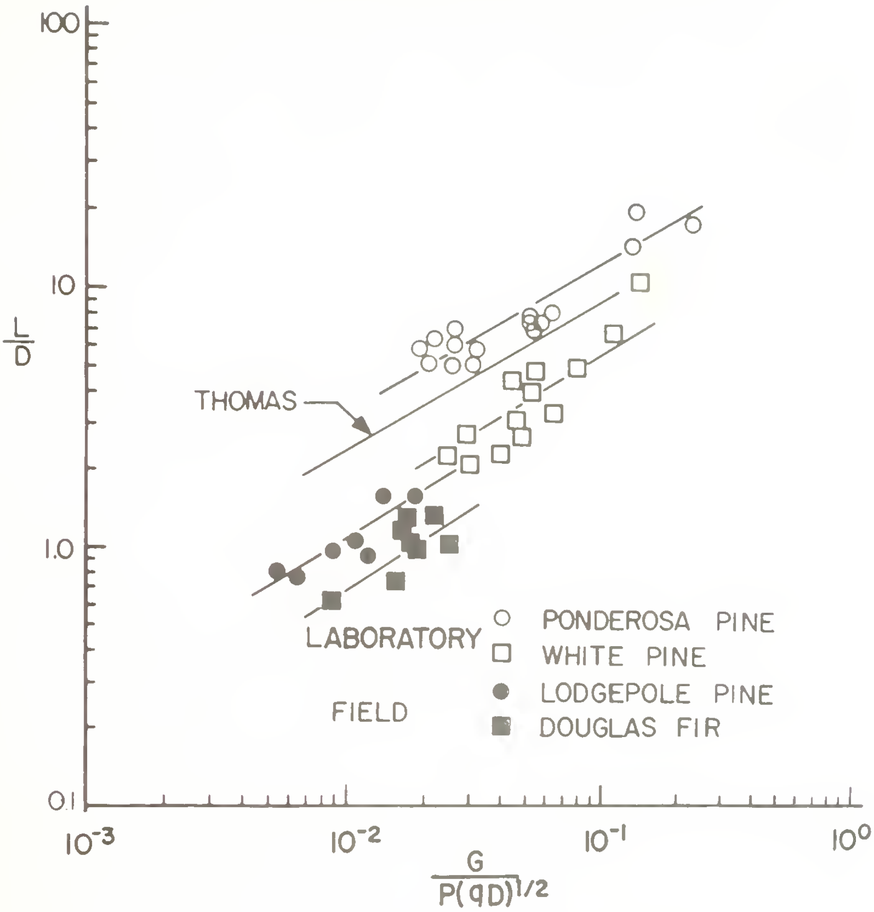

Figure 15. — Diffusion flame characteristics of laboratory and field test fires.

flame and had to be rejected. As a consequence, no relation between flame height and convection column velocity could be found. The sporadic nature of the data, because of wind influences, did not permit a complete description of the convection column velocity profile. The convection column energy therefore could not be computed, and no meaningful relation between fuel bed loading and convection column energy or velocity could be found.

However, there were sufficient data to show a relation between convection column velocity and temperature. The buoyancy force is directly proportional to the differential temperature between the gas and its surroundings. Because the relation between force and pressure is direct, a straight-line relation should exist between the dynamic pressure and the differential temperature. A plot of $q(\frac{T}{T_o})$ vs. $T-T_o$ (fig. 18) shows the data taken above maximum flame height. The straight-line equation for these data is:

$$q(\frac{T}{T_o}) = 4.07 \times 10^{-4}(T-T_o)$$

where

q = dynamic pressure—lb./ft.^{2}

T = convection column temperature—°F.

T_o = ambient temperature—°F.

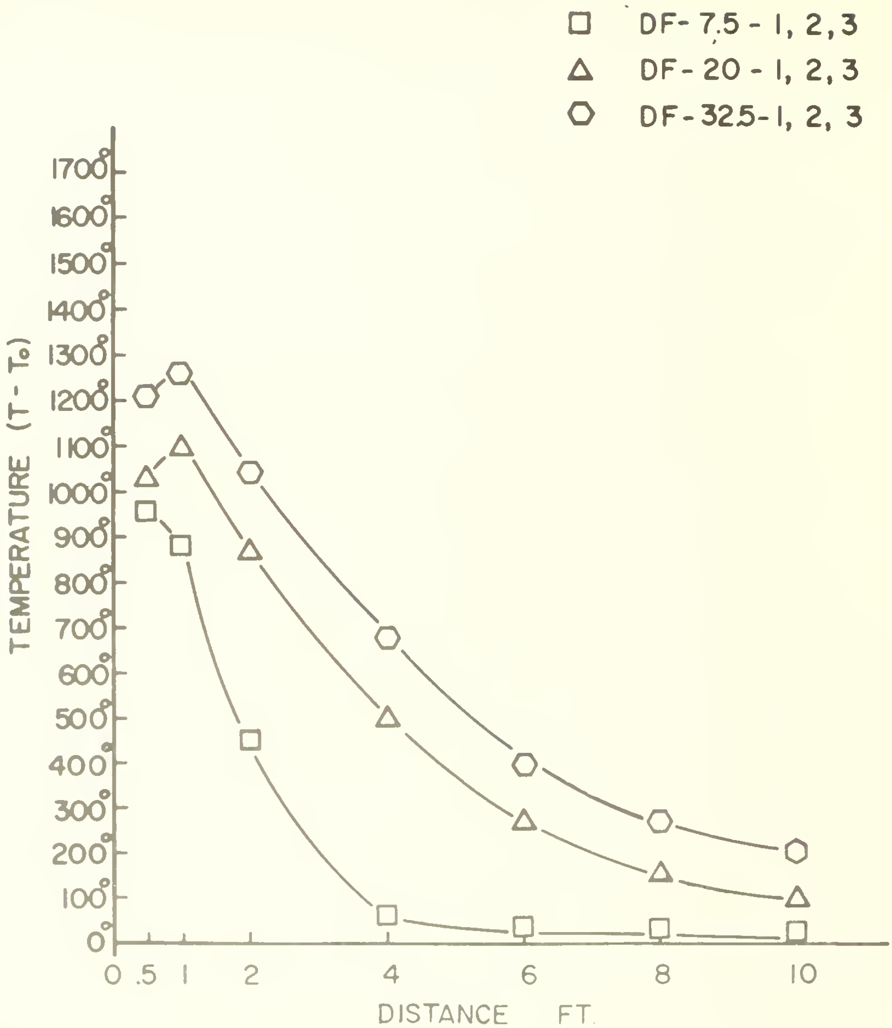

Figure 16. — Vertical temperature profile for Douglas-fir as measured in the flame zone.

The regression coefficient for this equation is 0.715 with 32 data points.

The velocity of the convection column is computed from the formula:

$$q = \frac{\rho V^2}{2g}$$

which reduces to:

$$V = \sqrt{\frac{(2g)}{\rho_0} \quad \frac{(qT)}{T_0}}$$

where

V = convection column velocity—ft./sec.

g = acceleration of gravity = 32.2 ft./sec.^{2}

p_o = ambient air density—lb./ft.^{3}

substituting for $q(\frac{T}{T_o})$ and evaluating gives:

$$V = 0.626\sqrt{T - T_o} \text{ ft./sec.}$$

This equation was plotted with the experimental data shown in figure 19. The convection column gas was assumed to be air in an atmospheric static pressure of 13.5 p.s.i.

Fuel bed compactness. — Comparison of

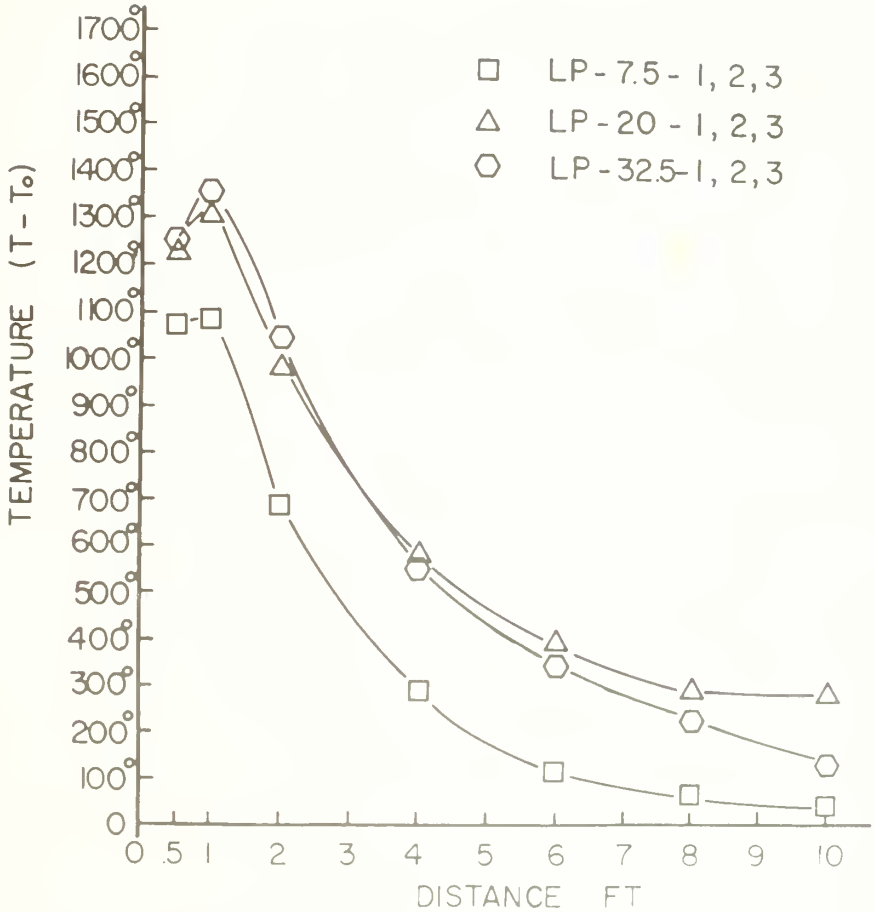

Figure 17. — Vertical temperature profile for lodgepole pine as measured in the flame zone.

compactness for needle fuel beds and dimensioned wood crib fuel beds showed definite differences in rate of spread at the same compactness values. By using the field data, laboratory data, and data of Fons et al. (1960), we analyzed the effects of compactness on rate of spread. The data used were for fires burned at moisture contents between 7 and 10 percent (table 10). Because of the limited number of points, this analysis shows only the separation of results in these two types of fuel bed models and the general trend: as compactness increased the rate of spread decreased (fig. 20). The relation has the form of:

Needle fuel beds $R = 95.3\ (1/\lambda)^{-1.05}$

Wood crib fuel beds $R = 12.5\ (1/\lambda)^{-1.30}$

where

R = rate of spread, ft./min.

and

$1/\lambda$ = compactness, ft.^{2}/ft.^{3}

Additional work incorporating the effects of fuel particle size may bring the two curves much closer.

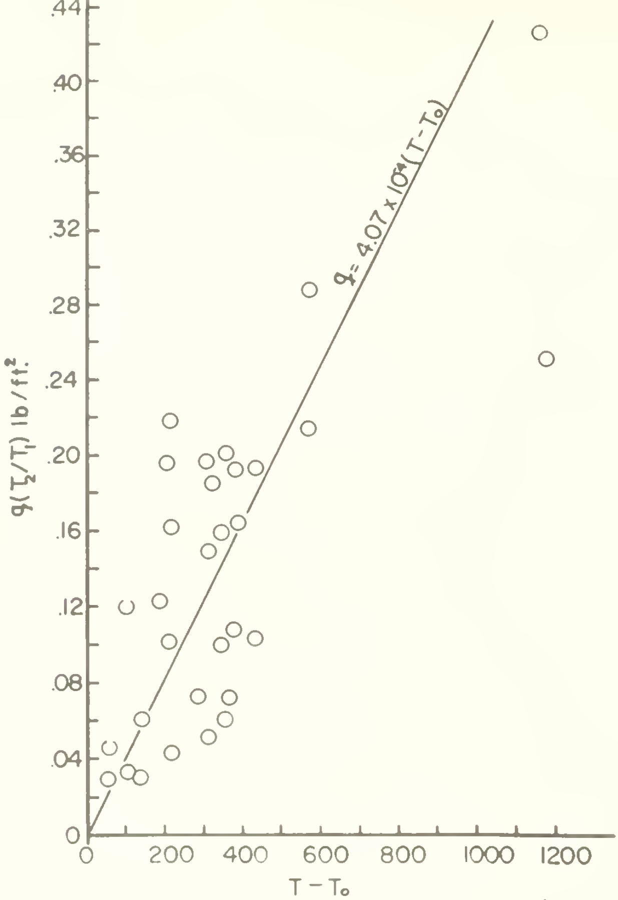

Figure 18. — Corrected dynamic pressure as a function of temperature for points above the flame.

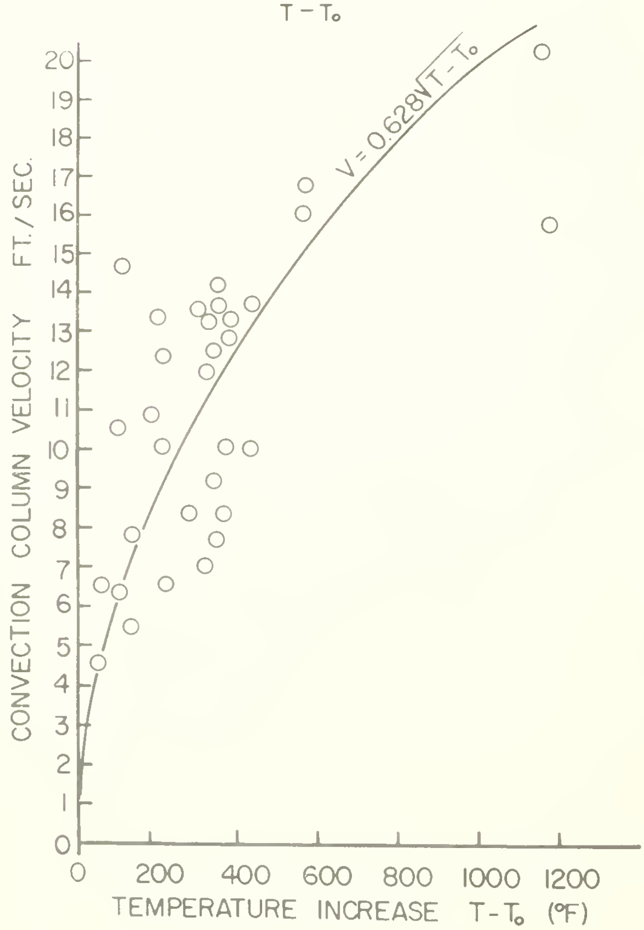

Figure 19. — Convection column velocity as a function of temperature at maximum flame height.

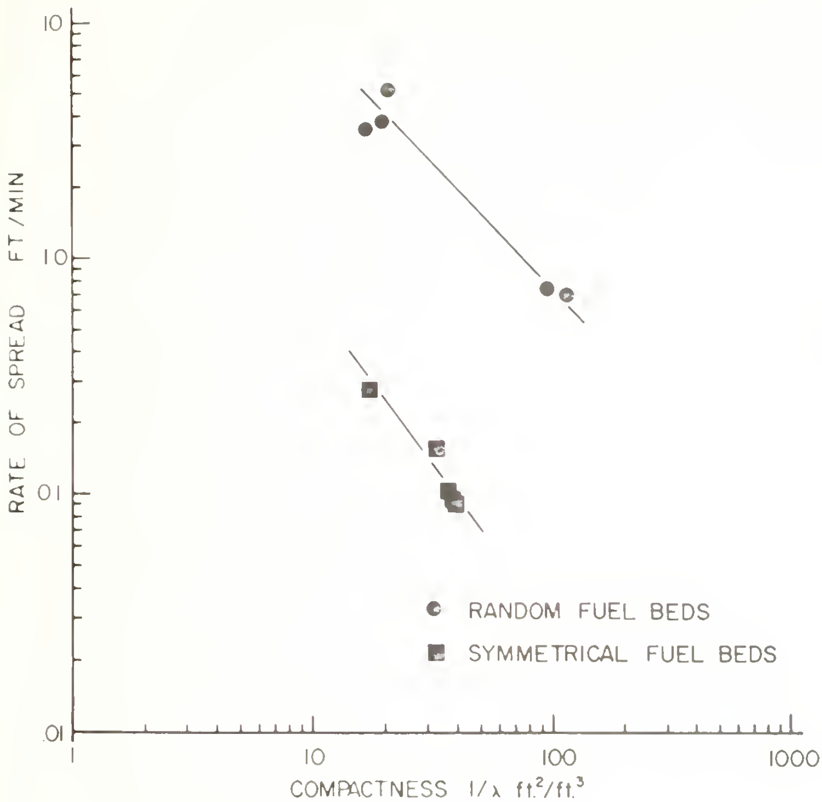

Figure 20. — Influence of compactness on rate of spread in two different fuel bed models.

Table 10. — **Compactness and rate of spread of random and symmetrical fuel beds**

Random fuel bed	Compactness	Rate of spread	Symmetrical fuel bed	Compactness	Rate of spread
	Ft.²/ft.³	F.p.m.		Ft.²/ft.³	F.p.m.
Lodgepole pine (32.5 T/A)	18.2	3.5	Wood crib No. 1[1] 2" × 2" sticks	17.7	0.275
Douglas-fir (20.0 T/A)	20.4	3.7	Wood crib 0.5" sticks	33.8	0.156
Douglas-fir (32.5 T/A)	23.8	5.1	Wood crib 0.75" sticks	37.3	0.103
Ponderosa pine (laboratory)	99.4	0.74	Wood crib 1.00" sticks	39.8	0.096
White pine (laboratory)	119.0	0.68	Wood crib 1.25" sticks	40.5	0.092

[1]Crib No. 1 was burned at the Forest Fire Laboratory, Missoula, Montana. The remainder of the wood cribs were prepared by Project Fire Model. The apparent disparity in compactness between crib No. 1 and the fire model cribs is caused by spacing differences.

CONCLUSIONS

1. Reproducible fuel beds were best prepared when the slash was procured from recently cut trees. Such trees were so uniform in moisture content that theoretical dry weight loadings of plots were easily achieved. Measurements of moisture in older slash deviated so widely that it was difficult to attain predetermined dry weight loadings.

2. This study strikingly demonstrated that a large percentage of logging slash is limbs and twigs of small diameter. The fuels that propagated the main forward spread of fire — needles and branches one-fourth inch and less in diameter — accounted for more than one-third of the dry weight of slash in the lodgepole pine and Douglas-fir plots.

3. Fire intensities can be correlated by relating flame length to the B.t.u./min./unit length of fireline front. However, more detailed information is required about fuel and fuel bed characteristics before various fire models can be compared directly. Prepared slash type fuel beds burned with intensities comparable to those reported by Byram for wildfires. This type of fire model may allow studies of characteristics associated with wildfires.

4. Fuel bed loading influenced rate of spread in a manner similar to that reported by Fahnestock. Higher rates of spread were experienced in our study because of the firing technique used. A wider range of loadings should be tested to determine the functional relation between loading and rate of spread.

5. Field and laboratory fires can be characterized by buoyant diffusion flame analysis using a general equation of the form

$$\frac{L}{D} = K\left(\frac{G}{\rho(gD)^{1/2}}\right)^n.$$

The distribution of data indicates the need for additional tests to refine the measurements of flame length, flame depth, and unit area burning rate.

6. Air velocity was more influential than loading on rate of spread. The relation between air velocity and rate of spread was an exponential function for both fuels tested. Additional laboratory and field testing will be necessary to separate the effects of air velocity and loading.

7. Measurements of convection column velocity are difficult to obtain in the field because of the effect of ambient winds. In spite of this difficulty, a relation between column velocity and temperature was established. Hence velocity of the convection column may be estimated if the temperature can be measured. Temperature profiles can be obtained but must be integrated with other fire parameters to be useful in fire analysis.

8. Comparison of rates of spread between needle and wood crib fuel beds showed large differences. These differences are attributed to the fuel particle size and its arrangement in the fuel bed. A careful analysis of fuel particle surface area-to-volume ratio and fuel bed compactness should account for most of the differences in the fire models.

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Initial Vegetal Development Following Prescribed Burning of Douglas-Fir in South-Central Idaho

by

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INITIAL VEGETAL DEVELOPMENT FOLLOWING PRESCRIBED BURNING OF DOUGLAS-FIR IN SOUTH-CENTRAL IDAHO

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INITIAL VEGETAL DEVELOPMENT FOLLOWING PRESCRIBED BURNING OF DOUGLAS-FIR IN SOUTH-CENTRAL IDAHO

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INTRODUCTION

Prescribed fires, particularly in logging slash, are not unusual in the forests of the northern Rocky Mountains. Burning is an effective means of reducing wildfire hazards and preparing timber sites for regeneration. Fires in standing timber, on the other hand, have become relatively uncommon in this age of smokejumpers, retardant bombers, and fast transportation. And, even though uncontrolled forest fires do occur occasionally, it is impractical to plan studies of specific forested areas that might be burned. The probability of a burned area large enough for study is low, and at best the occurrence of wildfire on areas marked for study would be extremely fortuitous. Thus when personnel of the Sawtooth National Forest intentionally burned 120 acres of standing Douglas-fir on the first day of August, 1963, the situation was virtually unique.

