# LOGGING SLASH FLAMMABILITY

by

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# ACKNOWLEDGMENT

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G. R. F.

Most of the experimental work reported in this paper was performed while the author was in the division of Forest Fire Research of the Intermountain Forest and Range Experiment Station. He is now a member of the staff of Forest Fire Research, Southern Forest Experiment Station, Alexandria, Louisiana.

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# INTRODUCTION

Some of the most disastrous forest fires in North American history burned in slash left from logging and land clearing. In the era before organized fire control, the names Miramichi, Peshtigo, Hinckley, and Cloquet stand for millions of acres blackened and thousands of lives snuffed out (*17*).[1] More recently the Half Moon Fire in Montana, the Tillamook Fire in Oregon, the Forks Fire in Washington, and the Dudley Lake Fire in Arizona, to name only a few, owed their irresistibility to the slash fuels that fed them. Over much of the West logging slash is now the most hazardous forest fuel, and it threatens to remain so for an indefinite period.

Slash is the residue left in the woods after timber has been harvested. It consists of foliage, twigs, branchwood, bark, rotten wood, and cull or otherwise unusable material. Most of this debris once comprised parts of the harvested crop trees, but sizable quantities are sometimes broken from the residual stand in logging. Leaving slash after the harvest of forest products is as inevitable as leaving the core after eating an apple. An apple core must be picked up because garbage is an eyesore and a public nuisance. Slash also is unsightly, but it requires treatment primarily because it is highly flammable.

To reduce or compensate for flammability, slash and cutover areas are treated in various ways, all of them expensive. In Montana, Idaho, and northeastern Washington, forestry and protection agencies annually spend about $3.75 million for slash disposal and extra fire protection on cutover lands. Effective expenditure of these funds has been difficult because means for measuring the fire hazard of slash have been inadequate. In 1948 the College of Forestry of the University of Idaho started comprehensive research on the slash problem in the northern Rocky Mountains. Since 1952 the University and the Intermountain Forest and Range Experiment Station have cooperated to study intensively the physical characteristics and flammability of slash fuels. Technical guidance and physical assistance in carrying on experiments have been generously provided by several cooperators. A description of the entire slash research program, including some information on early results, was published in 1955 (*31*).

The present publication reports more technically and in greater detail the results of the first 5 years of research on slash flammability. It states explicitly how various factors affect flammability and describes new methods for more accurate evaluation of the hazard of varied slash situations than has been possible hitherto.

## SPECIES STUDIED

Forests in the northern Rocky Mountains are rich in coniferous species. Opinion about their relative flammability varies widely, and unquestionably important differences between species do exist. To identify and measure meaningful differences, slash of the nine species that are most important commercially was used in the flammability investigations reported here. These species are: western white pine (*Pinus monticola* Dougl.), lodgepole pine (*P. contorta* Dougl.), ponderosa pine (*P. ponderosa* Laws.), western redcedar (*Thuja plicata* Donn), Douglas-fir (*Psuedotsuga menziesii* var. *glauca* (Beissn.) Franco), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), Engelmann spruce (*Picea engelmannii* Parry), grand fir (*Abies grandis* (Dougl.) Lindl.), and western larch (*Larix occidentalis* Nutt.).

## KIND AND LOCATION OF STUDIES

Research on slash flammability thus far has involved three major types of operations: (1) experimental burning to measure rate of fire spread and fire intensity; (2) continuous study of moisture content of slash from the time of cutting until the end of the current fire season; and (3) crown analysis to determine the relationship of tree crown weight and other characteristics to species, d.b.h., and crown length. Various sidelines to these three main lines of endeavor were pursued as possibilities of obtaining additional worthwhile information appeared.

All the experimental research reported herein was done on the Priest River Experimental Forest in northern Idaho. Most of the complete crown analyses were made there also. Crown length measurements, to permit extension of the basic crown weight relation to forest stands,

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[1] Italicized numbers in parentheses refer to items in the Bibliography.

Figure 1. **Upper,** extreme slash condition after cutting sawlogs and cedar poles in the western white pine type; **lower,** result of fire in heavy slash.

were made on permanent sample plots in northern Idaho and northeastern Washington. Additional determinations of crown weight and crown length in the lodgepole pine type east of the Continental Divide were made in central Montana. The main research installation was the so-called "outdoor slash laboratory" for experimental burning (fig. 2).