The basic objectives of this prescribed fire were sanitation and site preparation for silvicultural purposes. A stand of Douglas-fir in Neal Canyon on the Ketchum Ranger District had been logged over twice since 1950, and the remaining trees were mostly mistletoe-deformed saplings and poles. After the diseased trees were burned, parts of the area were planted and parts were direct-seeded to establish a new and healthy timber stand.

From a wildlife management viewpoint, the secondary effects of the fire were as significant as accomplishment of the primary objectives. Here, for example, was an opportunity to measure the heat output of a fire similar to an uncontrolled forest fire; to investigate the influence of a prefire plant community on postfire vegetal development; and to evaluate the postfire plant community as wildlife habitat. This paper is a report of the first 3 years of study on the Neal Canyon prescribed burn. Particular emphasis has been given to the relationship between big-game forage values in the forest community and the influence of fire on those values.

STUDY AREA

Neal Canyon is a small drainage off Eagle Creek and the Big Wood River about 6 miles north of Ketchum, Idaho. The 120-acre burned area is 1.5 miles east of U.S. Highway 93 in the northeast quarter of Section 13, Township 5 North, Range 17 East, Boise Meridian. Its general aspect is north-northeast, and the elevation is 6,500 to 7,000 feet. Since some parts of the area had been heavily disturbed during logging, the specific site selected for examination was a 20-acre patch of less-disturbed terrain on the lower middle slope (see fig. 1). The true aspect of the study site is N 10-20° E; the slope is 64 percent.

In this part of Idaho, summers are cool and winters rigorous. Annual precipitation at the Hailey and Sun Valley weather stations is 14 to 17 inches, most of which falls in the winter. Total snowfall at the respective stations averages 85 to 120 inches. The January mean minimums are within a few degrees of zero and the record minimums for the two stations are –36°

Figure 1.--A portion of the Neal Canyon prescribed fire area, July 1963.

F. and −46° F.[1] Forested sites usually are confined to north- and east-facing slopes, while the drier south slopes and valley bottoms are mostly sagebrush and grasslands. Soils in Neal Canyon are of limestone origin, rocky, poorly developed, and highly stable. Mechanical analyses of representative samples show at least 50-percent gravel and a shift from sandy loams on the surface to a sandy clay loam below 14 inches. Heavy overgrazing on a sheep driveway in Eagle Creek has caused plant community changes but very little surface erosion.

Wildlife use of Neal Canyon has not been studied in detail, but 50 elk were planted at Ketchum in 1934 to 1936 and the management unit for the Big Wood River herd currently supports about 600 animals.[2] In severe winters the range available to this herd and to the deer of the area is limited to about 30 square miles. Because of deep snow, Neal Canyon is probably not accessible during the critical winter period but it could be used throughout the rest of the year. In 1965, however, the observed use by big game was light.

METHODS

VEGETATION SAMPLING

In order to sample all components of the plant community, we divided the vegetation into five life-form groups. All herbaceous vegetation and woody plants under 18 inches in height were sampled with a series of twenty-five 2- by 2-foot quadrats. Plants were listed by species in each plot, and ground cover was estimated to the nearest quarterplot. For woody plants more than 18 inches high we used a modification of the quarter methods described by Cottam and Curtis[3] and Morisita.[4] From each of 20 points spaced at approximately 50-foot intervals we measured the distance in each quadrant to the nearest tree (over 4.5 feet tall), the nearest

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[1] U.S. Dep. Commerce, Weather Bureau. Climatography of the U.S. No. 86-8, 66 pp. Wash., D.C.: Government Printing Office. 1964.

[2] Tanner, Dale. The Big Wood River elk herd. Idaho Wildlife Rev. 18(3): 3-6. 1965.

[3] Cottam, Grant, and J. T. Curtis. The use of distance measures in phytosociological sampling. Ecology 37(3): 451-460. 1956.

[4] Morisita, Masaaki. A new method for the estimation of density by the spacing method applicable to non-randomly distributed populations. Physiol. and Ecol. 7: 134-144 (in Japanese), 1957. U.S. Dep. Agr. Transl. (mimeo.) 1960.

subtree (18 inches to 4.5 feet), the nearest tall shrub (over 8 feet), and the nearest low shrub (18 inches to 8 feet). Quadrants were oriented with the contour so that two of the distance measurements in each set of four could be corrected for slope. Trees were categorized by diameter class, and shrub size was estimated by measuring two diameters and the height of the plant crown.

To supplement these measurements, we have taken representative black and white and color photographs each year, both within the study area and from a permanent photographic point on the cross-canyon slope facing the burn. No individual shrubs were marked prior to burning, but representative marked plants of each important shrub species have been measured and photographed annually since the fire.

Calculations.--Techniques for converting quadrant-distance measurements to estimates of plant density lack the mathematical proofs required for application to populations with unknown distribution. Several formulas can be used. To provide an empirical test of method, fieldwork in 1964 was expanded to include both the distance to the nearest shrub and a total count of all shrubs within 50 feet of sampling points. Since plant densities in the circular plots were similar to density estimates using the angle method, the angle-method formula[5] has been used throughout the study.

PREFIRE VEGETATION

Before the Neal Canyon site was burned, vegetation consisted of 54 species, including six types of trees and 12 kinds of shrubs[6] (listed in Appendix 1). A summary description of the plant community, based on average numbers of plants and plant sizes per 1,000 square feet, is presented in table 1. As a result of the two timber sales, the number of overstory trees is lower than might have been recorded in an undisturbed forest community. However, there was no evidence in the form of burned snags or charred material on the ground to suggest that the stand had been recently disturbed other than by logging. A few large stumps show that trees up to 36 inches in diameter were present at one time, and increment cores from four of the dominant Douglas-firs revealed ages ranging from 28 to 170 years. A cross section from the largest willow stem tested had 34 annual growth rings. Figure 2 is representative of the prefire vegetation.

THE FIRE

Firing of the Neal Canyon site began just after 8:00 a.m., August 1, 1963, and was completed before 5:00 p.m. the same day. Moisture content of fuel-moisture sticks examined at 3:30 p.m. each day during the week preceding the fire had been a relatively constant 5 to 6 percent. During the firing period, air temperatures rose from the mid-50's to nearly 80° F. and the relative humidity dropped from around 50 percent to 10 percent or less.[7] Surface winds were mostly under 5 m.p.h. during the day, but fire-induced gusts to 30 m.p.h. were recorded during the peak of burning and estimates of wind velocities within the fire were even higher.

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[5] Mean area per plant = $\frac{\Sigma\Pi r2}{4N}$, where r is the distance to the nearest individual in a quadrant and N is the number of sampling points.

[6] Hitchcock, C. Leo, Arthur Cronquist, Marion Ownbey, and J. W. Thompson. Vascular plants of the Pacific Northwest. Univ. Wash. Press. 1955.

[7] Data from U.S. Weather Bureau mobile stations at Eagle Creek and on the hilltop above the fire show generally warmer and drier conditions at the hilltop. These figures represent a broad summary from both stations.

Figure 2.--Representative vegetation within the prescribed fire area, July 1963.

Table 1.--Average numbers of plants, by class, per 1,000 square feet Neal Canyon, before prescribed burn, July 1963

Plant class	Number	Size				
		D.b.h. (inches)				
Trees		0	0-1	1-3	3-8	8-15
Douglas-fir	31.4	3.3	10.2	10.2	7.0	0.7
Shrubs		Crown volume (cu.ft.)				
Acer glabrum	4.27	1,376.2				
Amelanchier alnifolia	.22	7.9				
Ceanothus velutinus	.06	.3				
Ribes lacustre	.89	16.8				
Ribes viscosissimum	.28	1.0				
Salix scouleriana	.33	254.1				
Sorbus scopulina	.11	60.7				
Symphoricarpos oreophilus	2.11	11.7				
Total	8.27	1,728.7				
Ground cover	Square feet					
Vegetation[1]	370					
Litter	570					
Bare ground	60					

[1] Frequencies of occurrence for common species in the ground layer were: Carex geyeri (52 percent), Arnica cordifolia (48 percent), Senecio cymbalaroides (44 percent), Calamagrostis rubescens (24 percent), seedlings of Pseudotsuga menziesii (20 percent), Ribes lacustre (20 percent), Epilobium angustifolium (20 percent), Poa nervosa (20 percent), and Potentilla glandulosa (20 percent).

Figure 3.--Firing the Neal Canyon site, August 1, 1963.

Firelines were burned out first, after which the major fire was started with a flame thrower on a pickup truck passing once across the middle of the site and again across the lower edge (fig. 3). With minor variations, the fire swept into the tree crowns almost immediately; and at progressive intervals the entire area was covered by running flame.

The intensity of the fire was measured by integrating devices described by Beaufait.[8] These consist of 1-gallon cans painted flat black and containing 3 liters of water at ambient temperature. The weight of water released as steam through a 1-cm. hole in the can lid is a measure of heat absorbed.

Eighteen pairs of these water-can analogs were placed on mineral soil (fig. 4) in six evenly spaced vertical lines within the 20-acre study area. Rolling rocks and logs destroyed 14 cans, but only four of the 18 pairs were lost. Water loss from the remaining 22 cans ranged from 340 to 1,765 grams, with a mean loss of 939.8 grams (table 2). According to Beaufait's unpublished data, this water loss is comparable to losses during a hot broadcast fire in deep, dry slash.

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[8] Beaufait, William R. An integrating device for evaluating prescribed fires. Forest Sci. 12(1): 27-29. 1966.

Figure 4.--Water-can heat integrating device.

Figure 5.--Representative photographs within the burned area immediately after the fire, August 1, 1963.

Table 2.--Grams of water lost from pairs of 3-liter water cans, August 1, 1963

Pair	Line						Mean
	1	2	3	4	5	6	
A	1,340	250	1,045	([1])	675	([1])	783.3
	([1])	325	([1])	([1])	1,065	([1])	
B	1,550	([1])	1,345	([1])	1,765	340	1,281.7
	1,340	([1])	([1])	([1])	1,350	([1])	
C	1,025	1,530	985	1,990	815	1,670	1,204.5
	625	435	([1])	([1])	1,365	1,605	
Mean	1,176.0	635.0	1,125.0	1,990.0	1,172.5	1,205.0	939.8

[1] Cans destroyed by rolling rocks or logs.

Measured losses of water (table 2) indicate that the fire may have been slightly less intense on line 2 and along the upper edge than in other parts of the plot. However, visual observations following the fire did not reveal any variation of fire effects. In general, all the litter and herbaceous material, all logs on the ground less than 3 inches in diameter, and all live stems smaller than 2 inches at the base were completely consumed (figs. 5 and 6). Interestingly, there was no conclusive evidence that the heat in small grassy openings (Table 2, pairs 3A and 3C) was any less intense than the heat beneath a dense clump of small trees (2A and 3B) or adjacent to large shrubs (5A and 6B).

Figure 6.--Panoramic view of the burned area on August 2, 1963, 1 day after the fire.

POSTFIRE VEGETATION

Shortly after the Neal Canyon prescribed fire, the new tree crop was planted and the roads were seeded with a domestic grass mixture, but no attempt was made to rehabilitate the burned slopes. To date, no overland soil movement has been recorded, and the rocks that rolled downhill during the fire probably represent the bulk of surface disturbance on the site.

Natural vegetation recovered rapidly following the fire (fig. 7). In 1 year, live ground cover returned to 27 percent, and in the second year it reached 69 percent--nearly double the live cover before the fire (tables 3 and 4). Of more significance perhaps is the fact that the three plant species most important in this resurgence (Moldavica parviflora, Ceanothus velutinus, and Iliamna rivularis) were either uncommon or not even recorded in the prefire plant community. None of these species have windborne seeds, and it must be concluded that new plants came from seeds buried deep enough in the soil to survive a fire.

In the second year, three species with light windborne seeds (Lactuca serriola, Epilobium paniculatum, and E. alpinum) appeared in great numbers, and resprouts from Arnica cordifolia and Ribes viscosissimum were recorded in nearly half of the quadrats. Surprisingly, the common fireweed (E. angustifolium) did not increase significantly, although the brilliant flowers were obvious in both the prefire and postfire communities.

Initial recovery of the shrub layer was dominated by plants resprouting from root systems that survived the fire. Comparison of tables 1, 3, and 4 reveals that some species are considerably more vigorous in this respect than others. Within 2 years, total density of shrubs had nearly doubled the prefire density, although no seedlings had reached the 18-inch height required for inclusion in the shrub-sampling category. Several species, notably mountain maple (Acer glabrum), serviceberry (Amelanchier alnifolia), Ribes viscosissimum, willow (Salix scouleriana), and elderberry (Sambucus racemosa) apparently increased in density because root crowns of single plants produced multiple sprouts.

A

B

Figure 7.--Prefire and sequential postfire vegetation on a representative photo plot. A. July 1963; B. August 1963; C. July 1964; D. July 1965.

Table 3.--Average numbers of plants, by class, per 1,000 square feet, Neal Canyon, 1 year after the fire

Plant class	Number	Crown volume (cu.ft.)
Shrubs		
Acer glabrum	0.63	3.9
Amelanchier alnifolia	.05	.5
Salix scouleriana	.15	16.4
Sambucus racemosa	.02	.3
Symphoricarpos oreophilus	.02	.1
Total	0.87	21.2
Ground cover		Square feet
Vegetation [1]		270
Litter		10
Bare ground		720

[1] Frequencies of occurrence for common species in the ground layer were *Moldavica parviflora* (96 percent), *Ceanothus velutinus* (92 percent), *Iliamna rivularis* (52 percent), *Ribes viscosissimum* (24 percent), *Arnica cordifolia* (24 percent), and *Pseudotsuga menziesii* (20 percent).

C

D

Table 4.--Average numbers of plants, by class, per 1,000 square feet Neal Canyon, 2 years after the fire

Plant class	Number	Crown volume (cu.ft.)
Shrubs		
Acer glabrum	5.70	154.7
Amelanchier alnifolia	1.10	7.4
Artemisia tridentata	.18	.1
Ceanothus velutinus	.18	.1
Ribes lacustre	.55	2.6
Ribes viscosissimum	1.47	1.5
Salix scouleriana	2.76	884.1
Sambucus racemosa	.74	27.9
Symphoricarpos oreophilus	2.58	8.9
Total	15.27	1,087.3

Ground cover	Square feet
Vegetation [1]	690
Litter	50
Bare ground	260

[1] Frequencies of occurrence for common species in the ground layer were Moldavica parviflora (100 percent), Lactuca serriola (96 percent), Ceanothus velutinus (92 percent), Epilobium paniculatum (88 percent), Arnica cordifolia (48 percent), Epilobium alpinum (48 percent), Ribes viscosissimum (44 percent), Iliamna rivularis (36 percent), Epilobium angustifolia (28 percent), Penstemon fruticosa (24 percent), Taraxicum officinale (24 percent), Aster conspicuus 20 percent), Calamogrostis rubescens (20 percent), and Phacelia hastata (20 percent).

These changes in density seem much less significant, however, than the changes in dominance brought about by different recovery rates and indicated by crown volume estimates (table 5). Note, for instance, that an average mountain maple shrub had recovered only 8 percent of prefire volume after 2 years, while a willow recovered to 14 percent in the first year and 42 percent in the second year. In terms of total shrub volume in the community, maple was reduced from nearly 80 percent to about 14 percent, and willow increased from 15 percent to more than 80 percent. Representative development of these two species is illustrated in figures 8 and 9.

Table 5.--Mean crown volumes of shrubs[1]

Shrub species	Prefire	Postfire	
	1963	1964	1965
	Cubic feet		
Acer glabrum	322.0 (77)	6.1 (41)	27.1 (31)
Amelanchier alnifolia	35.8 (4)	10.3 (3)	6.7 (6)
Ribes lacustre	18.9 (16)	--	4.7 (3)
Ribes viscosissimum	3.8 (5)	--	1.0 (8)
Salix scouleriana	763.0 (6)	105.9 (10)	320.3 (15)
Symphoricarpos oreophilus	5.6 (38)	4.7 (1)	3.4 (14)

[1] Numbers of shrubs measured are in parentheses.

Samples of other shrub species in the burned area are smaller than samples for willow and maple but nevertheless demonstrate important changes. The two *Ribes* species, for example, are very obviously and differentially affected by fire. Before the area was burned, *R. lacustre* was represented by more and larger plants than *R. viscosissimum*. Both are recovering crown volume at about the same rate, but *R. viscosissimum* has increased tremendously in density, whereas *R. lacustre* is only slowly approaching prefire densities. In addition, *R. viscosissimum* seedlings have become one of several important components of the groundcover layer.

Figure 8.--Mountain maple (*A. glabrum*) resprouting 1 and 2 years after fire.

Figure 9.--Scouler willow (S. scouleriana) resprouting 1 and 2 years after fire. Note the dense growth of Moldavica in the ground layer vegetation.

One shrub species from the prefire community has evidently disappeared, but two others are increasing in importance. Mountain ash (Sorbus scopulina) was eliminated by burning and probably will not reappear until birds bring in new seeds. On the other hand, snowbrush (C. velutinus) is not now a dominant species because it did not resprout, but 92 percent of the frequency quadrats contain snowbrush seedlings. Finally, elderberry (Sambucus racemosa) was present before the fire but was not recorded in the shrub layer sample. Two years after the fire, quick resprouting had raised elderberry to the third largest volume component of the shrub stand.

Two shrub species demonstrated peculiar regrowth patterns that appear to be artifacts of sampling but may in fact be normal. Although the small number of samples precludes a meaningful statistical test, measurements of both serviceberry and snowberry (Symphoricarpos oreophilus) indicate a loss of crown volume between the first and second postfire periods. Photographs of representative plants confirm a thin, spreading crown of vigorous shoots in the first year followed by twig growth to a more compact and dense-leafed crown in the second year.

Trees on the Neal Canyon site are not yet large or dense enough to be detected in the samples. However, the few lodgepole pines on the site have abundantly spot-seeded limited areas, and the planted Douglas-fir has survived well and has made very satisfactory growth.

DISCUSSION

The first 2 years following a fire are a relatively insignificant part of the time required for development of a forest community. Yet these years are extremely important, because so many irreversible patterns are established by an initial surge of plant growth on a bare mineral seedbed. In the Neal Canyon site, some early developments, particularly the appearance of new herbaceous species, were surprising. Other unexpected occurrences are certainly possible, but barring another major disturbance it appears that the vegetal evolution and wildlife habitat potential of this forest site have been established.

Perhaps the most important result of this fire was the rehabilitation of big-game forage plants. Although shrubs in the second year had reached only 63 percent of the total crown volume recorded before the fire, forage values had at least doubled. Maple and willow accounted for about 95 percent of shrub volume before the fire, but the average maple was more than 7 feet high and willow averaged nearly 16 feet. Most of the annual growth was well out of reach of big-game animals. After the fire, maple and willow were still dominant, but maple averaged less than 4 feet in height and willow less than 7 feet. All of the annual growth was available, and most of it was succulent and presumably highly nutritious. In addition, shrub dominance was dramatically shifted from maple, which has only medium palatability, to the more palatable and productive willow. This postfire combination of greater availability and improved composition has vastly improved big-game habitat in Neal Canyon.

For the future, sudden regrowth of large shrubs may not be desirable. At present increment rates, willow will grow out of reach in a few years and maple could follow in a short period. Continuation of wildlife values will eventually devolve on plant species currently subdominant in the stand.

Unless there is an unforeseen deviation in vegetal development, snowbrush will become the most important forage shrubs on this study site. Already present in more than 90 percent of the frequency quadrats, snowbrush seedlings are large and vigorous throughout the burned area (fig. 10). On a nearby similar site burned by wildfire in 1950, snowbrush has increased in the plant community to the virtual exclusion of other species (fig. 11). Since snowbrush is usually rated a desirable forage plant, the big-game habitat potential of the prescribed fire area promises to remain high even after the tall shrubs have grown out of reach.

It is doubtful that the study site will be as totally smothered by snowbrush as the older wildfire area. Serviceberry, snowberry, and Ribes viscosissimum have all increased in density since the prescribed fire, and their crown volumes should considerably exceed prefire volumes before snowbrush reaches maturity. Thus the habitat will probably have a desirable diversity of forage as well as a high production potential. The mixture of species also demonstrates one way in which the Neal Canyon shrub community may be atypical. Of the dozen woody shrubs recorded, none is totally worthless as big-game forage, and the beneficial changes reported here are simply shifts in dominance from less palatable or productive species to more valuable shrubs. It is notable, however, that the immediate improvement in forage production and the potential for continuing production were both determined by plant responses to fire.

Figure 10.--Snowbrush (Ceanothus velutinus) seedlings 2 years old, Neal Canyon study area, 1965.

The long-term development of the forest community on this site can also be predicted. Considering the spacing of the planted Douglas-fir, overstory shade could begin to influence the snowbrush within as few as 10 years. By reputation, and as evidenced by its meager showing in the prefire vegetation, snowbrush is intolerant to shade. These shrubs will deteriorate, and conceivably will disappear within 20 years--leaving only a blanket of seeds to lie dormant until the next fire. When the snowbrush disappears so will most of the wildlife-production potential of this stand, because the two tall shrub species will already be out of reach and other species are thinly scattered.

Willow and maple will again reverse dominance: willow will decline and maple will increase because of their differential tolerance to overstory competition. We can also expect the two Ribes species to switch positions; the less tolerant R. viscosissimum will lose any comparative advantages it gained following the fire. At this point, the response of snowberry and serviceberry cannot be predicted, and the samples of other shrub species may be too small to provide valid behavioral information.

If succession is uninterrupted, the vegetation in this stand will probably be similar to the prefire vegetation (table 1) in about 40 years. Wildlife habitat values will reach a maximum during the first 15 years and then begin a slow decline to the poor forage production usual in a mature timber stand. As these changes occur, studies will be continued to determine rates of plant development and habitat values for each stage of forest succession. This information will be extremely helpful in planning long-term maintenance of wildlife populations in Neal Canyon and in other areas having similar vegetation. All things considered, the Neal Canyon prescribed fire should provide information pertinent to wildlife management that will have far more dollar value than the cost of the fire or the worth of the eventual crop of timber.

Figure 11.--A site near the Neal Canyon Study area, burned by wildfire in 1950. Note how snowbrush dominates.

CAUTION

Effects of prescribed burning in Neal Canyon were exceptionally favorable. Timber management objectives were achieved, wildlife habitat was markedly improved, and watershed protection was not compromised. However, it is important to recognize that fire would produce vastly different results in other ecological situations.

As an example, figure 12 contrasts vegetal ground cover that has developed in Neal Canyon with cover that has become established following the Sleeping Child wildfire (1961) in western Montana. After 4 full years of recovery, the Sleeping Child burn had only 36-percent ground cover--about 60 percent of the cover existing before the fire. Moreover, much of this vegetation is domestic grasses that were seeded to prevent erosion. Shrub recovery has been equally slow, and the present wildlife habitat values of the area are insignificant when compared to the losses from timber destruction and watershed damage. Fire can be useful as a management tool for improving wildlife habitat only when we can predict and fully understand the results it will produce in specific locations.

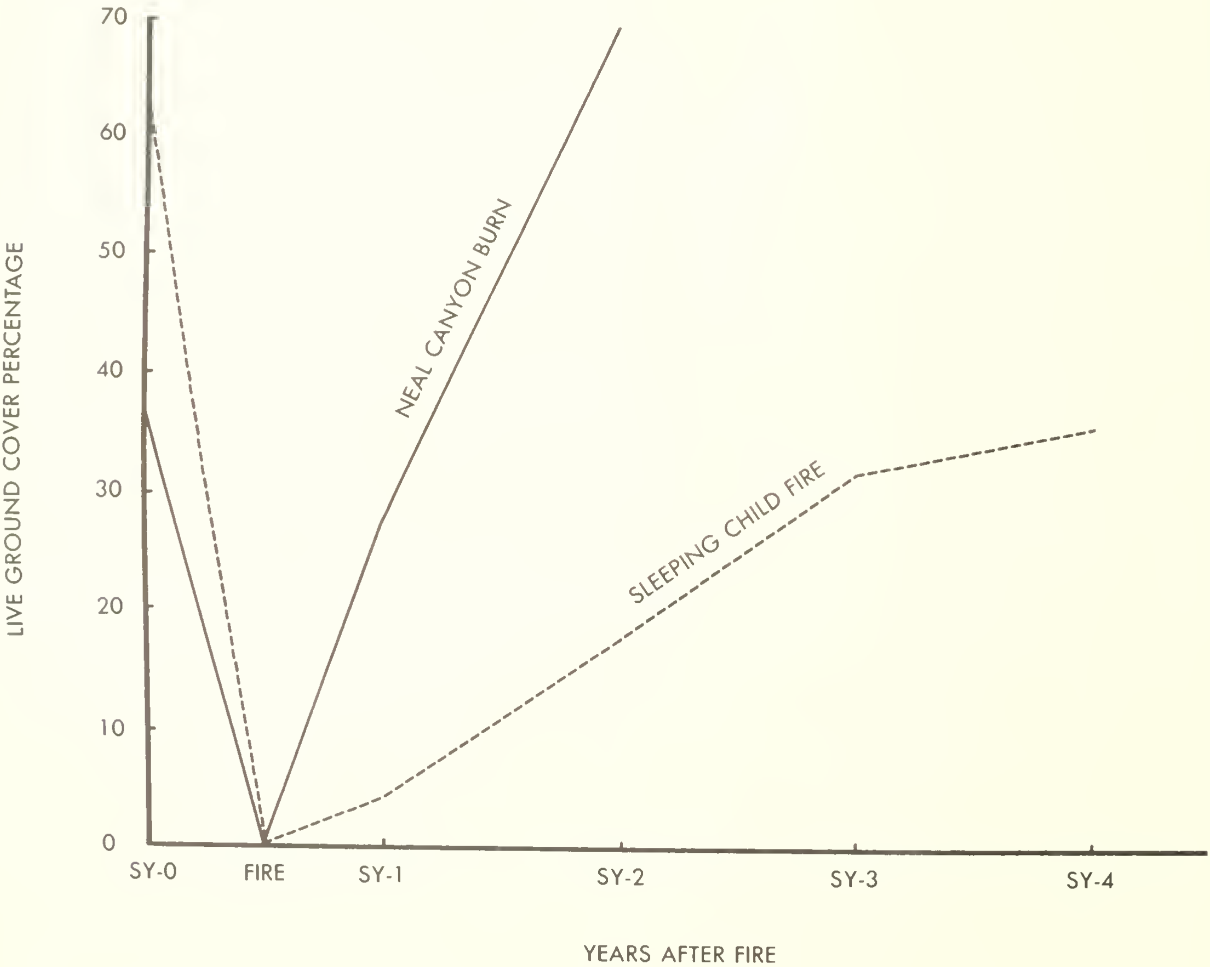

Figure 12.--Development of vegetal cover after the Neal Canyon burn and the Sleeping Child wildfire.

APPENDIX 1

PLANT SPECIES PRESENT ON NEAL CANYON PRESCRIBED FIRE SITE, 1963-65[1]

(Nomenclature follows Hitchcock et al.)

Species	Prefire	Postfire	
	1963	1964	1965
Trees			
Abies lasiocarpa*	x		
Picea engelmannii*	x		
Pinus contorta*	x		
Pinus flexilis*	x		
Populus tremuloides*	x		
Pseudotsuga menziesii	20	20	4
Shrubs			
Acer glabrum	12	4	x
Amelanchier alnifolia	x	x	x
Artemisia tridentata	x	x	
Ceanothus velutinus	x	92	92
Cornus stolonifera*	x		
Penstemon fruticosus	8	4	24
Ribes lacustre	20	x	x
Ribes viscosissimum	4	24	44
Salix scouleriana	x	x	x
Sambucus racemosa	x	x	x
Sorbus scopulina*	x		
Symphoricarpos oreophilus	12	x	x
Herbaceous and low woody plants			
Agropyron inerme	8	x	
Antennaria rosea*	x		
Arabis drummondi[2]	x		x
Arabis holboellii*	4		
Arnica cordifolia	48	24	48
Aster conspicuus	8	12	20
Berberis repens	x	4	
Bromus tectorum**		4	4
Calamagrostis rubescens	24	x	20
Capsella bursa-pastoris**		x	x
Carex spp.	4	12	-
Carex geyeri	52		12
Carex rossii**			12
Castilleja miniata*	8		
Cirsium vulgare	12	4	4
Clematis columbiana	4	x	x
Collinsia parviflora	8	x	4

(continued next page)

PLANT SPECIES PRESENT ON NEAL CANYON PRESCRIBED FIRE SITE, 1963-65 (con.)

(Nomenclature follows Hitchcock et al.)

Species	Prefire 1963	Postfire 1964	Postfire 1965
Herbaceous and low woody plants (con.)			
Conzya canadensis**		x	
Corydalis aurea**		4	4
Cryptantha affinis	4	x	4
Descurainia richardsonii	x	x	x
Epilobium alpinum[2]	-	x	48
Epilobium angustifolium	20	12	28
Epilobium paniculatum**		8	88
Frasera speciosa	16	-	4
Galium sp.*	x		
Heuchera parviflora*	x		
Iliamna rivularis**		52	36
Lactuca serriola**		12	96
Lithospermum ruderale	x		x
Moldavica parviflora**		96	100
Osmorhiza sp.*	x		
Phacelia hastata	x	8	20
Poa nervosa*	20		
Potentilla spp.	20		
Potentilla arguta	x		
Potentilla glandulosa	x		x
Potentilla gracilis*	x		
Pyrola secunda*	12		
Pyrola virens*	x		
Senecio cymbalarioides	44	4	4
Smilacina racemosa[2]	x	x	4
Spergularia rubra**			4
Taraxacum officinale	8	4	24
Tragopogon dubius**		x	x
Trisetum spicatum*	12		
Triticum aestivum**		x	8
Valeriana acutiloba[2]*	x		
Verbascum thapus**			4
Viola adunca[2]	12	8	12

[1] "x" indicates species was present in the stand but not detected in sample quadrats. Numerical designations are percentage frequency of occurrence in twenty-five 2- by 2-foot quadrats.

[2] Tentative identification pending collection of a flowering specimen.

* Present in prefire community but not in the postfire community.

** Not present in the prefire community.

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- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
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U. S. FOREST SERVICE
RESEARCH PAPER INT-30
1966

FIRE SPREAD CHARACTERISTICS DETERMINED IN THE LABORATORY

by

RICHARD C. ROTHERMEL and HAL E. ANDERSON

INTERMOUNTAIN FOREST & RANGE EXPERIMENT STATION
FOREST SERVICE
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FIRE SPREAD CHARACTERISTICS DETERMINED IN THE LABORATORY

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U.S. Department of Agriculture
Ogden, Utah
Joseph F. Pechanec, Director

CONTENTS

Fire Spread Characteristics Determined in the Laboratory

INTRODUCTION

A study of the mechanisms of fire spread was conducted from January 1961 to January 1964 by the Fire Physics Research project located at the Northern Forest Fire Laboratory. The research program was supported by the U.S. Forest Service and the National Science Foundation. This report presents the major findings of that study and is part of a continuing program conducted by the Forest Service to obtain a better understanding of forest fires.

Light forest material such as pine needles, leaves, and rotten wood are recognized as the fuels in which fires start and spread in early stages (*7*, *9*, *15*).[1] Such fires often burn on the ground in a thin layer of fuel without generating enough heat to carry them into the tree crowns. Running crown fires are dangerous to approach and are therefore difficult to control or instrument for research purposes. The small initial fire burning in a flat bed, however, can be studied successfully in the laboratory.

Moisture content of the fuel and velocity of the air over it are two primary factors that determine the rate of spread and other burning characteristics of a fire. Laboratory research on the mechanisms of fire spread was directed at understanding the influence of these two factors on the behavior of fire in a mat-type fuel bed of randomly placed pine needles.

Past research in forest fuels (*8*, *10*, *11*) was hampered by the variability of outdoor weather conditions. Consequently, most of the work in the last decade (*5*, *13*, *14*, *17*) has been directed toward controlled environmental conditions and controlled fuel bed characteristics. In most of these investigations, fuel particles larger than 0.25 inch thick have been arranged in a geometric pattern. This provides an idealized model which is easily duplicated, but does not represent the randomized arrangement nor the particle size of forest fuels that contribute to the start and early spread of a forest fire. This study of the mechanisms of fire spread is aimed at providing this information.

PURPOSE

This study was designed to find the relative importance of fuel moisture and wind upon the rate of fire spread in light forest fuels. Systematic investigations of a physical phenomenon often produce an insight into its cause and effect. Through this technique, the authors hoped to gain a better understanding of the basic mechanisms of fire spread, which would enable them to develop hypotheses to be analyzed in future experiments.

Several questions of technique and instrumentation also needed answers. Could a reproducible fuel bed be constructed with pine needles? Could the environmental system of the laboratory maintain stable conditions long enough to complete a test fire? How could flame dimensions be measured consistently? How could the energy released by the fire be measured? What is the best technique for measuring low velocities of air movement?

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[1] Italic numbers in parentheses refer to Literature Cited, page 24.

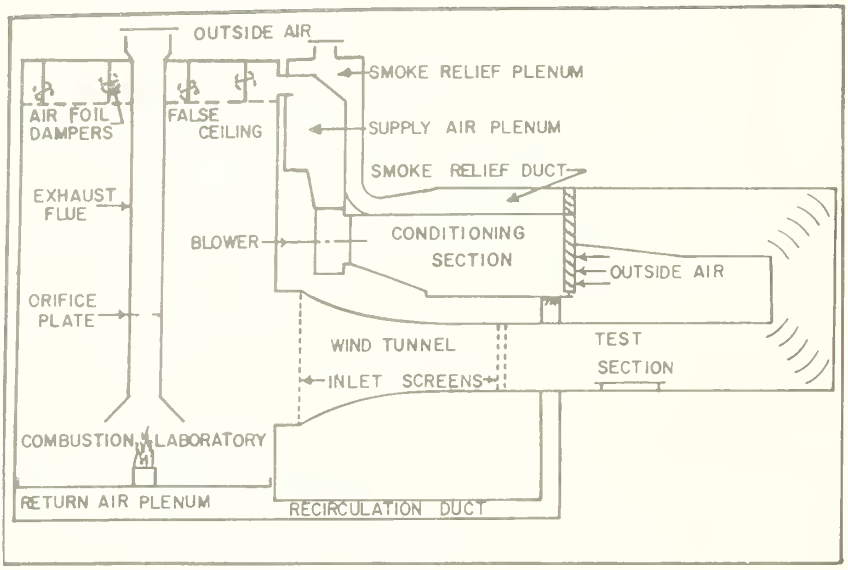


Figure 1. --Profile section of the combustion research facilities at the Northern Forest Fire Laboratory, Missoula, Mont.

METHOD

FACILITIES

These experiments were conducted at the Northern Forest Fire Laboratory in Missoula, Montana. The combustion facilities there consist of two wind tunnels, a still-air combustion laboratory, and an environmental conditioning section (fig. 1). The large wind tunnel has a 10- by 10-foot cross section and is capable of velocities up to 8 m.p.h. The combustion laboratory in which the no-wind experiments were conducted is 66 feet high and 44 feet square. A flue exhaust hood, located in the center of the room, may be raised or lowered to accommodate the size of the fire. The exhaust velocity may be controlled automatically. The air circulated through the combustion laboratory and wind tunnels is conditioned to the desired temperature and humidity in a series of heaters, chillers, and water spray nozzles. The tabulation below describes the range of environmental conditions and limits of control used.

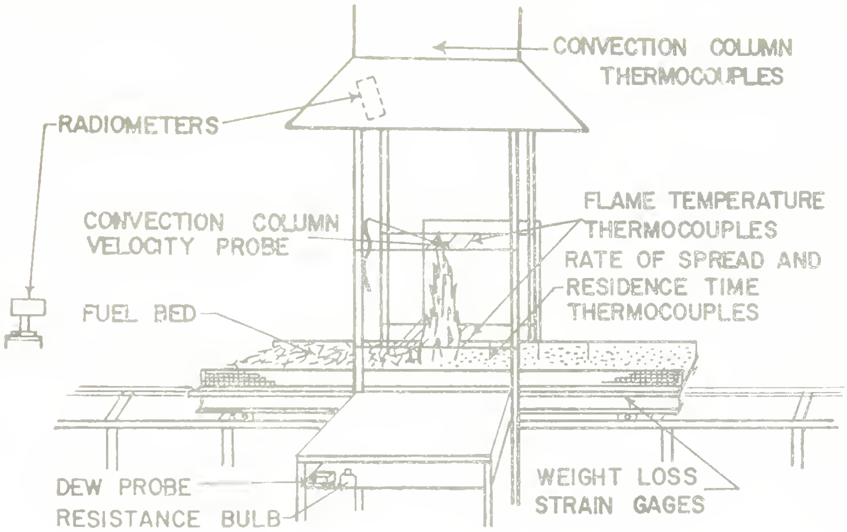
	Range	Control
Relative humidity (percent)	6.4 → 75	±1.5
Air temperature (°F.)	89° → 97°	±1°F.
Air velocity (ft./min.)	0 → 704	±2.0 percent

EXPERIMENTAL TECHNIQUE

The experiments were conducted in two phases. In the first phase we investigated the effect of fuel moisture on rate of fire spread in still air. In the second, we studied the effect of wind on fire spread with fuels at three distinct moisture content levels.

All primary experiments were conducted on a fuel bed 8 feet long and 1.5 feet wide. The fuel was needles of ponderosa pine and white pine. The fuel was preconditioned for several days at the same air temperature and relative humidity conditions that would prevail during the test burnings. This determined the fuel moisture content. The ponderosa pine needle beds

Figure 2. --Instrumentation used in the combustion laboratory. A similar arrangement was used in the wind tunnel.



were 3 inches thick and loaded at 0.5 lb./ft. . The white pine needle beds were 2 inches thick and loaded at 0.33 lb./ft. . Uniform loading was achieved by spreading 1 pound of needles 1 inch deep over 4 feet of the 8-foot bed. Successive layers were added until loading was completed by techniques for collecting and processing already described by Schuette (16). Additional information concerning initial experiments and determination of fuel bed size was published by Anderson (1).

Fuel beds were ignited at one end across their entire width by means of an alcohol trough. In the absence of wind the fuel bed was moved on a track at the same rate as the fire progressed (fig. 2). This kept the flame centered under the exhaust hood and overhead instrumentation. In the wind tunnel, the fuel bed was stationary 2 feet above the floor. A ground plane surrounded the bed and was held flush with the top surface of the fuel.

In the wind tunnel a boundary layer trip fence or air spoiler was placed on the ground plane 1 foot ahead of the fuel bed. The spoiler started a wake that developed quickly into a turbulent boundary layer over the entire fuel bed. Without the spoiler, the free-stream air passed directly over the surface of the pine needles in the first portion of the fuel bed. As a consequence the rate of spread was four to seven times faster over the first half than over the last half of the fuel bed. The spoiler prevented this acceleration and permitted the fire to stabilize within the first 2 feet. (For further explanation of this phenomenon and results of boundary layer investigation with a hot wire anemometer, see Appendix B.)

INSTRUMENTATION

The instrumentation was designed to eliminate need for visual observations. However, visual observations of rate of spread and flame dimensions were used until the instrument system was proved reliable. Similar instrumentation (fig. 2) was used in the combustion laboratory and the wind tunnel; provisions were made for the fact that the flame front was stationary in the combustion laboratory but mobile in the wind tunnel.

Weight-loss system.--A system for weighing the fuel bed continuously during the fire was developed to permit the energy release rate of the fire to be determined. The original system used four cantilever beams with a strain gage on the top and bottom of each beam. The gages were arranged in a Wheatstone bridge circuit. The output of the bridge was amplified and recorded on a strip chart recorder. An improved version of the system incorporates force rings in place of the cantilever beams (3).

The recorded trace of weight loss was linear with time during the steady state of the fire. The slope of the trace began decreasing when the fire reached the end of the bed, and was essentially flat when the flames ceased. This indicated that most of the fuel is consumed in the fire front, and not in the afterburning and glowing combustion.

Fuel bed thermocouples.--Thermocouples of 30-gage chromel-alumel wire were placed in the fuel bed one-fourth inch beneath the upper surface of the pine needles (4). The thermocouples were spaced 9 inches apart along the longitudinal centerline of the fuel bed and were used primarily to locate the leading and trailing edges of the fire. The thermocouple signal was recorded continuously on strip chart oscillograph recorders. When the fire reached the thermocouple, the recorder trace rose sharply. When the rear of the fire passed over the thermocouple, the trace became erratic and finally dropped. The drop indicated that the major flame front had passed.

From these traces, the rate of spread of the fire was determined by the time required for the flame front to travel the 9 inches between thermocouples. Residence time of the fire, i.e., the time flaming exists at one point, was taken as the difference between rise time and drop time of the thermocouple. The flame depth of the fire, i.e., the distance from the leading edge of the flame to the trailing edge, was computed by multiplying rate of spread by residence time.

Radiometers.--Gier & Dunkle[2] directional radiometers were used to measure irradiance from the fires. In the wind tunnel, only overhead measurements were made. In the combustion laboratory, measurements were taken with an instrument 18 feet in front of the fire.

Photographs.--Several photographic techniques were tried for recording flame dimensions. The best results were obtained with Plus-X film with 1-second exposure at f:11. Flame height, flame length, and flame angle were measured from the photographs. Flame depth measured from photographs was shorter than flame depth obtained by thermocouple techniques when the fire was being driven by wind.