## SUMMARY OF RESULTS

The generally accepted definition of flammability is "the relative ease with which fuels ignite and burn regardless of the quantity of the fuels" (*43*). In the research described here, flammability means burning rate and fire intensity as affected by all qualitative and quantitative characteristics of the fuel. Ease of ignition is not discussed in this study since effective fire-starting agencies may be assumed to exist.

### General Characteristics of Slash

All kinds of conifer slash are so similar chemically that physical characteristics appear to determine how slash burns. The general appearance of tree crowns — length, width, density, diameter, and length of branches — is a good rough indication of relative flammability. In general, tolerant species have more needles and fine twigs than intolerant species. The relative amount of this fine material decreases with age. *Loss of needles is the most important change in slash during the first few years after cutting.* Some splitting of bark and checking of wood also occur, but decay is not noticeable under northern Rocky Mountain conditions. Continuity of fine material within the fuel bed varies with distribution of foliage and twigs on branches and retention or loss of needles as slash ages. Compaction of the fuel bed usually reduces flammability, but much less so than reduction in amount of fine slash components.

### Drying Rate

Moisture content of freshly cut slash varies from less than 100 percent to more than 350 percent. Time required for moisture content of fine material to reach 10 percent varies from 2 weeks to several months, depending on treatment and exposure to sun and wind. *Sometimes the slow drying rate of unlopped tops may obviate the need for early disposal, but usually enough quick-*

*drying, lopped or broken material is present to cause high hazard.* Slash in exposed locations — in heavily cut areas, especially those on southerly aspects — requires treatment soon after cutting during the fire season. During the first summer after cutting, moisture in wood more than 4 inches in diameter becomes evenly distributed and declines to about 30 to 40 percent.

### Measurement

*The quantity of slash that will result from cutting a given stand can be estimated with acceptable accuracy from measurements of the standing trees.* Crown weight is proportional to the product of d.b.h. and crown length. Tables of crown weight by d.b.h. classes have been prepared using average crown length values. Although these tables are subject to considerable error if used to estimate the crown weight of an individual tree, they can be used in conjunction with stand tables to obtain satisfactory estimates of slash weight per acre. Greater accuracy can be attained by measuring representative crown lengths in each stand to be estimated. Weight of slash per thousand board feet cut varies widely with species and size of timber. Factors are provided for use in estimating the relative quantities of slash on different areas; these estimates, in turn, indicate the relative size of the disposal job and form a basis for estimating what should be charged for disposal.

### Rate of Fire Spread

*During the year of cutting, quantity of slash is the main factor affecting rate of spread, but lesser effects of species characteristics are noticeable. Thereafter species becomes more important because of differences in rate of decomposition.* For fresh and 1-year-old slash, experiments have developed relative flammability factors and rankings for the species studied on a pound-for-pound basis. These factors can be multiplied by quantity factors to calculate over-all relative flammability ratings. From these measurements it appears that rate of spread in slash has been underrated by the Region 1 fuel-type classification system.

Results of experimental burning indicate that increasing relative humidity proportionately reduces rate of fire spread. This effect is about twice as great in 1-year-old slash as in fresh.

Figure 2. Outdoor slash laboratory at Priest River Experimental Forest where experimental burning and study of slash characteristics were carried on.

### Intensity of Slash Fires

*Fire intensity, measured in terms of heat radiation, closely parallels rate of spread.* Because large quantities of attached foliage are held above the ground and well aerated, fires are especially hot in heavy concentrations of fresh and 1-year-old western white pine and lodgepole pine slash and in fresh Douglas-fir and grand fir slash. When a large area is burning rapidly, flames reach high into the air and often pulsate rhythmically. Gases in the convection column above the main body of flames commonly ignite when heavy slash concentrations burn; this ignition of gases and the presence of dense black smoke indicate incomplete combustion. Maximum emissivity of experimental slash fires approximates 0.30.

### Application of Research Findings

The study of slash flammability was designed to increase basic knowledge of slash as a forest fire fuel. Results of the experimental burnings have given specific information applicable to conditions in the northern Rocky Mountains, but possibly more important are indications of principles that may guide in selection of slash treatment anywhere it is needed. *By ap-*

*plying factors for slash quantity, rate of fire spread, and fire intensity, relative hazard can be calculated as a basis for establishing priorities in slash treatment.* Taken individually these factors have little meaning; for example, no species of slash can be called more flammable than another if the quantities of each are not specified. Information on drying rate indicates when treatment should be applied. Kind of treatment must be determined on the basis of such considerations as: (1) values to be protected, and their susceptibility to damage by fire; (2) ability to abate the hazard; (3) ability to protect the area if the hazard is not abated; (4) availability of manpower and equipment for hazard reduction and protection; (5) relative costs of hazard reduction and protection; and (6) effect of possible slash treatments on land management objectives.

From the standpoint of fire control alone, slash disposal seems to be necessary wherever heavy concentrations of slash retain needles for several years, especially when these concentrations are in exposed locations. Intensive protection in lieu of disposal has the best chance of success in slash that loses its foliage early, that is not abundant, and that is protected from extreme drying conditions. All gradations are found between extremes of each of these conditions.

### Need for Further Research

Following is a list of needed research projects. Information gained from them would help to answer several basic questions and would facilitate application of what is already known.

1. Evaluation of effectiveness of various types of slash treatment as means for fire protection.
2. Evaluation of slash treatments according to cost and benefit.
3. Development of methods and machines that will reduce the slash problem to the minimum, especially through modification of logging practices.
4. Improvement of techniques of using fire for slash disposal; study of effects of slash-burning fires.
5. Investigation of possible uses for slash.

## CHARACTERISTICS OF SLASH FUEL COMPONENTS

Knowledge of the characteristics of slash is a step toward better understanding of fuels generally found in forests of the inland Northwest. Tree crowns are the major source of fine forest fuels except in open stands having a ground cover of grass. Even in grassy forests fallen tree crown materials are the fuels that burn hottest and longest. Fons (*13*) has shown mathematical relationships between physical characteristics of idealized fuel beds and rate of fire spread. Probably fire behavior in forest fuels as they occur naturally never can be reduced to an equation, but better knowledge of fuels will lead to better understanding of fire behavior. This section treats logging slash as a fuel, and includes measurements of physical characteristics heretofore unavailable.

### CHEMICAL CHARACTERISTICS

The chemistry of wood has been studied intensively in the development and improvement of forest products. *From the standpoint of forest fire control, the most important finding is that all species have essentially the same chemical components in approximately the same proportions.* Cellulose and lignin comprise 88 to 98 percent of wood by weight (*44*). The amount of extractives in ordinary forest fuels varies, but the quantity of highly flammable fats and volatile oils rarely exceeds 8 percent. Variants from ordinary wood fuels, such as pitchy stumps and knots, have higher percentages of these flammable materials; hence fires in such fuels are very hard to extinguish and pose special problems in fire control. However, the chemical composition of all wood species is so nearly the same that quantity, arrangement, and moisture content are the fuel characteristics that most directly affect the combustion of wood. This is equally true for foliage and bark. Although in exceptional cases highly flammable extractives may be important, physical rather than chemical characteristics of the fuel particles and the fuel bed chiefly determine flammability.

### PHYSICAL CHARACTERISTICS

The components of logging slash come in a multitude of sizes and shapes. Fine fuel components exert greatest influence on rate of fire spread and fire intensity; hence consideration of their characteristics provides a background for appraisal of flammability. Large components increase fire persistence and resistance to extinguishment, and physically obstruct suppression measures.

#### General Consideration of Tree Crowns

Certain general characteristics of tree crowns indicate properties of the slash that will result when the trees are cut. Width of crown obviously is related to length of the branches; to a lesser degree it also indicates diameter of the branches, since long branches must be relatively thick. Width of crown also indicates distribution of fine material, especially foliage, which usually is concentrated near the ends of branches. Long branches are relatively bare of fine material over most of their length, whereas short branches may have needles and twigs throughout the length of the branch.

Amount of daylight that can be seen through a crown in silhouette or from below shows relative amount and distribution of fine material also. Crowns that appear generally thin, like those of western larch, have relatively little foliage and fine twigs. Little light passes through the crown of Engelmann spruce because it has a large amount of foliage on a rather dense network of fine twigs. When needles are borne in clumps, light can pass through in spots, as it does in ponderosa pine particularly. Figure 3 shows distinctive crown characteristics typical of four northern Rocky Mountain species.