Environment monitors.--Air temperature was measured with a platinum resistance bulb Dewpoint temperature was measured with a salt-saturated heater bobbin and a resistance bulb. Air velocity was measured with pressure probes connected to a microdifferential transducer and amplifier.

RESULTS

The results were analyzed with the object of exploring phenomena and relative influences of various parameters. No hypotheses were tested, but empirical formulas were developed to demonstrate the effects of wind and fuel moisture on the fire. The results of these tests, together with the studies by others, are beginning to reveal the characteristics of fires and should eventually lead to an understanding of the basic laws governing fires.

A complete list of the results for each fire is presented in Appendix B.

[2] Trade names are used for identification only and do not imply endorsement or recommendation by the U.S. Forest Service.

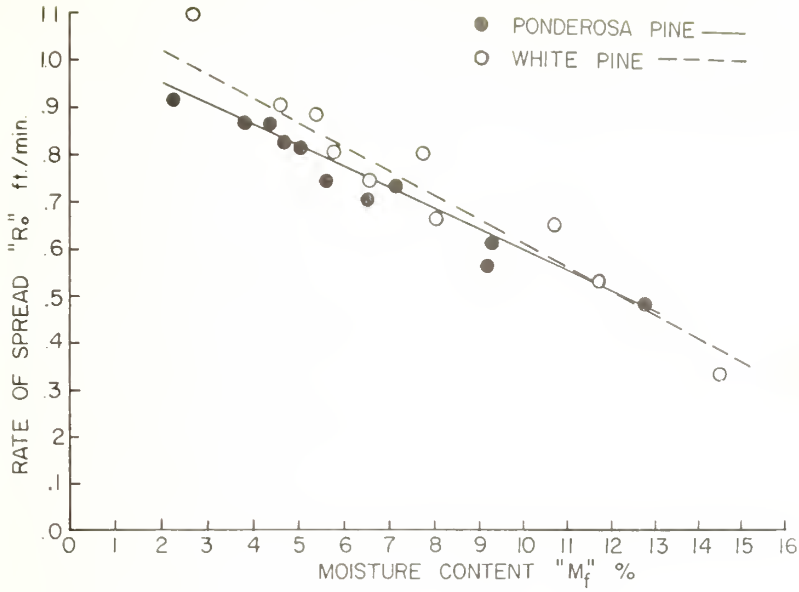


Figure 3.--Correlation of experimental values of rate of spread and prediction equation.

INFLUENCE OF MOISTURE IN ABSENCE OF WIND

We noted early in the program that the rates of spread in both kinds of fuel were strikingly similar (1). A regression analysis over the range of fuel moistures used showed that a linear relation gave the best fit with the data (fig. 3). The equations for rate of spread are:

ponderosa pine $$R_o = 1.04 - 0.044\ M_f \quad (1)$$

white pine $$R_o = 1.12 - 0.051\ M_f \quad (2)$$

where:

R_o = rate of spread in ft./min., and

M_f = fuel moisture content, fraction of ovendry weight.

Equations (1) and (2) may be made dimensionless by dividing both sides of the equation by the rate of spread at $M_f = 0$.

Thus for ponderosa pine $$\frac{R_o}{R_{M_f=o}} = 1 - 0.0423\ M_f \quad (3)$$

and for white pine $$\frac{R_o}{R_{M_f=o}} = 1 - 0.0455\ M_f \quad (4)$$

These equations show that the rate of spread in our ponderosa pine needle fuel beds decreased by 4.23 percent for each 1-percent increase in fuel moisture. Rate of spread in white pine needle fuel beds decreased by 4.55 percent for each 1-percent increase in fuel moisture. If the effect of moisture remains linear as moisture content increases, the ponderosa pine needles would not sustain a rate of spread at a fuel moisture of 24 percent in the still air environment. Similarly, the limit for white pine needles would be 22 percent.

The similarity of the equations for these two fuels is surprising because of the contrast in flame size. The ponderosa pine beds burned with flames 3 to 4 feet high, and the fuel was well burned out. The white pine beds burned with flame heights closer to 1 foot high, and considerable unburned fuel was left beneath the ashes on the surface. Even though the equations are similar, we should not expect that they will predict rate of spread over the wide variety of compactness and fuel geometry that can be found in the field.

EFFECT OF WIND UPON RATE OF SPREAD

Ponderosa pine.--A plot of the logarithm of rate of spread in ponderosa pine needle fires against air velocity on a linear scale produced a straight line graph for each fuel moisture level. The equation for rate of spread in ponderosa pine needles assumes the form:

$$R_{pp} = R_o \, e^{rU} \tag{5}$$

where:

R_{pp} = rate of spread in ponderosa pine needles, ft./min.

R_o = rate of spread at $U = 0$, ft./min.

U = air velocity, ft./min.

r = constant, min./ft.

e = base of natural logarithms.

A regression analysis for each moisture condition gave r values of:

0.00389 at M_f = 4.5 percent

0.00376 at M_f = 7.3 percent

0.00362 at M_f = 9.6 percent

A weighted average r value = 0.0038.

Substituting the average value of r and the equation for R_o gives

$$R_{pp} = (1.04 - 0.044\, M_f) \exp 0.0038U. \tag{6}$$

Equation (6) is plotted using the experimental points in figure 4. The equation predicts rate of spread from U = 0 to at least U = 700 ft./min. where U is the free-stream air velocity above the boundary layer of the fuel. A linear relation with moisture is predicted by equation (6).

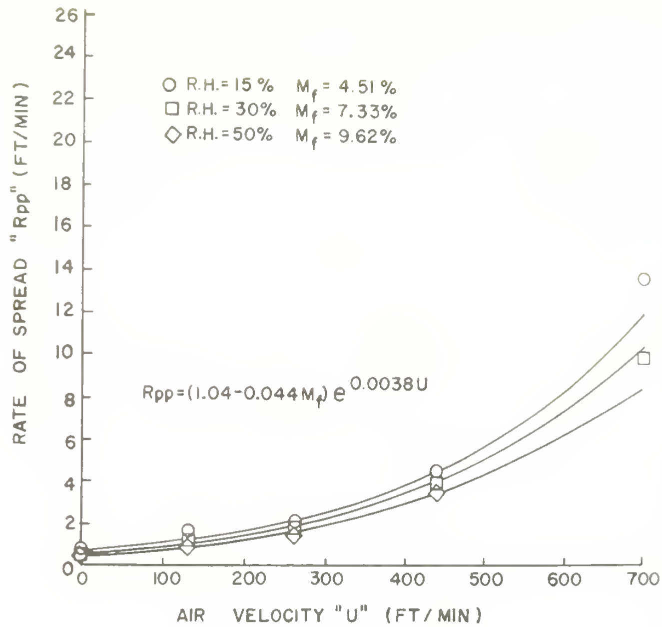
White pine.--The rate of spread of fire in white pine needles also increases as windspeed increases, but at a faster rate than in ponderosa pine needles. An exponential equation can be fitted to the data (fig. 5), but it is good for free-stream air velocities only up to 440 ft./min. The equation is

$$R_{wp} = R_o \, e^{0.006U}, \tag{7}$$

substituting for R_o gives

$$R_{wp} = (1.12 - 0.051\, M_f) \exp 0.006U. \tag{8}$$

Figure 4.--Influence of air velocity upon rate of spread at three fuel moisture levels in ponderosa pine needles.



A more elaborate equation fits the data up to 704 ft./min.; however, it is easier to compare coefficients if the equations are of the same form.

If we assume the exponential curve is the correct form for describing rate of spread with wind, then the deviation of the data from the curve at 704 ft./min. is probably due to a cooling effect of the increased windspeed. Possibly there is an upper limit to air velocity in which fire can burn without being blown out. Such a limit would be at a lower velocity for small flames. The white pine fire with its small flame may show the effects of this limit even though rate of spread is still increasing. Comparative flame sizes of ponderosa pine and white pine may be seen in figures 6 and 7 at 704 ft./min. and 15 percent relative humidity.

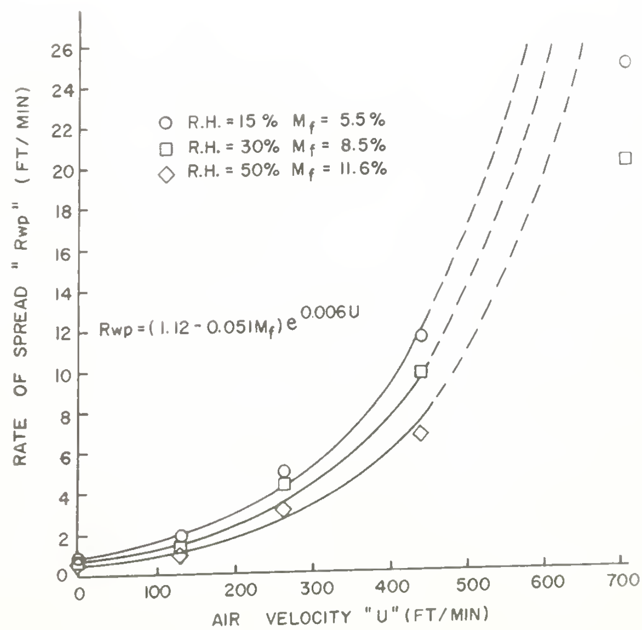


Figure 5.--Influence of air velocity upon rate of spread at three moisture levels in white pine needles

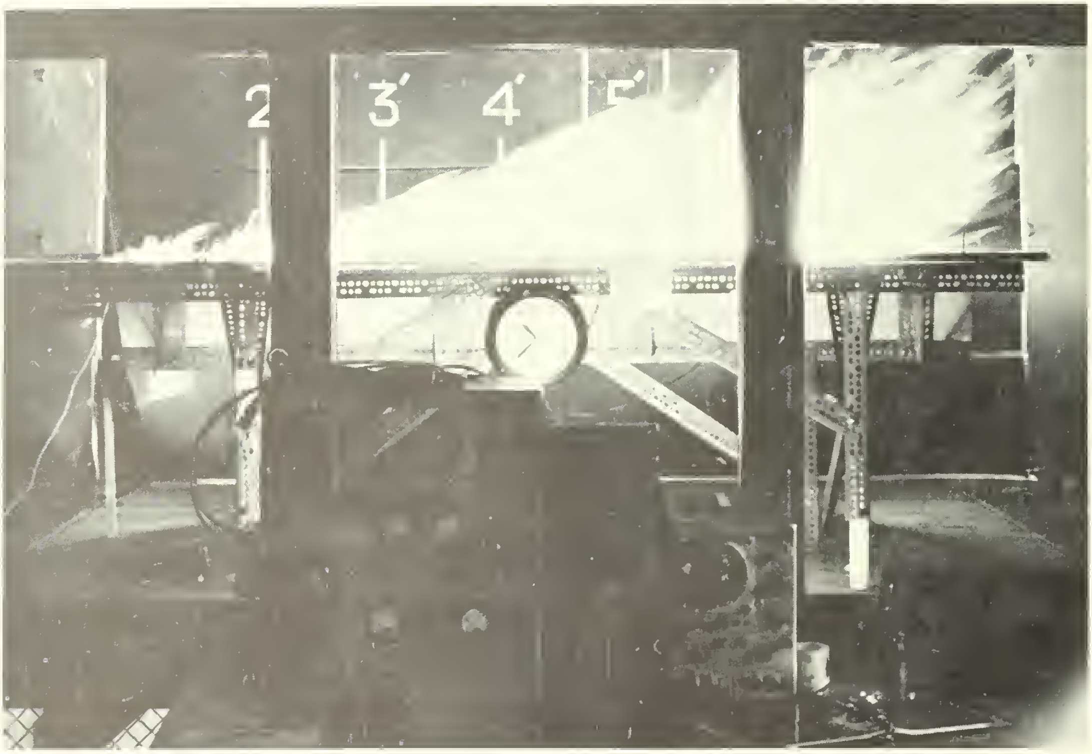


Figure 6.--Flame size in ponderosa pine needles at 704 ft./min. airspeed.

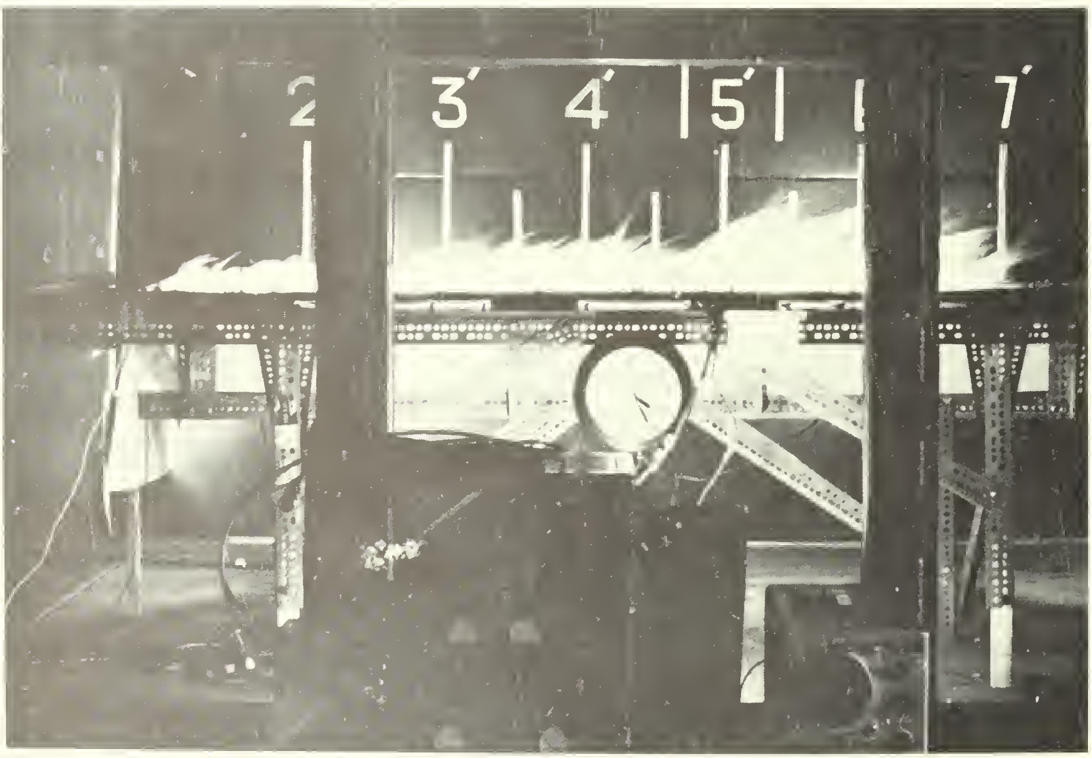


Figure 7.--Flame size in white pine needles at 704 ft./min. airspeed.

DISCUSSION OF RATE OF SPREAD

The experiments demonstrated that fuel moisture and wind do affect rate of spread and showed the relative magnitude of that effect in a specific fuel bed. We have not shown how these parameters exert their influences on the fire, however. Some insight into the processes involved may be obtained from the following observations.

It is not difficult to picture moisture as a dampening agent which must be driven from a fuel before its temperature can be raised to ignition point. Just how the heat gets to the fuel to drive out the moisture by radiation, convection, or mass transport is not clear and is a matter of controversy among some fire researchers. We must answer this question before we can successfully develop mathematical models for rate of spread.

A fuel bed with a propagating fire burns much differently in the absence of wind than in the presence of wind. In the absence of external air movement, the fire creates an indraft and moves against this airflow into the unburned fuel. The leading flame surface is a thin, well-defined sheet (fig. 8). The base of this sheet forms in the gases issuing from the newly ignited fuel. If there is any preheating of the fuel ahead of the fire, it must be due to radiation because there is no mass transport (firebrands) and the convective flow is toward the fire, not away from it. The radiation source may be from either the overhead flames or from within the fuel bed.

Wind creates a much more complex situation. Wind tips the flame forward, and sporadic burning occurs at the base of the flame where it contacts the unburned fuel (fig. 9). This burning appears to play a key role in propagation of the fire. Observation of this phenomenon with high-speed motion pictures and visual observation of many laboratory fires indicate that the sporadic flames are caused by an accumulation of ignitible gases which have collected at the surface of the fuel bed just ahead of the fire. The fire itself provides the pilot flame that ignites the gases--which burn in a direction away from the fire, and appear as a jet of hot gas issuing from the fire.

The source of the unburned gases is not clear, but may be very important in forming a mathematical model of rate of spread. Gases may be formed in the actively burning portion of the fuel bed and may be blown forward through the fuel to rise in front of the fire; they may not ignite before reaching the surface because of an improper fuel/air ratio. They may be a product of pyrolysis of the unburned fuel ahead of the fire.

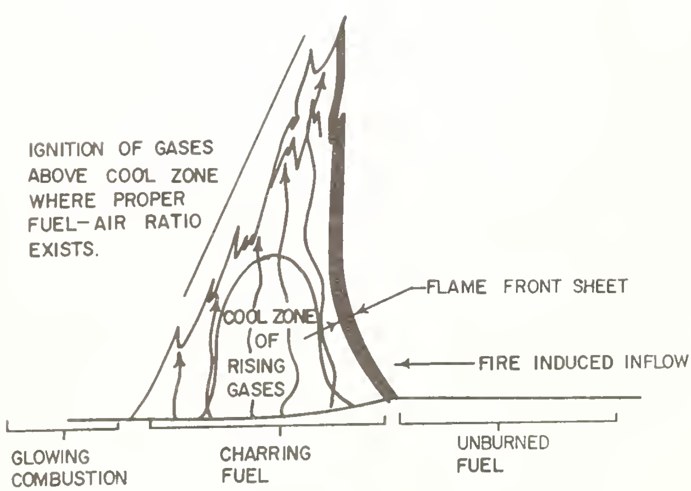


Figure 8.--Flaming zone combustion characteristics in the absence of wind.

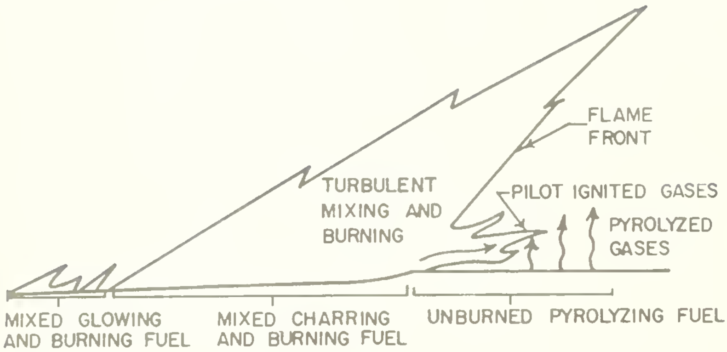


Figure 9.--Flaming zone combustion characteristics in the presence of wind.

If they are combustible gases from unburned fuel ahead of the fire, then this fuel must be receiving sufficient heat to drive the gases off before it is engulfed by the fire. Again the heat may come from several sources--radiant heat from the fuel bed, radiant heat from the overhead flame which is now tipped forward very close to the fuel, or it may be convective heat carried by the wind blowing through the fire. Mass transport of firebrands was not observed in laboratory fires but may be very important in natural uncontrolled fires. Some simple experiments were conducted to answer some of these questions.

Heat shield.--The most straightforward method of observing the effect of radiation is to shield the unburned fuel so that radiation from the flame cannot heat it. A horizontal sheet of asbestos was placed above the fuel bed in the combustion laboratory just high enough to permit the fuel bed to be moved under it without scraping the needles out of position. The fuel bed was ponderosa pine needles, 3.5 feet wide, 8 feet long, and 3 inches deep. Burned in still air, the rate of spread in the first half of the bed (which was not shielded) was 1.18 ft./min. When the fire reached the 4-foot mark, the bed was positioned so the shield stayed just ahead of the flame but did not touch it. The rate of spread decreased to 0.72 ft./min. Blocking the radiation from the flame thus reduced the rate of spread by 39 percent. Interestingly, the fuel burnout was much more nearly complete when the fire was slowed by the shield than when it was unimpeded. This was very evident to the eye because ash content changed from black residue to grey ash where the fire had been slowed.

A similar experiment was performed in the wind tunnel with the air velocity at 5 m.p.h., air temperature at 90° F., and relative humidity at 14.5 percent. The ponderosa pine needle fuel bed was standard size--1.5 feet wide, 8 feet long, and 3 inches deep. The shield was moved so that it stayed 1 to 1.5 inches ahead of the fire. The rate of spread was 1.42 ft./min., whereas without the shield it would have been 4.5 ft./min. The shield therefore reduced rate of spread by 68.5 percent. This reduction cannot be attributed solely to radiation, however, because convective heat would also be blocked from the fuel downwind from the fire.

Needle temperature.--In a second experiment, a 5-mil (.005-inch) chromel-alumel thermocouple was placed inside the fascicles of a hollowed-out ponderosa pine needle; the needles were held tightly around the thermocouple with fine thread wrapped around the fascicle needle. The thermocouple inside the needle provided a temperature history of whatever heat impulse was received by the needle. Because of the low mass of the needle and the small size of the thermocouple, the temperature response was reasonably fast.