Length, width, and density of crown affect the total amount of solid material present. Width is the best single indicator, but a dense, narrow crown can be rather heavy. Table 1 lists typical gross characteristics for the species included in this study. Crowns of open-grown trees of any species tend to diverge from the typical by becoming broader, longer, and usually denser than those in closed stands. Beyond a certain number, as yet unknown, variation in number of dominant trees per acre may not affect quantity of slash.

Observation of gross crown characteristics provides a basis for adjusting calculations of slash quantity to allow for abnormal conditions. Crowns of pole-blighted western white pine are short and thin and produce less slash than healthy trees. Douglas-fir heavily infected with mistletoe has much fine material concentrated

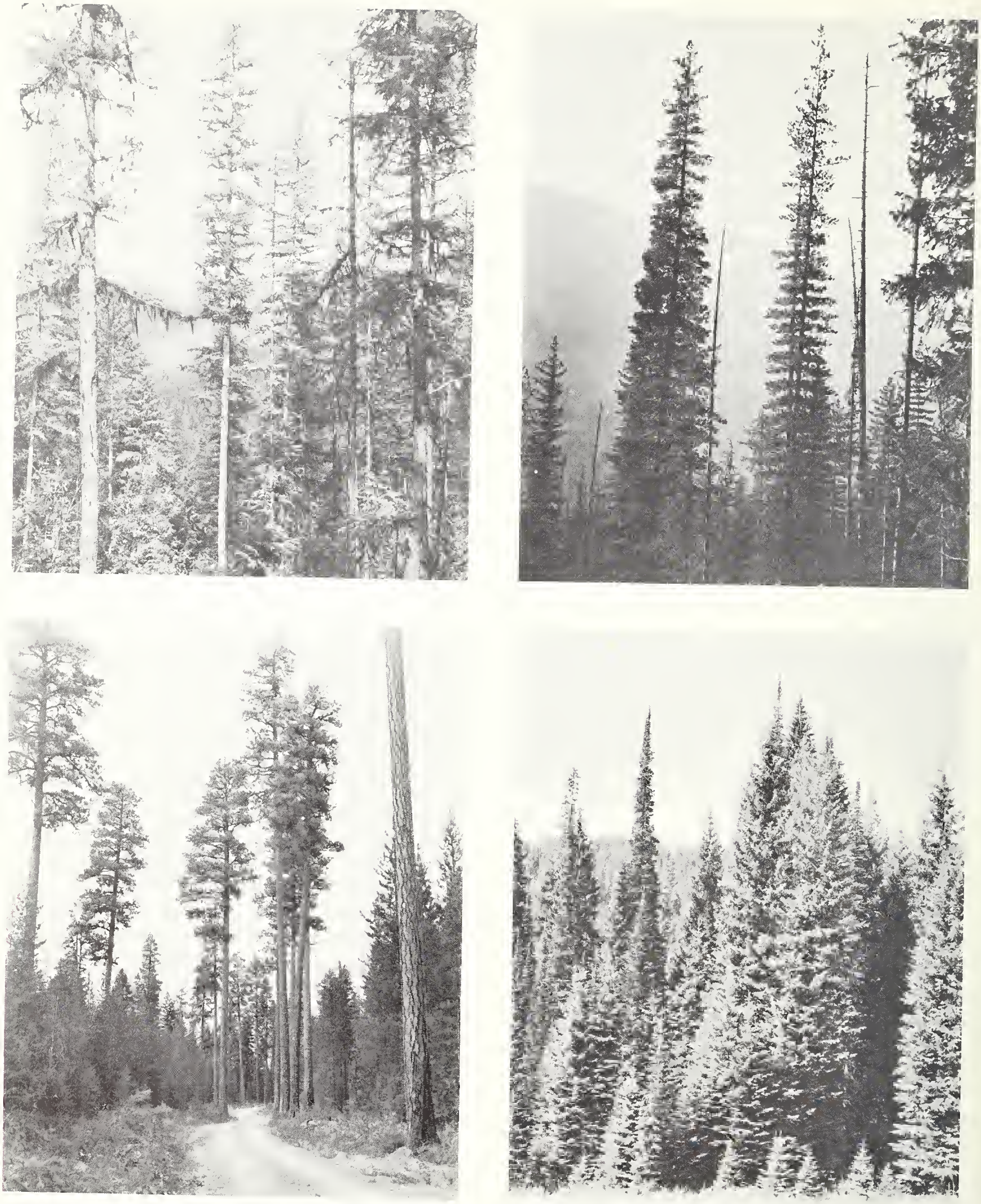


Figure 3. Crowns of some northern Rocky Mountain conifers, illustrating characteristics listed in table 1. **Upper left,** western larch; **upper right,** western white pine; **lower left,** ponderosa pine; **lower right,** Engelmann spruce.

Table 1.--Gross crown characteristics of nine northern Rocky Mountain timber species

| Species | Typical characteristics | | | | |
|---|---|---|---|---|---|
| | Length | Width | Density | Continuity | Special features |
| Western white pine | Medium to long | Narrow | Low to medium | Low to medium | Often thinned and shortened by pole blight |
| Lodgepole pine | Short | Narrow | Low | Low | None |
| Ponderosa pine | Short to medium | Wide | Medium | Low | None |
| Western redcedar | Long | Medium to wide | Medium to dense | Medium to high | Crowns of residual trees in heavily cut stands become thin |
| Douglas-fir | Short to medium | Medium | Medium | Medium to high | Subject to large witches'-brooms |
| Western hemlock | Long | Wide | Dense | High | None |
| Engelmann spruce | Very long | Narrow to medium | Very dense | High | None |
| Grand fir | Long | Narrow to wide | Dense | Low to high | Crown often narrows and lengthens in old trees |
| Western larch | Short to medium | Narrow | Low | Low to medium | Frequently has witches'-brooms |

in witches'-brooms. Whether the total amount of fine slash is increased by mistletoe is not known, but distribution certainly is affected.