The needle was placed on the surface of the fuel bed. In still air, any temperature rise in the needle must be attributed to radiation because the induced airflow caused by the fire is toward the fire; hence no convective heat could be carried from the fire to the needle.

Figure 10 shows the temperature rise of a needle which was placed 7 feet in front of the fire. The ponderosa pine needle fuel bed was of standard size. The average flame height was 3.74 feet. Even though the instrumented needle was 7 feet from the end of the fuel bed where the fire was ignited, the temperature began to rise immediately when the fire had burned 6 inches into the bed and the flames were 1 to 2 feet high. The temperature continued to rise as the fire burned closer and the temperature measured inside the needle passed the boiling temperature of water when the fire was still 1 foot away. This test clearly shows that radiation from the flame can preheat the needle while it is two flame lengths away. When it is close to the fire, radiation from the fuel within the bed may also be contributing to the temperature rise. The combined effect is sufficient to drive the moisture out of the fuel and raise the temperature toward ignition point before the fire engulfs the fuel. The surface temperature of the needle would be hotter than the temperature measured inside the needle. It is reasonable to assume that products of pyrolysis would also be coming from the needle during the preheating.

A fire being driven by wind is more difficult to analyze because the airflow is from the fire toward the unburned fuel. The needle temperature indicates only the total heating and cannot separate the methods of heat transport. To make this separation, an aspirated thermocouple was placed just beneath the surface of the fuel next to the instrumented needle. To assure rapid response, the aspirated thermocouple was made of 1-mil wire; the housing was 3-mil brass shim stock covered with insulation. The tube with the thermocouple inside was oriented vertically so that the thermocouple would respond only to a small collimated portion of the flame when it was directly overhead. Air was drawn off the surface of the fuel bed and pulled past the thermocouple with a vacuum pump and hoses.

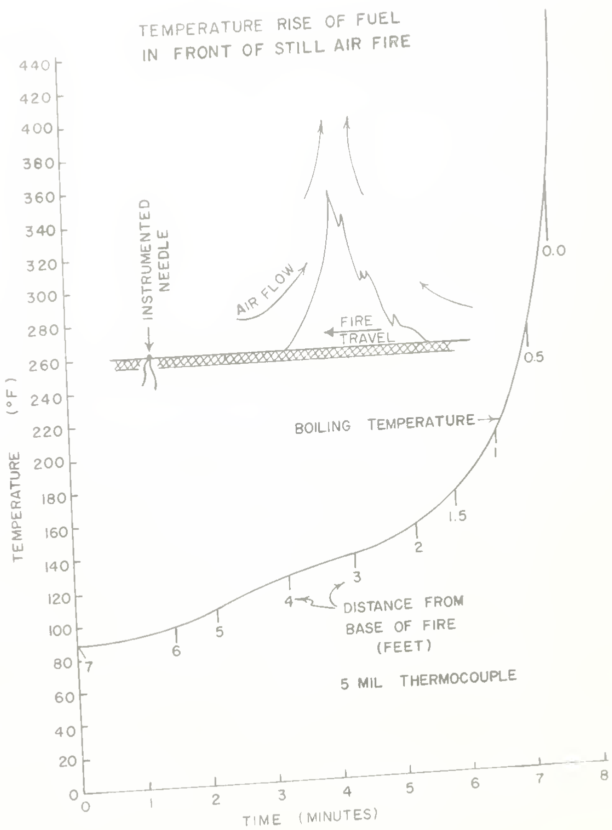


Figure 10.--Temperature rise of fuel in front of still-air fire.

If the temperature rise of the needle is to be attributed to convective heating from the air passing over it, then the air temperature must be hotter than the needle. For this test a 1-mil thermocouple was placed inside the needle--instead of the 5-mil used in the "no wind" test. The needle was hollowed sufficiently to allow the thermocouple to be positioned just beneath the surface. The needle and inlet to the aspirated thermocouple were placed 7 feet from the forward edge of an 8-foot fuel bed. The bed was 3.5 feet wide and 3 inches deep with ponderosa pine needles. The free-stream air velocity was 5 m.p.h., air temperature was 90° F., and relative humidity was 12.5 percent. Fuel moisture content was about 4 percent. Even though 1-mil thermocouples were used in both the aspirated thermocouple and the needle, the response of the needle thermocouple to heat impinging on the surface would be slower than that of the aspirated thermocouple because of the time necessary for the heat to be conducted from the surface of the needle to the thermocouple.

The temperature trace from the two thermocouples (fig. 11) shows that the air temperature began to rise almost immediately. The needle temperature began to rise when the fire was still more than 6 feet away. Except for a dip in the curve when the fire was 1.5 feet from the instruments, the air temperature remained higher than the needle temperature. If it is assumed that the lag of the needle temperature was not enough to account for the difference in temperatures, then the air temperature was indeed hotter than the needle and capable of transferring heat to it. This test does not rule out radiant heat transfer because the needle temperature is responsive to both types of heating. It would have eliminated convective preheating if the air temperature had been cooler than the needle temperature.

Note also the sharp increase in both temperatures as the fire comes close and the flame comes overhead. Boiling temperature of the needle was passed when the fire was about 8 inches from the needle. The chart did not extend to ignition temperature of 608° F., but both temperatures were heading for it simultaneously. During this portion of the fire, the sporadic burning at the surface was close upon the needle and possibly touching it. The high temperature of the needle before the fire reached it presents the possibility that preheating releases combustible gases ahead of the fire.

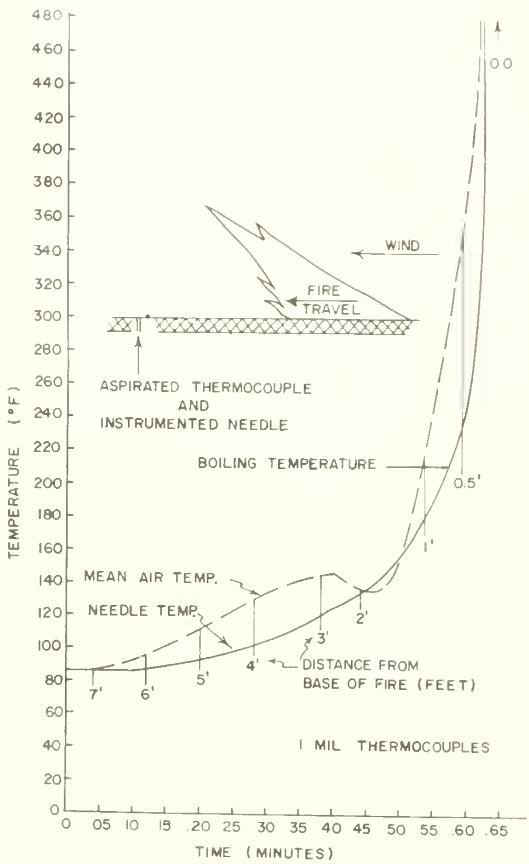


Figure 11.--Temperature rise of air and fuel in front of wind-driven fire.

SUMMARY OF DISCUSSION

The thermocouple inside the needle shows that preheating of the fuel begins at a considerable distance (two or more flame lengths) ahead of the fire. The temperature of the needle passes boiling temperature of water before the fire reaches it. Heating in the absence of wind must result from radiation because the direction of airflow is from the needle toward the fire. In the presence of wind, preheating may be caused by both convection and radiation. Fires burning in wind exhibit burning on the surface of the fuel ahead of the main flame front. This burning is in gases which have accumulated there from an unknown source. Possibly these gases may result from pyrolysis in the fuel ahead of the fire or from the combustion zone within the flame.

The mechanism of fire spread in fine fuels may be described as a series of ignitions in which the temperature of fuel ahead of the fire rises, slowly at first as the water is expelled and then rapidly as the fire draws close. In a steady state fire, the fuel reaches pilot ignition temperature simultaneously with the arrival of the fire.

CHARACTERISTICS OF RATE-OF-SPREAD CURVES

There has been considerable conjecture about the shape of the rate-of-spread curve in a wind-influenced fire. Thomas and Pickard (19) have shown in crib fires that as windspeed increases, its effect on rate of spread progressively decreases. They show that this effect of windspeed appears to approach a limit as wind velocity increases. Byram et al. (6) at the Southern Forest Fire Laboratory in Macon, Georgia, have shown a linear increase in rate of spread as air velocity increases in crib fires. Velocities thus far tested have not been high enough to indicate whether a limiting value will be approached. Our tests with two similar mat-type fuel beds have produced curves that increase as wind velocity increases. Perhaps they too will approach a maximum rate of spread at a higher velocity. It seems reasonable to assume that an upper limit exists. For large outdoor fires, however, the upper limit may fall outside the atmospheric range of wind velocities. Similarly, increasing rate-of-spread curves were found in the lodgepole pine and Douglas-fir logging slash fires,[3] and by Fons (11) in outdoor ponderosa pine fires. These curve shapes are shown in figure 12.

This diverse behavior may be explained by the surface area-to-volume ratio of the fuel particles, σ, and the porosity, λ, of the fuel bed. Fine fuels, such as pine needles, have a large surface-to-volume ratio. They have a short ignition delay time, and individual needles, once ignited, sustain combustion. Emmons (9) shows how the surface-to-volume ratio is important in preheating fuel elements by radiation. A large value of σ also facilitates better convective heat transfer. Table 1 shows the rate of spread of several fuels having different values of σ and λ at the same air velocity and having nearly the same fuel moisture content. Recent work at the laboratory indicates the burning characteristics may be related to the product of the fuel particle surface area-to-volume ratio and the fuel bed porosity ($\sigma\lambda$). This is a non-dimensional parameter. A plot of the data in table 1 vs. ($\sigma\lambda$) is shown in figure 13.

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[3] Anderson, Hal E., Arthur P. Brackebusch, Robert W. Mutch, and R. C. Rothermel. Mechanisms of fire spread research progress report no. 2 (field study). U.S. Forest Serv. Res. Pap. INT-28, 1966. (In press.)

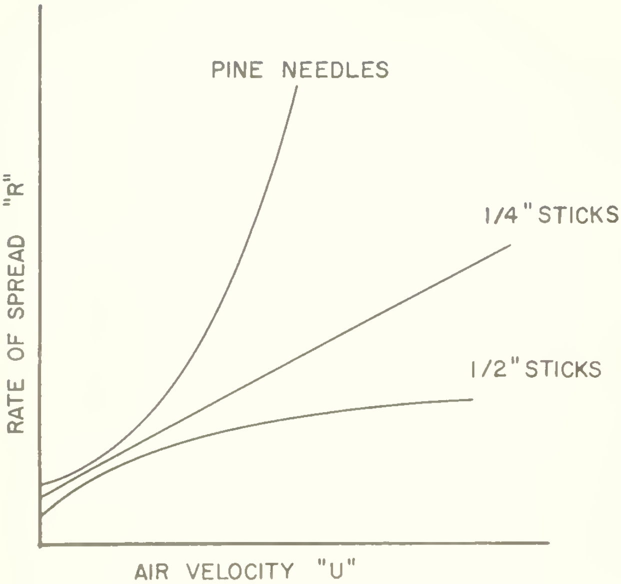

Figure 12.--Possible curve shapes for rate of spread in wind as influenced by size of fuel particles.

Table 1.--Fuel particle size and fuel bed porosity used in these and other fire experiments

Fuel	Fuel surface-to-volume ratio	Fuel bed void volume-to-surface area ratio[1]	($\sigma\lambda$)	R at U = 600 ft./min.
	σ ft.^{2}/ft.^{3}	λ ft.^{3}/ft.^{2}	Dimensionless	Ft./min.
White pine needles	2,790	6×10^{-3}	16.7	12.0
Ponderosa pine needles	1,741	8.46×10^{-3}	14.7	6.5
$\frac{1}{4}$-inch sticks	192	2.47×10^{-2}	4.74	0.775
$\frac{1}{2}$-inch sticks	96	3.86×10^{-2}	3.70	0.456

[1] Meanings of the terms "compactness," "porosity," and the symbol λ are sometimes confused. The porosity of a fuel bed is defined as the void volume of the bed divided by the surface area of the fuel in the bed and is represented by the symbol λ with the units ft.^{3}/ft.^{2}. Compactness is the reciprocal of porosity. The void volume of the fuel bed is the total geometric volume minus the volume occupied by the fuel. The surface area of the fuel is that of all the fuel within the volume.

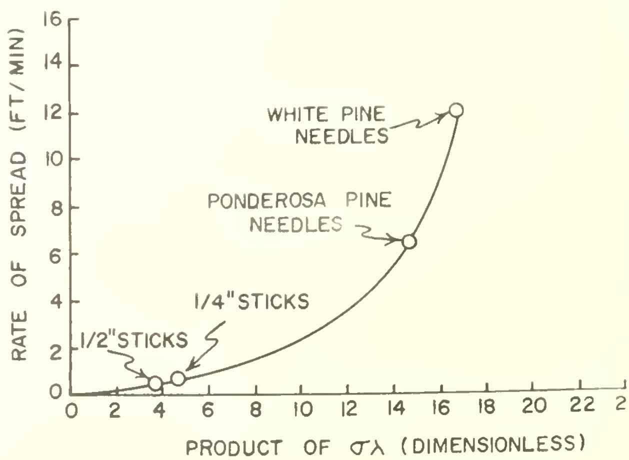

Figure 13

RELATION BETWEEN FIRE BEHAVIOR AND ENERGY RELEASE RATE

Fire increases the temperature of the air associated with it and thereby lowers its density. Buoyancy causes the less dense air to rise and thus form the familiar convection column. If wind is present, the vertical buoyancy forces compete with the horizontal wind force, and the flame tilts away from the vertical. The amount of tilt depends on the relative magnitude of the fire and wind forces. We are very much interested in the amount of tilt and the amount of heat that is carried horizontally, because of the resultant preheating in the unburned fuel and the increase in rate of spread (fig. 14). Unfortunately the vertical forces that a fire generates over its entire area are difficult, if not impossible, to measure or compute. However, the energy rates of the fire and wind can be measured and these energy values may help to explain fire behavior.

The conservation of energy relationship for the fire may be written:

$$E\ \text{potential} = E\ \text{combustion} + E\ \text{residue} + E\ \text{loss} \tag{9}$$

where:

E potential = heat content of the fuel

E combustion = heat released by the fire

E residue = heat content of the unburned fuel and ashes

E loss = heat content of unburned fuel in the convection column.

Since the potential energy of the fuel is equal to the weight of the fuel multiplied by the heat content per unit weight, the change in weight is proportional to the energy released by the fire.

$$\Delta\ \text{wt.} \approx E\ \text{potential} - E\ \text{residue} = E\ \text{combustion} + E\ \text{loss} \tag{10}$$

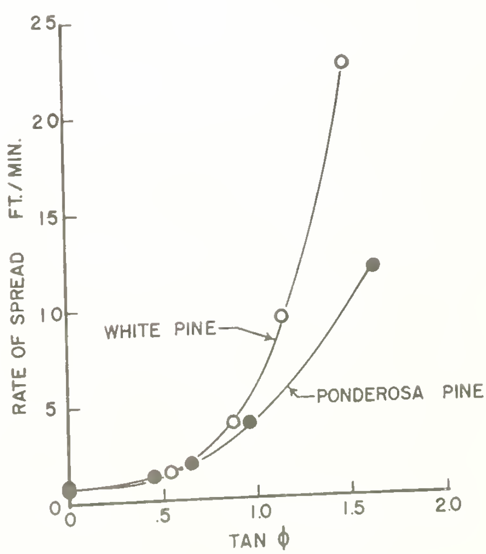

Figure 14.--Relation of flame angle and rate of spread under influence of air velocity.

Fons (12) showed that under no-wind conditions E loss is approximately 5 percent of the potential energy of the fuel. Assuming that E loss remains small with wind, E combustion = Δ wt. $\times$ heat content of fuel. Since we are interested in rate changes rather than total changes, the rate of weight loss is used and gives the rate of combustion (B.t.u. per minute). The energy release rate per unit area of burning fuel may now be defined as the equivalent unit energy release rate, E_R, and is obtained by dividing the combustion rate by the combustion area.

$$E_R = \frac{\text{(Weight loss rate) (Energy equivalent of fuel)}}{\text{(Combustion area)}} \text{ B.t.u./ft.}^2\text{/min.} \qquad (11)$$

The energy rate per unit area of the wind tunnel airstream equals the dynamic pressure times the air velocity. The tangent of the flame angle should then be proportional to these two quantities:

$$\text{Tan } \varphi \approx \frac{qU}{E_R J} \qquad (12)$$

where:

φ = flame angle

q = dynamic pressure of airstream lb./ft.^{2}

U = air velocity ft./min.

E_R = equivalent unit energy release rate B.t.u./ft.^{2}/min.

J = mechanical equivalent of heat ft. lb./B.t.u.

Tan φ plotted against qU/E_RJ (fig. 15) is a straight line on log log paper, with no evidence of dependence upon moisture or species for all conditions under which fires were burned. This relation also shows a correlation to rate of spread when a sufficiently wide fuel bed is used. The relation qU/E_RJ may also prove to be a valuable dimensionless parameter for scaling indoor fires to outdoor fires.

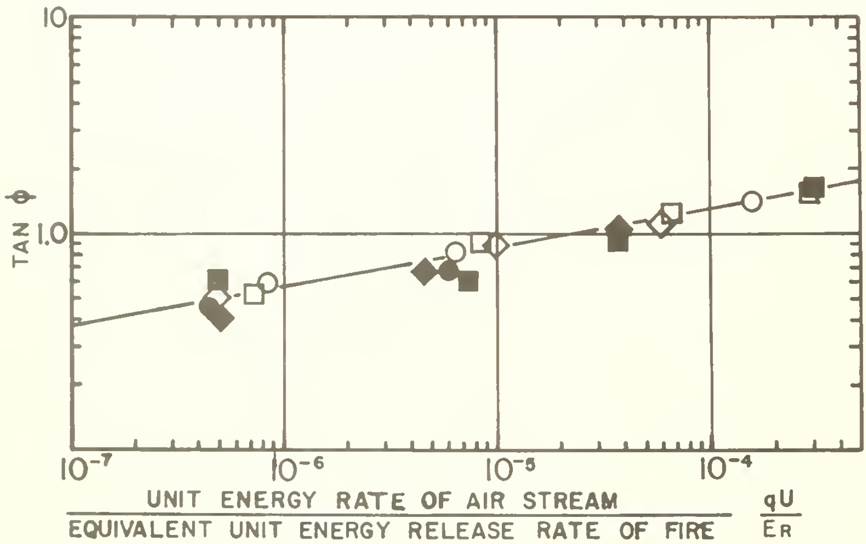

Figure 15.--Dependence of Tan φ upon unit energy rate of fire and airstream.

The flame angle and the rate of spread have been shown to depend upon the combustion rate per unit area of the fire. Similarly, E_R can be shown to be dependent upon wind. Figure 16 shows a reduction of E_R as air velocity increases. An analysis of variance did not indicate a significant difference in E_R for the fuel moistures used in these experiments. The independence of E_R to fuel moisture is less obvious in the absence of wind. Without wind, the flame depth is shallow, and edge effects are stronger. Further testing with a wider range of fuel moisture and a better determination of combustion area may show a dependence of E_R upon fuel moisture.

A simple regression analysis of E_R on U produces the equations:

ponderosa pine $$E_R = \frac{3240}{1+0.0069U} \qquad (13)$$

white pine $$E_R = \frac{2740}{1+0.0088U} \qquad (14)$$

where:

E_R = equivalent unit energy release rate B.t.u./ft.^{2}/min.

U = air velocity ft./min.

Further study is needed to develop a hypothesis that will relate E_R to fuel bed loading, fuel particle size, fuel bed compactness, and air velocity.

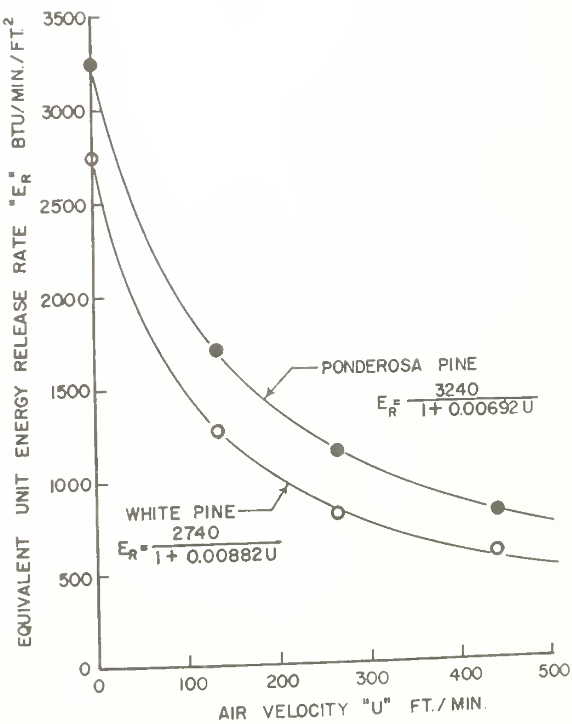

Figure 16.--Influence of air velocity upon equivalent unit energy release rate.

A cursory look at fires would not indicate that E_R should decrease as air velocity increases. In mat-type fuel beds, this decrease is explained by the fact that as air velocity increases, combustion area increases faster than total heat release from the fire. It is true that total heat output of the fire, after first decreasing slightly, increases with additional air velocity; but at the same time the fire is burning over a much larger area and not burning as deep--thereby lowering the heat output per unit area. In fuel beds such as ours, that are restricted in width, the combustion area is directly proportional to flame depth, where flame depth is the distance from the leading edge of the fire to the rear of the fire front. The fire front does not include residual burning behind the main fire. The relation between flame depth and rate of spread is shown in figure 17. In this figure, moisture and wind influences have already shown their effect on rate of spread, and they are not apparently separable.

While flame depth is increasing, the vertical depth of burn into the fuel bed is decreasing. At 704 ft./min. (8 m.p.h.) unburned needles could be found in the lower layers of the ponderosa pine fuel beds. Unburned needles could not be found when air was moving slower. Data on burning depth are presented only in the data summation tables of this paper, pages 31-34.

If the fuel bed porosity, λ, were high enough to permit burnout of fuel to the full depth even in very high air velocities, combustion rate might increase faster than flame depth and E_R would not decrease as air velocity increases. Again, the need for more research on fuel bed parameters λ and σ becomes apparent.

FIRE CHARACTERISTIC CURVE

The preceding discussion has shown a relation between the rate of unit energy release of the fire and the resulting flame angle in the presence of wind. This relation indicates that if E_R is large the flame will not be tipped and rate of spread will be small. As wind increases, the flame tips, and rate of spread increases as E_R decreases. A plot of rate of spread versus

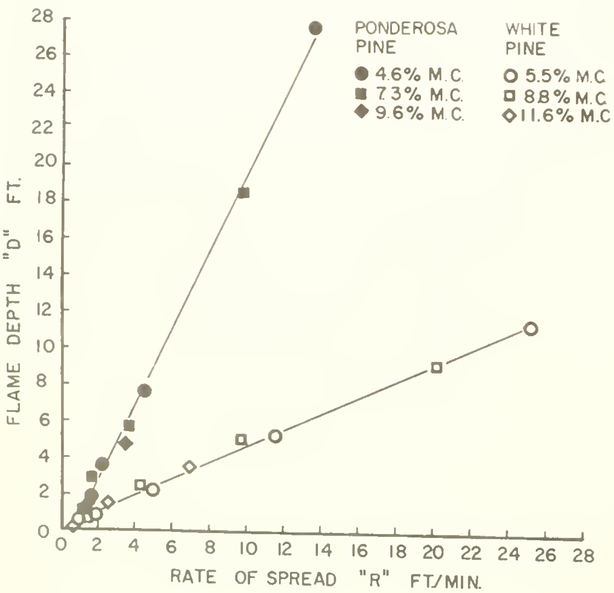

Figure 17.--Influence of moisture and air velocity on rate of spread and flame depth.

E_R confirms this and produces the fire characteristic curve shown in figure 18. Fires that have a very low and nearly constant rate of spread, a large ratio of flame length to flame depth, and a high unit energy release rate are at one end of this curve. These characteristics are similar to those of a fire storm, which is a high-intensity stationary fire. At the other end of the curve are fires that show a very rapid rate of spread, a low ratio of flame length to depth, and a low but nearly constant rate of unit energy release. These are the characteristics of runaway fires that burn in fine light fuels. This curve illustrates the rapid increase in rate of spread that results when the convection column weakens and tips because the unit energy release rate is low.

The knee of the curve (transition zone) marks the area of minimum values for several important fire characteristics--including flame length, total energy release rate, and the peak irradiance (measured by an overhead radiometer). Presence of the transition zone may reflect a change in the mechanism of rate of spread as was discussed earlier (see figures 8 and 9).

This is the only curve that could be found that relates rate of spread of both fuels to a common parameter along the same line. Each point on the curve represents a single velocity at which all values of fuel moisture for that velocity are averaged. The effects of varying size of the fuel particles and configuration of the fuel bed upon this curve will be very interesting to see.

DIFFUSION FLAME ANALYSIS

The general principles of diffusion flame theory presented by Thomas (18, 20) applied to fires in mat-type fuel beds (2, p. 18) if the characteristic length, D, in equation (15) is revised to equal the distance from the front of the fire to the rear:

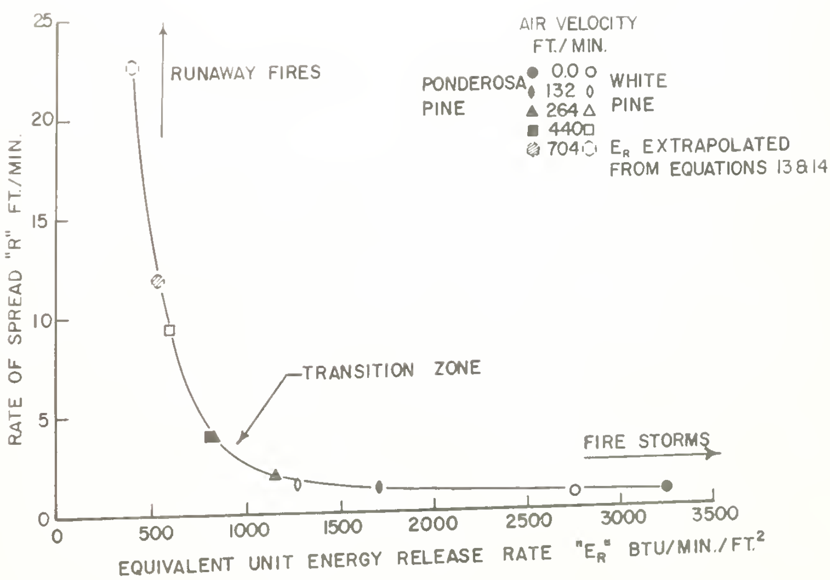

Figure 18.--Fire characteristic curve relating rate of spread and equivalent unit energy release rate.

$$\frac{L}{D} = K \frac{(m'')^{n}}{\rho (gD)^{\frac{1}{2}}} \tag{15}$$

where:

L = flame length in feet (distance from base to tip of fire)

D = flame depth in feet

m'' = unit mass flow rate in lbs./min./ft.^{2}

ρ = air density (8.1×10^{-2} lbs./ft.^{3})

g = gravitational constant (1.152×10^{5} ft./min.^{2}).

To represent the orifice diameter, we used flame depth rather than some equivalent dimension based on the square root of flame depth multiplied by fuel bed width. The value of m'' (mass flow rate of combustion gases per unit area) was determined from the weight loss data in much the same manner as the equivalent unit energy release rate E_R was computed. When results of this analysis were compared to the relation developed by Thomas' equation (16), they showed good correlation (fig. 19).

$$\frac{L}{D} = 42 \frac{(m'')^{0.6}}{\rho (gD)^{\frac{1}{2}}} \tag{16}$$

The dimension of flame depth appears to be the correct measure to use, and radial symmetry is unnecessary. For our fuel beds the numerical values on both sides of the equation increased as moisture content increased.

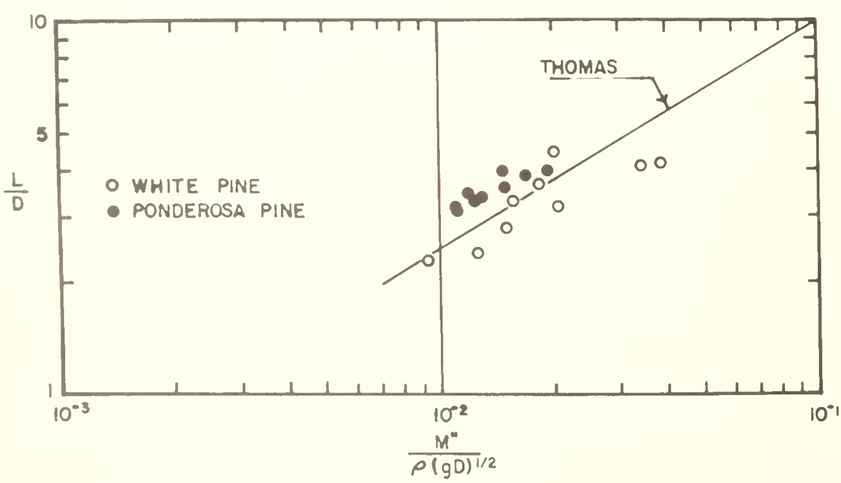

Figure 19.--Diffusion flame characteristics of fires under no-wind conditions compared to values in Thomas' equation.

Thomas extended his work to include the influence of air velocity; we checked our data against his analysis. The values for each moisture level were averaged at each air velocity. The relations tested were of the form:

$$\frac{L}{D}\left(\frac{U^2}{gD}\right)^{0.11} = K\,\frac{(m'')^n}{\rho\,(gD)^{\frac{1}{2}}} \tag{17}$$

These were compared to Thomas' results (fig. 20). A slight difference is evident between white pine and ponderosa pine fires, but a single line can approximate the relation for both fuels. The equation of this line, plotted from our data, is:

$$\frac{L}{D}\left(\frac{U^2}{gD}\right)^{0.11} = 164\,\frac{(m'')^{0.97}}{\rho\,(gD)^{\frac{1}{2}}} \tag{18}$$

whereas Thomas obtained this equation:

$$\frac{L}{D}\left(\frac{U^2}{gD}\right)^{0.11} = 70\,\frac{(m'')^{0.43}}{\rho\,(gD)^{\frac{1}{2}}} \tag{19}$$

The difference apparent between the two sets of data may be attributed to differences in measurement techniques, or possibly to variations in size of fuel particles.

A series of outdoor fires was studied in prepared fuel beds of logging slash during the summer of 1962 (2, p. 18). The fuel was lodgepole pine and Douglas-fir needles, and branch wood up to 2 inches in diameter. The fuel beds, 6 feet wide by 60 feet long, were ignited at one end. We recorded data similar to those recorded for the laboratory fires.

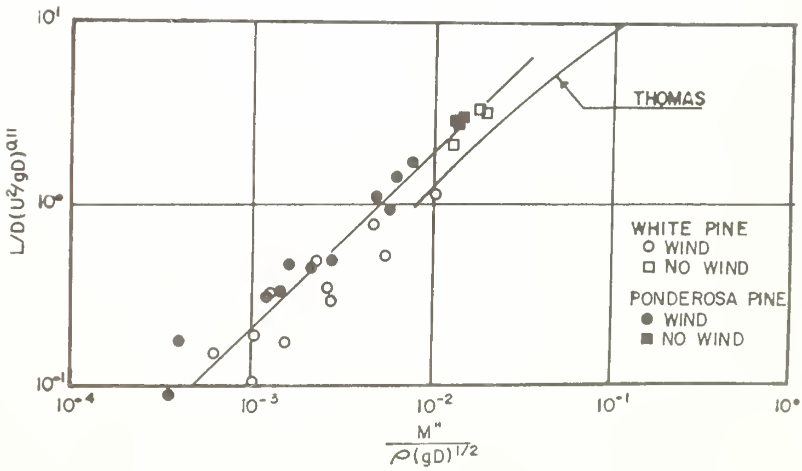

Figure 20.--Diffusion flame characteristics for laboratory fires under the influence of wind.

The outdoor fires were checked by the diffusion flame analysis for wind to determine their correlation with laboratory fires. Since the actual rate of weight loss could not be measured, we used maximum burning rate to compute mass flow rate of the combustion gases. The mass flow rate was determined from the equation:

$$m'' = \frac{W_o R}{D} \text{ lbs./ft.}^2\text{/min.} \tag{20}$$

where:

W_o = loading in lbs./ft.^{2}

R = rate of spread in ft./min.

D = flame depth in feet.

The relation given in equation (17) was applied and the data were plotted (fig. 21).

The field data (fig. 21) fell to the right of the pine needle laboratory data and Thomas' ½-inch stick data. This was expected because all the fuel was assumed to be contributing to the mass flow rate m" in the fire front. In a heterogeneous fuel bed the fine fuels ignite first and therefore contribute most heavily to the fire front. If the fine fuels up to one-fourth inch in diameter are assumed to be supporting the initial flame size, then m" is reduced to a value that alines the field data with the laboratory pine needle data. If all the fuel up to one-half inch in diameter is assumed to be contributing, then the field data aline with Thomas' ½-inch crib data.

This demonstrates a possible use for the diffusion flame characteristic equation provided the size classification of the fuel is known. When this is known, the burning rate per unit area, or mass flow rate, can be determined. If forest fuel can be classified so that loading and size percentages are known, estimates of mass flow rate (m") and equivalent unit energy release rate (E_R) can be made. If E_R can be so estimated for outdoor fires, it may be possible to relate fires of different sizes with the fire characteristic curve (fig. 18).

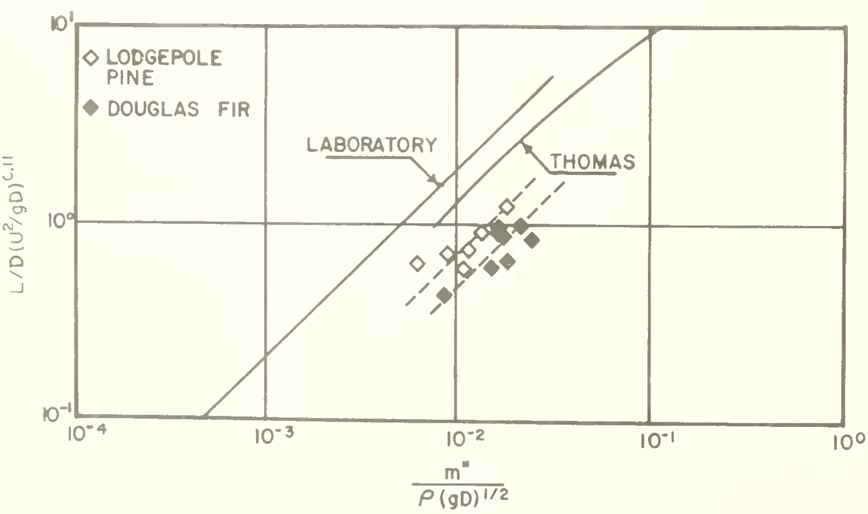

Figure 21.--Diffusion flame characteristics for field fires under the influence of wind.

SUMMARY AND CONCLUSIONS

Our studies of the effects of fuel moisture and wind upon the rate of fire spread in ponderosa pine and white pine needle fuel beds have shown the following:

1. As wind increased, the fire spread at an increasing rate.

2. The fire was carried in the surface fuel particles.

3. Flame depth increased and vertical depth of burn decreased as windspeed increased.

4. In the absence of wind, rate of spread decreased linearly as fuel moisture increased.

Additional experiments were conducted to aid in explaining how fire is propagated. For these, a thermocouple was placed inside a needle to register changes in temperature. These experiments showed the following:

1. The thermocouple began to show rise in temperature when the fire was still two flame lengths away.

2. Temperature inside the needle became higher than that for the boiling point of water before the fire reached it.

3. In the absence of wind, the initial rise in temperature must be due to radiation from the overhead flame because of the large distance from the fire and because air is flowing toward the fire, not away from it.

4. When the fire draws close to the needle, radiation from within the fuel bed may also contribute to the temperature rise.

5. In the presence of wind, the air temperature at the surface of the fuel bed was found to be hotter than the fuel; therefore, both convective heating and radiant heating can contribute to the rise in temperature of the fuel particles.

6. In the presence of wind, combustible gases may form on the surface of the fuel bed ahead of the main flame front. The exact source of these gases is not known. These gases seem to be ignited periodically by the fire and to sweep ahead of the main fire front along the surface of the fuel. They appear to play a major role in the mechanism of fire spread in the presence of wind.

Results of this study of the effect of wind upon rate of spread in fine fuels do not correspond to results of other studies that used cribs made of dimensioned sticks. Possibly this may be explained by differences in the fuel particle size, σ, and fuel bed porosity, λ. There was a correlation between rate of spread and the product of σ and λ.

These studies revealed the importance of the equivalent unit energy release rate. Rate of spread plotted against equivalent unit energy release rate produces a curve on which the average values of both fuel types fall. This curve clearly demonstrates the characteristics of a fire; therefore it is named the fire characteristic curve. Fires having low rates of spread and high rates of energy release are at one end of the curve and have many characteristics of a fire storm. Fires with rapid rates of spread and low, nearly constant, energy release values are at the other end of the curve and have the characteristics of runaway fires. The knee of the curve represents a transition zone in which the mechanism of spread is changing from the no-wind to the wind model. Several important parameters reach minimum values at the transition zone.

Diffusion flame analysis that Thomas used on crib fires was applicable to mat-type fuel bed fires if flame depth was used in place of equivalent orifice diameter. The use of this analysis may enable us to predict burning rates of outdoor fires from their flame dimensions.

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APPENDIX A

Symbol		Definition	Measure
A_c	=	area of combustion at surface of fuel	ft.^{2}
B	=	rate of weight loss (burning rate)	lbs./min.
D	=	depth of flame zone from leading edge of fire to trailing edge of fire front	ft.
E_R	=	equivalent unit area energy release rate	B.t.u./ft.^{2}/min.
H	=	low heat of combustion value of fuel	B.t.u./lb.
I_{OH}	=	peak overhead irradiance	B.t.u./ft.^{2}/HR
I_T	=	total radiant heat received during passage of the flame	B.t.u./ft.^{2}
I_{18}	=	irradiance to a point 18 feet forward of the fire	B.t.u./ft.^{2}/HR
J	=	mechanical equivalent of heat	ft. lb./B.t.u.
L	=	flame length from midpoint of flame depth to tip of flame	ft.
L_v	=	vertical height of flame tip above fuel surface	ft.
M_a	=	unit mass of air	lb./ft.^{3}
M_f	=	fuel moisture content	percent
M_g	=	unit mass of convection column gases	lb./ft.^{3}
Q	=	total heat release rate	B.t.u./lb.
R	=	rate of spread at any condition	ft./min.
RH	=	relative humidity	percent
R_o	=	rate of spread in absence of wind	ft./min.
R_{pp}	=	rate of spread in ponderosa pine needles	ft./min.
R_{wp}	=	rate of spread in white pine needles	ft./min.
T_o	=	ambient temperature	°F.
tb	=	burn thickness	ft.
U	=	velocity of air	ft./min.
V	=	velocity of convection column	ft./min.
W_o	=	unit area loading of ovendry fuel	lb./ft.^{2}
g	=	acceleration due to gravity	ft./min.^{2}
m"	=	mass flow rate of combustible gases per unit area	lb./ft.^{2}/min.
q	=	dynamic pressure of air stream	lb./ft.^{2}
θ	=	residence time of flaming zone at any point in fuel bed	min.
λ	=	void volume per unit of fuel surface area	ft.^{3}/ft.^{2}
ρ	=	air density	lb./ft.^{3}
σ	=	fuel particle surface area per unit volume	ft.^{2}/ft.^{3}
φ	=	deflection angle of flame from vertical	degrees

APPENDIX B

INFLUENCE OF SURFACE FLOW OF WIND UPON RATE OF SPREAD

A series of preliminary fires in the wind tunnel was used to check instrumentation and experimental techniques. During these tests the fire spread four to seven times faster in the first half of the fuel bed. The flames were tipped considerably farther in the first 4 feet; this indicated a stronger influence of the wind upon this portion of the fire.

In a smoke test, a tight rolling vortex was observed over the first 2 feet of the fuel bed; its diameter gradually increased, and the vortex dissipated over the last 4 feet of the bed. The boundary layer was investigated with a constant-current hot wire anemometer. The hot wire confirmed the visual observations of the smoke and showed the vortex formation, breakup, and dissipation (fig. 22). The center of the vortex gradually rose from 1 inch at fuel bed station, 0.5 foot to 3 inches at station 1.0 foot, and to 5.0 inches at station 2.0 feet. During this time

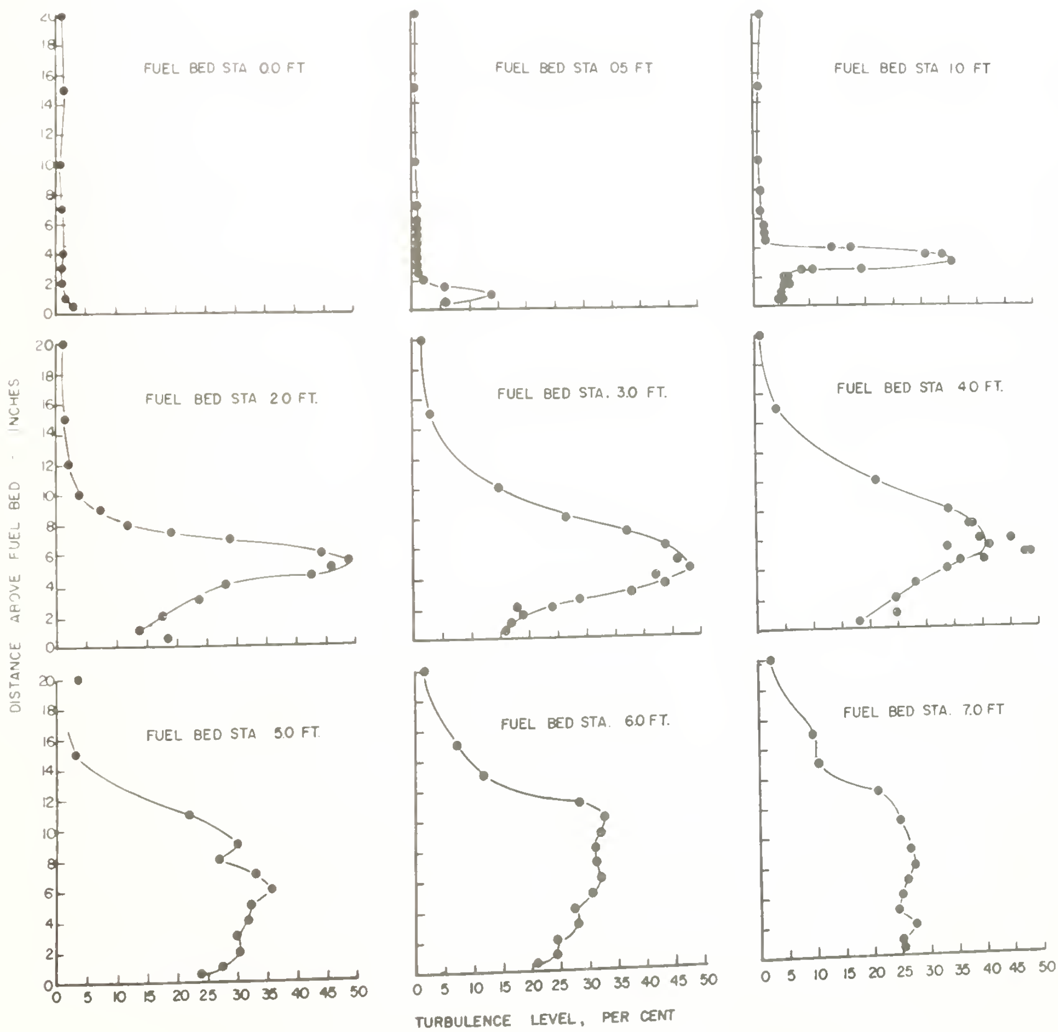

Figure 22.--Surface layer turbulence over ponderosa pine needle fuel bed at free-stream air velocity of 3 m.p.h.

the diameter of the vortex grew larger until at 4.0 feet it no longer held any well-defined shape and broke up. At 5, 6, and 7 feet the air motion appeared to be random; and the turbulence level, which had been as high as 50 percent, decreased to 25 to 30 percent at 7 feet.

These measurements were made over the fuel bed in the absence of any fire and, of course, the same turbulence pattern would not exist if the fuel bed were burning. The measurements do show, however, that when the fuel bed is ignited at station zero, the free-stream air velocity extends down to the surface of the fuel bed and can tip the weak flame almost 90° over the unburned fuel. The free-stream air velocity is then dominant over the flame until the energy output of the fire builds up and straightens the flame. This did not occur until the fire was well into the fuel.

The solution to the problem was to lift the free-stream air velocity above the surface of the fuel at station 0.0 by placing a trip fence or spoiler across the fuel bed 1 foot ahead of the fuel bed. The trip fence was 1-5/8 inches high and induced a turbulent boundary layer which was surprisingly uniform over the entire length of the fuel bed. Results of a hot wire turbulence survey with the spoiler in place (fig. 23) showed that beyond 2 feet the vortex appears to have dissipated and the maximum turbulence levels are about 30 percent.

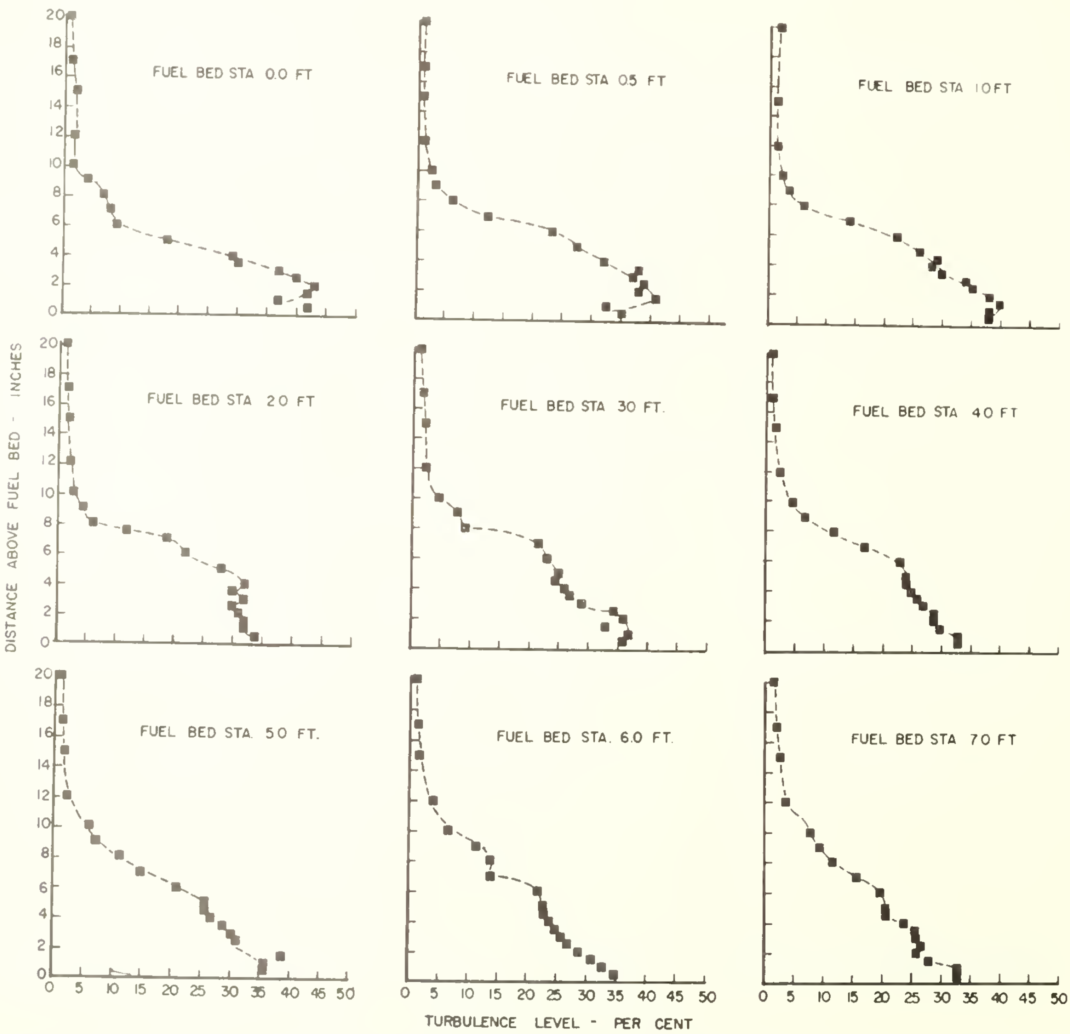

Figure 23.--Surface layer turbulence over ponderosa pine needle fuel bed with spoiler at free-stream air velocity of 3 m.p.h.

Fuel beds burned behind the spoiler produced a uniform rate of spread from 2 feet to 7.5 feet. Typical rate of spread data for fires burned with and without the spoiler are shown in figure 24. All wind tunnel data presented in this report were taken with the spoiler in place.

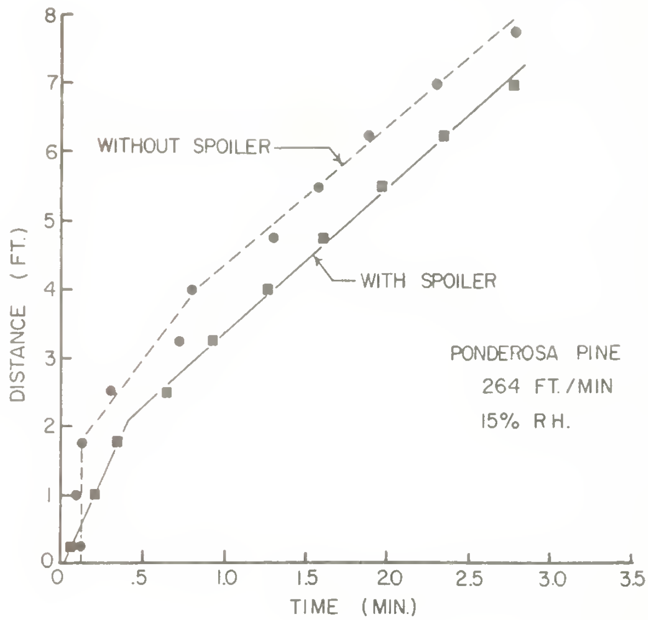

Figure 24.--Effect of surface layer turbulence on rate of spread with and without a spoiler.

Table 2

Fire no.	Test area ambient conditions 3/		Fuel and fuel bed parameters			Burning parameters				Flame dimensions			Heat variables				
	T_o	RH	M_f	W_o	H	R	θ	B	A_c	t_b	D	L	E	E_R	I_{OH}	I_T	I_{le}
	°F	%	%	lb/ft²	Btu/lb	ft/min	min	lb/min	ft²	ft	ft	ft	Btu/min	Btu/ft² min	Btu/ft² hr	Btu/ft²	Btu/ft² hr
PP-1-C	93	13	4.[illegible]	[illegible]	8869	0.84[illegible]	0.50	-	[illegible].63	-	[illegible].42	[illegible].2	-	-	-	-	15.4
PP-2-C	92.5	13.5	4.41	0.48	8869	0.860	0.50	-	0.65	-	[illegible].43	[illegible]	-	-	-	-	[illegible]5.6
PP-3-C	92	12	4.38	0.48	8869	0.900	0.51	-	0.69	-	[illegible].46	3.8	-	-	-	-	15.6
PP-17-C	91.8	15.4	4.97	[illegible].48	8869	0.863	0.59	0.[illegible]40	1.29	[illegible].13	[illegible].86	3.5	4789	-	-	-	1[illegible].0
PP-18-C	90.7	15.5	4.78	0.48	8869	[illegible].805	[illegible].66	[illegible].550	[illegible].4	[illegible]	[illegible].76	[illegible].5	4[illegible]	-	-	-	15.4
[illegible]	[illegible].0	[illegible]	5.26	[illegible].4	[illegible]	[illegible].792	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible].5	4[illegible]80	-	-	-	14.6
PP-26-C	91	15.6	4.46	0.48	8840	0.840	1.09	0.601	1.37	[illegible].25	.915	3.[illegible]5	5315	3880	79	5.31	11.55
PP-27-C	90.8	15.7	4.51	0.48	8840	[illegible].800	1.27	0.548	1.53	.24	1.02	3.51	4844	3265	79	5.58	11.55
PP-28-C	90.6	15.7	4.93	0.48	8840	.846	1.07	[illegible].532	1.36	0.22	0.91	3.29	4700	3440	83.8	5.60	11.55
PP-4-C	92	75	13.15	0.48	8869	[illegible].470	[illegible].31	-	0.2[illegible]	-	[illegible]5	[illegible]	-	-	-	-	6.1
PP-5-C	91	75	12.21	0.49	8869	0.495	0.32	-	0.24	-	0.16	3.2	-	-	-	-	6.6
PP-6-C	92	75	12.88	0.48	8869	0.495	0.21	-	[illegible].17	-	0.11	3.3		-	-	-	7.8
PP-7-C	91	52	9.26	0.48	8869	[illegible].60	[illegible].10		0.99	-	[illegible].66	4.0	-	-	-	-	10.2
PP-8-C	92	53	9.39	0.48	8869	0.63	0.95	-	0.90	-	0.60	4.0		-	-	-	9.8
PP-9-C	92	53	9.26	0.48	8869	0.625	0.87	-	0.83	-	0.55	4.0	-	-	-	-	11.7
PP-32-C	90.5	50	9.16	0.45	8840	[illegible].532	1.33	0.481	1.06	0.33	0.708	2.85	4250	4000	53.81	5.72	6.93
PP-33-C	90.7	50.4	9.11	0.45	8840	0.586	1.57	0.433	1.38	0.27	0.918	2.91	3830	2780	52.22	5.02	7.16
PP-34-C	90.5	50.8	9.20	0.45	8840	0.603	1.39	0.394	1.25	0.25	0.836	2.75	3330	2660	44.33	4.15	6.74
PP-10-C	92	33	6.92	0.48	8869	0.804	0.73	-	0.98	-	0.65	3.4	-	-	-	-	[illegible]
PP-11-C	92	34	7.28	0.48	8869	0.735	0.58	-	0.97	-	0.64	4.0	-	-	-	-	13.2
PP-12-C	91	34	7.25	0.48	8869	0.690	0.65	-	1.05	-	0.70	3.8	-	-	-	-	12.3
PP-29-C	90.5	30.2	6.48	0.47	8840	0.674	1.176	0.44	1.19	0.23	0.793	3.16	4420	3715	53.85	4.51	8.09
PP-30-C	91	30.6	6.52	0.47	8840	0.718	1.318	0.418	1.42	[illegible].20	0.946	3.28	3980	2800	71.21	5.60	[illegible].63
PP-31-C	90.8	30.1	6.53	0.47	8840	0.740	1.313	0.438	1.46	0.21	[illegible].972	3.04	3862	2650	6335	4.84	8.66
PP-13-C	91	22	5.96	0.47	8869	0.830	0.720	-	0.90	-	0.60	3.58	-	-	-	-	14.18
PP-14-C	91.2	22.5	5.54	0.47	8869	0.719	0.550	-	0.60	-	0.40	3.17	-	-	-	-	13.08
PP-15-C	92	22.5	5.64	0.47	8869	0.669	0.500	-	0.50	-	0.33	3.16	-	-	-	-	11.18
PP-16-C	92	21.5	5.76	0.47	8869	0.781	0.730	-	0.86	-	0.57	3.44	-	-	-	-	13.72
PP-20-C	90.9	9.8	3.81	0.48	8869	0.88	0.59	0.61	1.25	0.15	0.83	2.83	5410	4328	-	-	15.81
PP-21-C	92.0	8.1	3.83	0.48	8869	0.91	0.65	0.55	1.22	0.15	0.81	2.79	4878	3998	-	-	16.20
PP-22-C	91.8	9.2	3.77	0.48	8869	0.82	0.60	0.63	1.19	0.17	0.79	2.74	5587	4695	-	-	17.43
PP-23-C	99	6.6	2.24	0.49	8869	0.92	0.58	-	1.35	-	0.90	3.30	-	-	-	-	17.22

Table 3

Fire no.	Test area ambient conditions[3]		Fuel and fuel bed parameters			Burning parameters				Flame dimensions			Heat variables				
	T_o	RH	M_f	W_o	H	R	Θ	B	A_c	t_b	D	L	E	E_R	I_{OH}	I_T	I_{18}
	°F	%	%	lb/ft^2	Btu/lb	ft min	min	[illegible] min	ft^2	ft	ft	ft	Btu/min	Btu ft^2 min	Btu/ft^2 hr	Btu/ft^2	Btu ft hr
WP-1-C	93	14	5.16	0.47	8476	0.855	0.34	-	0.86	-	0.57	0.9	-	-	-	-	[illegible]
WP-2-C	92	13	5.55	0.47	8476	0.942	.40	-	.87		.5	1.1	-	-	-	-	4.2
WP-3-C	93	12	5.37	0.47	8476	0.865	0.34	-	.83	-	[illegible]	1.0	-		-	-	3.7
WP-17-C	91.5	15	5.71	0.47	8476	0.829	.44	-	0.60	-	.4	1.[illegible]2	-	-	-	-	3.60
WP-18-C	90.5	15.5	5.50	0.47	8476	0.785	.38	0.35	.51	0.14	.34	[illegible]7	296[illegible]	[illegible]818		-	2.89
WP-19-C	91.3	16.3	6.04	0.47	8476	0.811	0.42	0.30	.36	0.19	0.24	.94	2543	7064	-	-	1.80
WP-26-C	91	15.7	5.23	0.47	8422	0.93	0.67	.185	.94	.07	.624	1.42	1557	1656	19.0	1.16	3.08
WP-27-C	90	15.7	5.52	0.47	8422	0.91	0.63	[illegible]	.86	.0[illegible]	.574	1.36	1870	2174	12.68	0.78	3.27
WP-28-C	90.7	15.8	5.42	0.47	8422	0.825	0.4[illegible]	[illegible]40	.57	.06	0.380	1.05	1179	2068	11.08	0.74	[illegible]
WP-4-C	91	74	14.33	0.48	8476	0.386	0.36	-	0.21	-	0.14	0.75	-	-	-	-	[illegible].4
WP-5-C	92	74	17.62	0.15	8476	-	-	-	-	-	-	.50	-	-	-	-	1.[illegible]
WP-6-C	92	74	13.59	0.48	8476	0.405	0.28	-	0.17	-	.11	0.79	-	-	-	-	[illegible]
WP-7-C	93	73	15.47	0.47	8476	0.344	0.21	-	0.11	-	0.07	0.88	-	-	-	-	[illegible]
WP-8-C	92	52	11.48	0.47	8476	0.55	0.48	-	.39	-	0.26	0.86	-	-	-	-	2.4
WP-9-C	92	51	11.28	0.47	8476	0.54	0.48	-	0.39	-	0.26	1.20	-	-	-	-	2.6
WP-10-C	92	52	12.32	0.47	8476	0.55	0.43	-	0.35	-	0.23	1.17	-	-	-	-	2.5
WP-32-C	90.7	50.2	10.30	0.45	8422	0.638	0.562	0.183	0.54	0.11	0.359	1.14	1540	2860	13.46	1.17	1.54
WP-33-C	90.9	50.1	10.89	0.45	8422	0.668	0.367	0.178	0.38	0.10	0.245	1.02	1495	4068	5.55	0.46	1.54
WP-34-C	90.4	50.8	10.89	0.45	8422	0.663	0.342	0.18	0.34	0.10	0.227	0.96	1515	4447	4.75	0.41	1.46
WP-11-C	92	33.5	8.13	0.47	8476	0.758	0.60	-	0.60	-	0.40	1.3	-	-	-	-	2.5
WP-12-C	92	32.5	7.84	0.48	8476	0.585	0.43	-	0.47	-	0.31	1.1	-	-	-	-	2.4
WP-13-C	92.5	33	8.00	0.47	8476	0.684	0.64	-	0.38	-	0.25	1.1	-	-	-	-	2.7
WP-29-C	90.0	30.1	7.47	0.46	8422	0.755	0.417	0.140	0.47	0.07	0.315	1.4	1179	2495	15.83	1.16	2.31
WP-30-C	91	29.8	7.95	0.46	8422	0.804	0.50	0.164	0.60	0.07	0.402	1.31	1383	2294	15.83	1.09	2.31
WP-31-C	90.8	30.9	7.73	0.46	8422	0.878	0.43	0.176	0.57	0.07	0.378	1.4	1482	2615	14.25	0.92	2.5
WP-14-C	91.5	21.5	6.46	0.47	8476	0.804	0.54	-	0.65	-	0.43	0.745	-	-	-	-	2.62
WP-15-C	91.5	23.0	6.53	0.47	8476	0.714	0.61	-	0.65	-	0.43	0.980	-	-	-	-	2.50
WP-16-C	92.0	24.5	6.61	0.47	8476	0.753	0.46	-	0.53	-	0.35	0.745	-	-	-	-	3.10
WP-20-C	91.3	8.2	4.47	0.48	8476	1.02	0.63	-	0.72	-	0.48	0.88	-	-	-	-	4.44
WP-21-C	91.5	7.8	4.37	0.48	8476	0.85	0.47	0.14	0.45	0.08	0.30	0.71	1187	2638	-	-	3.62
WP-22-C	92	10.8	4.66	0.48	8476	0.85	0.53	0.31	0.51	0.17	0.34	0.91	2628	5153	-	-	3.54
WP-23-C	100	6.4	2.69	0.49	8476	1.10	0.66	0.223	1.19	0.06	0.79	1.15	1907	1603	-	-	6.54

1/ Ponderosa pine (Pinus ponderosa Laws)
2/ Western white pine (P. monticola Dougl.)
3/ Other parameter held constant throughout the study:

Ponderosa pine:

ρ = 31.6 lb/ft^3

σ = 1836 ft^2/ft^3

λ = 0.010 ft^3/ft^2

Western white pine

ρ = 34.3 lb/ft^3

σ = 1980 ft^2/ft^3

λ = 0.084 ft^3/ft^2

Table 4

Fire No.	Test area ambient conditions 2/ U	T_o	RH	Fuel and fuel bed parameters M_f	W_o	H	Burning parameters R	θ	B	A_o	T_b	Flame dimensions D	L	H	ϕ	Heat variables E	E_R	I_{OH}	I_T
	ft/min	°F	%	%	lb/ft²	Btu/lb	ft/min	min	lb/min	ft²	ft	ft	ft	ft	deg.	Btu/min	Btu/ft² min	Btu/ft² hr	Btu/ft²
PP-1-WL	132	95.5	16.3	4.53	0.48	8869	1.52	0.96	0.65	2.19	0.15	1.46	2.39	2.13	28.6	5,760	2,617	56.0	2.06
PP-2-WL	132	97.0	15.5	4.56	0.48	8869	1.68	1.38	0.562	3.48	0.12	2.32	2.61	2.38	25.7	4,490	1,423	68.0	2.27
PP-3-WL	132	91.8	15	4.22	0.48	8869	1.67	1.13	0.605	2.82	0.12	1.88	2.13	1.99	20.8	5,360	1,892	66.7	2.24
PP-4-WL	264	96	14.3	3.74	0.48	8869	2.40	1.86	0.791	6.69	0.12	4.46	2.12	1.71	45	7,020	1,043	79.9	1.88
PP-5-WL	264	97	13	3.78	0.48	8869	2.84	1.60	1.03	6.81	0.13	4.54	2.28	1.94	43	9,140	1,344	73.0	1.44
PP-6-WL	264	92.3	15.9	5.10	0.47	8877	1.89	1.47	0.48	4.17	0.13	2.78	2.02	1.72	43	4,265	1,017	55.2	1.65
PP-37-WL	264	90.3	15.1	4.63	0.48	8812	2.12	1.62	0.58	5.15	0.09	3.43	2.12	1.74	35	4,870	999	57.4	1.53
PP-38-WL	264	90.6	15.7	4.63	0.48	8812	2.01	1.40	0.593	4.22	0.10	2.81	2.28	1.72	39	5,000	1,238	52.3	1.46
PP-39-WL	264	90.7	15.5	4.52	0.48	8812	2.06	1.70	0.624	5.24	0.06	3.49	2.32	1.99	30	5,500	1,043	63.8	1.74
PP-7-WL	440	95	12.7	4.14	0.48	8869	3.71	1.72	1.12	9.57	0.11	6.38	2.83	1.75	53.2	10,630	1,034	85.0	1.29
PP-8-WL	440	94.5	15.4	4.55	0.48	8877	3.52	1.88	1.02	9.90	0.10	6.60	2.68	1.75	46.6	9,020	911	81.6	1.31
PP-9-WL	440	90.0	15.5	5.01	0.48	8869	3.95	1.74	0.97	9.24	0.09	6.16	2.94	1.92	47.8	8,600	928	92.4	1.32
PP-45-WL	440	91.0	15.6	4.96	0.48	8812	4.88	1.64	1.22	12.0	0.09	8.00	--	--	45	10,750	840	70.2	0.81
PP-46-WL	440	91.2	15.5	4.80	0.48	8812	5.34	2.03	0.80	16.2	0.05	10.8	--	--	41	7,060	436	77.2	0.81
PP-47-WL	440	91.6	15.0	4.72	0.48	8812	5.48	1.42	0.87	11.7	0.05	7.78	--	--	41	7,650	656	76.5	0.79
PP-41-WL	704	90	15	4.78	0.48	8812	16.7	2.04	1.93	51.2	0.04	34.1	--	--	57	17,000	332	104	0.35
PP-42-WL	704	90	15	4.75	0.48	8812	12.7	1.99	--	38.0	--	25.3	3.66	1.82	56	--	--	107	0.48
PP-43-WL	704	90	15	4.97	0.48	8812	13.8	2.15	2.24	44.6	0.06	29.7	3.37	1.53	61	19,700	442	112	0.45
PP-44-WL	704	90	15	5.06	0.48	8812	11.6	1.84	2.10	32.0	0.07	21.3	3.53	1.63	57	18,500	583	115	0.56
PP-10-WL	132	91	30.8	7.46	0.46	8877	1.17	1.02	0.25	1.79	0.08	1.19	1.84	1.73	21	2,219	1,238	43.4	2.08
PP-11-WL	132	91.3	31.8	7.60	0.46	8877	1.24	1.12	0.31	2.09	0.09	1.39	1.69	1.55	25	2,779	1,326	49.6	2.27
PP-12-WL	132	92.5	30.0	7.50	0.46	8877	1.17	0.98	0.33	1.71	0.10	1.14	1.67	1.52	23	2,956	1,724	40.8	1.97
PP-31-WL	132	89.9	30.6	6.93	0.47	8812	1.11	0.94	0.321	1.56	0.11	1.04	2.85	2.49	28	2,830	1,812	47.2	2.41
PP-32-WL	132	90.6	30.0	7.17	0.46	8812	1.33	0.76	0.393	1.52	.11	1.01	2.32	1.93	34	3,460	2,281	38.3	1.63
PP-13-WL	264	92.2	31.4	7.54	0.46	8877	1.72	1.66	0.50	4.28	0.11	2.85	1.61	1.36	31	4,439	1,034	42.7	1.40
PP-14-WL	264	91.8	30.7	7.50	0.46	8877	1.96	1.53	0.48	4.49	0.09	2.99	1.48	1.28	30	4,261	946	44.6	1.27
PP-15-WL	264	91.6	30.5	7.27	.46	8877	1.85	1.56	0.35	4.32	0.07	2.88	1.55	1.38	32	3,107	716	48.2	1.46
PP-16-WL	440	91.5	31.8	7.87	0.46	8812	3.76	1.50	.84	8.45	0.08	5.63	1.72	1.29	46	7,402	875	49.7	0.75
PP-17-WL	440	92.0	30.5	7.72	0.46	8812	4.10	2.01	0.83	12.33	0.08	8.22	2.04	1.54	40	7,314	592	68.2	0.93
PP-18-WL	440	91.5	31.2	7.77	0.46	8812	4.95	2.25	0.70	16.68	0.05	11.12	1.90	1.47	44	6,168	371	58.6	0.67
PP-34-WL	440	90.4	30.0	8.06	.46	8812	3.57	1.52	0.85	8.15	0.08	5.43	2.71	1.90	44	7,500	919	56.7	0.90
PP-35-WL	440	90.8	30.0	8.20	0.46	8812	3.60	1.69	0.74	9.12	0.07	6.08	2.84	2.10	41	6,550	716	56.1	0.88
PP-28-WL	704	90	30	7.32	0.46	8812	9.81	2.02	1.19	29.7	0.04	19.8	3.32	1.59	56	10,420	354	63.8	0.36
PP-29-WL	704	90	30	7.32	0.46	8812	10.5	1.74	1.26	27.5	0.05	18.3	3.68	1.63	61	11,170	407	68.9	0.37
PP-30-WL	704	90	30	6.12	0.47	8812	9.3	1.87	1.45	26.1	0.06	17.4	4.19	1.71	61	12,800	486	91.9	0.55
PP-19-WL	132	90	50.9	9.49	0.45	8812	0.794	0.78	0.20	0.93	0.10	0.62	1.73	1.51	26	1,763	1,901	26.8	1.92
PP-20-WL	132	90.2	50.5	9.50	0.45	8812	0.874	0.86	0.206	1.13	0.09	0.75	1.35	1.24	19	1,818	1,653	26.8	1.74
PP-21-WL	132	90.1	50.2	9.43	.45	8812	0.921	0.93	0.21	1.29	0.08	0.86	1.47	1.32	20	1,853	1,441	30.4	1.25
PP-22-WL	264	90.5	50.8	9.82	0.45	8812	1.543	0.91	0.352	2.10	0.09	1.40	1.85	1.47	36	3,105	1,476	26.1	0.96
PP-23-WL	264	90.9	50.9	9.94	0.45	8812	1.568	1.03	0.358	2.43	0.09	1.62	1.78	1.49	31	3,160	1,308	34.4	1.23
PP-24-WL	264	90.1	50.5	10.03	0.45	8812	1.436	0.98	0.366	2.16	0.09	1.41	1.82	1.46	35	3,230	1,547	30.6	1.20
PP-25-WL	440	90.8	48.5	9.51	0.45	8812	3.54	1.31	0.638	6.96	0.07	4.64	2.59	1.72	46	5,620	813	44.6	0.70
PP-26-WL	440	90.5	49.6	9.80	0.45	8812	3.65	1.45	0.689	7.83	0.07	5.22	2.69	1.78	48	5,586	778	44.0	0.68
PP-27-WL	440	90.7	50.5	10.07	0.45	8812	3.23	1.38	0.700	6.69	0.08	4.46	2.31	1.56	46	6,165	919	37.0	0.65

Table 5

Fire No.	Test area ambient conditions2/			Fuel and fuel bed parameters			Burning parameters					Flame dimensions				Heat variables			
	U	T_o	RH	M_f	W_o	H	R	Θ	P	A_c	T_b	D	L	H	ϕ	E	E_R	I_{ov}	I_T
	ft/min	°F	%	%	lb/ft²	Btu/lb	ft/min	min	lb/min	ft²	ft	ft	ft	ft	deg.	Btu/ft-min	Btu/ft² min	Btu/ft² hr	Btu/ft²
WP-1-WL	132	94	15.5	5.25	0.47	8476	1.76	0.42	0.135	1.11	0.03	0.74	0.59	0.54	25	1,143	1,027	17.9	0.58
WP-2-WL	132	93	16	5.31	0.47	8476	2.22	0.401	--	1.34	--	0.89	0.85	0.71	34.2	--	--	16.6	0.43
WP-3-WL	32	96	14	5.76	0.33	8476	1.78	0.669	0.162	1.79	0.05	1.19	-	--	25	1,372	766	23.0	[illegible]
WP-45-WL	132	91	14.9	5.51	0.32	8422	1.91	0.298	0.142	1.68	0.02	1.12	1.00	0.82	32	1,230	1,406	19.1	0.57
WP-4-WL	264	92.5	16.1	5.17	0.32	8476	5.00	0.36	--	2.70	--	1.80	--	--	38	--	--	19.5	[illegible]
WP-5-WL	264	94	13.4	4.40	0.32	8476	4.16	0.62	0.41	3.81	0.05	2.58	0.61	[illegible]	37.5	[illegible]	893	20.0	[illegible]
WP-6-WL	264	94	13.5	4.60	0.32	8476	4.81	0.57	--	4.11	--	2.74	[illegible]	[illegible]	37.5	--	455	25.9	[illegible]
WP-41-WL	264	89.5	15.4	5.40	0.32	8422	5.34	[illegible]	[illegible]	2.81	[illegible]	1.87	1.28	0.87	44	[illegible]	1,204	21.65	0.23
WP-42-WL	264	90	15.2	5.19	0.32	8422	5.64	0.36	0.392	3.05	.04	2.03	[illegible]	[illegible]	39	3,300	1,086	26.1	0.26
WP-[illegible]-WC	440	91	16.1	6.02	0.31	8476	10.64	0.68	0.79	10.86	0.04	7.24	0.95	0.67	44	6,696	[illegible]	30.8	0.16
WP-8-WL	440	94.5	16.4	6.01	0.31	8476	12.83	0.38	0.844	7.31	0.04	4.87	0.94	0.65	47	7,150	977	27.4	[illegible]
WP-9-WL	440	94	15.6	6.30	0.31	8476	10.20	0.48	--	7.35	--	4.90	0.81	0.57	45	--	--	29.3	[illegible]
WP-43-WL	440	90.4	15.1	5.60	0.32	8422	10.65	0.40	0.678	6.38	0.03	4.25	1.18	0.72	43	5,710	893	26.2	.14
WP-44-WL	440	90.5	15.3	5.20	0.32	8422	13.30	0.38	0.673	7.58	0.03	5.05	1.23	0.82	42	5,660	750	28.7	[illegible]
WP-46-WL	704	91.2	14.8	5.57	0.32	8422	32	0.40	1.80	19.20	0.03	12.80	1.18	0.67	[illegible]	15,20	792	33.2	[illegible]
WP-47-WL	704	91.6	14.8	5.41	0.32	8422	26.9	0.56	1.37	22.59	0.03	15.06	1.72	0.87	58	11,500	514	38.2	[illegible]
WP-48-WL	704	90	15	5.70	0.31	8422	20.9	0.44	1.55	13.80	0.04	9.20	1.37	0.64	58	13,100	943	37.0	[illegible]
WP-49-WL	704	90	15	5.88	0.31	8422	21.2	0.40	1.67	12.72	[illegible]	8.48	1.12	0.66	51	14,050	1,112	35.7	[illegible]
WP-10-WL	132	92.2	31.1	8.70	0.30	8422	1.40	0.45	0.122	0.95	0.05	0.63	0.48	0.45	30	1,027	1,095	12.75	[illegible]
WP-11-WL	132	92.7	30.8	8.61	0.31	8422	1.34	0.66	0.117	1.32	0.05	0.88	0.45	0.40	30	985	750	12.75	.53
WP-12-WL	132	91.5	31.5	8.94	0.30	8422	1.40	0.54	0.22	1.14	.09	0.76	0.52	0.48	24	1,853	1,625	14.02	.5
WP-13-WL	264	92.1	31.2	8.19	0.31	8422	3.91	0.74	0.35	4.34	0.05	2.89	0.48	0.45	30	1,027	682	17.85	[illegible]
WP-14-WL	264	92.1	30.4	8.57	0.31	8422	--	0.61	0.36	6.11	0.03	4.07	0.45	0.4	30	985	497	16.6	--
WP-15-WL	264	91.6	31.0	8.31	0.31	8422	4.72	0.621	0.30	4.40	.04	2.93	0.52	0.48	24	1,853	573	22.9	[illegible]
WP-20-WL	264	91.5	31.3	8.19	0.31	8422	5.00	0.67	0.36	5.03	0.04	3.35	.52	0.40	43	3,032	606	14.02	.16
WP-32-WL	264	90.3	30.9	8.30	0.31	8422	4.14	0.36	0.325	2.24	0.04	1.49	[illegible]	0.75	39	2,740	1,221	15.7	0.21
WP-33-WL	264	90.9	30.5	8.55	0.31	8422	4.16	0.26	0.356	1.62	0.05	1.08	1.00	0.75	39	3,000	1,853	14.0	0.19
WP-16-WL	440	91.6	31.4	8.51	0.31	8422	10.63	0.51	0.38	8.13	0.02	5.42	0.72	0.46	53	3,200	396	21.3	[illegible]
WP-17-WL	440	92.2	30.9	9.31	0.30	8422	9.43	0.504	--	7.13	--	4.75	0.80	0.49	57	--	--	21.0	0.13
WP-18-WL	440	92.5	30.5	9.43	0.30	8422	11.11	0.709	0.60	11.82	0.03	7.88	0.79	0.48	55	5,011	430	17.8	0.09
WP-19-WL	440	92.1	30.9	9.39	0.30	8422	11.11	0.45	0.312	7.50	0.01	5.00	0.72	0.48	51	2,630	707	20.4	0.10
WP-34-WL	440	90.6	30.1	8.26	0.31	8422	8.42	0.46	0.361	5.82	0.02	3.88	1.62	0.86	45	3,040	522	22.95	0.15
WP-35-WL	440	90.8	29.9	8.51	0.31	8422	7.47	0.47	0.326	5.28	0.02	3.52	1.29	0.79	51	2,750	522	23.29	0.18
WP-37-WL	704	90	30	9.42	0.30	8422	22.2	0.478	0.734	15.45	0.02	10.3	1.55	0.70	60	6,180	396	28.0	0.07
WP-38-WL	704	90	30	9.70	0.30	8422	25.8	0.44	0.455	17.03	0.01	11.35	1.49	0.72	57	3,830	227	28.0	0.06
WP-39-WL	704	90	30	9.70	0.30	8422	17.5	0.426	0.755	11.18	0.02	7.45	1.54	0.85	55	6,360	573	30.6	0.10
WP-40-WL	704	90	30	8.50	0.31	8422	17.5	0.415	0.926	10.89	0.03	7.26	1.59	0.85	57	7,800	716	28.7	0.09
WP-25-WL	132	90.2	50.5	11.15	0.30	8422	0.781	0.69	0.124	0.81	0.09	0.54	0.68	0.59	25	1,045	1,289	6.38	0.48
WP-26-WL	132	90.5	50.5	11.50	0.30	8422	--	0.46	--	0.50	--	0.33	0.59	0.51	25	--	--	7.33	--
WP-27-WL	132	91	50.0	11.09	0.30	8422	1.12	0.61	0.218	1.02	0.11	0.68	0.81	0.69	28	1,836	1,819	8.92	0.45
WP-28-WL	132	90.1	50.0	11.23	0.30	8422	1.01	0.55	0.138	0.84	0.07	0.56	0.72	0.62	31	1,162	1,381	9.30	0.54
WP-21-WL	264	90.2	50.1	11.81	0.29	8422	2.17	0.72	0.20	2.34	0.06	1.56	0.85	0.62	40	1,684	716	12.75	0.33
WP-22-WL	264	90.1	50.0	12.19	0.29	8422	2.44	0.62	--	2.27	--	1.51	0.72	0.53	42	--	--	12.45	0.29
WP-23-WL	264	90.8	50.3	11.79	0.29	8422	2.70	0.50	0.144	2.03	0.03	1.35	0.87	0.63	42	1,213	598	12.00	0.25
WP-24-WL	264	91	50.0	11.68	0.29	8422	2.88	0.52	0.171	2.25	0.04	1.50	0.82	0.57	43	1,440	640	15.3	0.30
WP-29-WL	440	90.6	50.2	11.60	0.30	8422	6.41	0.48	0.243	4.65	0.02	3.1	1.15	0.78	46	2,047	438	15.6	0.14
WP-30-WL	440	90.8	50.0	11.87	0.29	8422	7.48	0.46	0.37	5.16	0.04	3.44	1.15	0.71	50	3,117	606	15.6	0.12
WP-31-WL	440	90.3	50.5	11.76	0.29	8422	7.04	0.58	0.323	6.08	0.05	4.05	1.19	0.76	50	2,720	446	17.85	0.14

Table 6

Fire No.	Species	Loading	Test area ambient conditions T_o	U	RH	Fuel and fuel bed parameters M_f	W_o	H	Burning parameters R	Θ	B	Flame dimensions D	L	Heat variables Q	E_R
		tons/acre	°F	ft/min	%	%	lbs/ft^2	Btu/lb	ft/min	min	lb/min	ft	ft	Btu/min	Btu/ft^2 min
1	D.F.	32.5	87	4.0	28	8.4	1.35	8332	5.15	1.85	41.64	9.51	5.98	346,944	6,082
2	D.F.	20.0	87	4.5	28	7.9	0.74	8332	5.05	0.75	22.32	3.80	4.07	185,970	8,165
3	D.F.	7.5	90	3.0	24	7.3	0.50	8332	2.59	0.78	1.01	2.03	2.64	8,415	5,332
4	L.P.P.	32.5	93	5.0	20	8.1	1.45	8709	9.10	--	--	--	8.46	--	--
5	L.P.P.	20.0	92	7.0	21	7.7	0.93	8709	5.90	1.14	6.28	6.72	6.58	54,693	7,141
6	L.P.P.	7.5	92	7.0	22	7.4	0.34	8709	4.70	0.94	1.49	4.43	3.48	12,976	3,135
7	D.F.	32.5	81	3.0	32	7.0	1.35	8332	7.20	0.82	7.99	5.90	6.40	66,573	13,748
8	D.F.	20.0	85	7.5	27	6.7	0.74	8332	4.82	0.80	2.81	3.84	4.14	23,413	7,749
9	D.F.	7.5	89	4.5	23	6.3	0.50	8332	5.30	0.65	1.72	3.43	2.59	14,331	6,416
10	L.P.P.	32.5	93	3.5	18	6.3	1.45	8709	3.40	1.94	9.58	6.58	7.17	83,432	6,532
11	L.P.P.	20.0	93	3.5	18	6.3	0.93	8709	2.70	1.33	3.34	3.58	5.83	29,088	6,096
12	L.P.P.	7.5	94	5.0	16	6.3	0.34	8709	5.22	0.72	1.27	3.77	3.77	11,060	4,093
13	D.F.	32.5	91	2.0	22	5.8	1.35	8332	5.40	1.00	7.26	5.38	7.09	60,490	11,248
14	D.F.	20.0	92	4.0	21	5.8	0.74	8332	3.39	0.91	2.28	3.10	3.88	18,997	6,749
15	D.F.	7.5	92	2.0	21	5.7	0.50	8332	--	--	--	--	2.50	--	--
16	L.P.P.	32.5	71	2.5	61	8.1	1.45	8709	4.80	1.21	8.47	5.83	9.52	73,765	10,451
17	L.P.P.	20.0	70	0.5	61	7.7	0.93	8709	1.79	2.76	4.64	4.94	3.93	40,410	2,961
18	L.P.P.	7.5	70	0.5	61	7.4	0.34	8709	1.80	--	--	--	3.82	--	--

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Project headquarters 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)
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