### Size Distribution of Crown Components

Relatively little work has been attempted on classifying crown components according to size. Storey and associates (*38*) give total weights of foliage and branchwood in relation to trunk diameter and crown length. This publication supplements their findings by providing a further classification of branchwood by size. Table 2 summarizes findings thus far on proportional weights of fuel material in the different size classes for nine northern Rocky Mountain species. These figures are based on a composite crown sample taken from one tree of each species. The sample consisted of three healthy and apparently typical branches, one each from the top, middle, and bottom one-third of the crown. Most of the sample trees were young, merchantable, and 90 to 100 years old. Hemlock and spruce were older.

The most interesting feature shown in table 2 is that quantity of both foliage and very fine twigs is related to tolerance. In the samples, needles comprised only 11.7 percent of total crown weight in western larch, a very intolerant species, but 36.8 percent in the very tolerant grand fir. Other species between these two extremes are arranged in the table in approximate order from least to most tolerant. Western hemlock, a tolerant species, appears to be out of place, possibly because the sample tree was older and less vigorous than those of other species. If weights of needles and of twigs less than one-eighth inch in diameter are combined, the contrast between tolerant and intolerant species is accentuated.

Proportional amount of fine material increases with height in the crown. The greatest increases are in larch, ponderosa pine, and lodgepole pine, whose lower branches become large in diameter with increasing age.

Proportional weight of branchwood increases as d.b.h. increases. Rate of increase in percent of branchwood as d.b.h. increases does not differ significantly between western larch and Engelmann spruce, two very dissimilar species. Therefore, the relation may be the same for all species.

### Surface Area and Solid Volume

Fuel burns only where it is in contact with air; the more extensive the contact, the faster and more efficient the combustion. Fresh slash has a high ratio of surface area to volume. Olson and Fahnestock (*31*) report that, on an average, 1 pound of fresh Douglas-fir slash has 25 square feet of surface area. At this rate 15 tons of slash on an acre of ground would have 750,000 square feet, or 17.2 acres, of contact with the air. Compressed into a solid having the specific gravity of Douglas-fir wood, the same amount of slash would occupy 1,120 cubic feet, about the equivalent of a sheet of ¼-inch plywood covering the acre. Such a sheet of plywood could hardly be considered a fire hazard; its weight equivalent of slash would be a serious hazard because of high surface-volume ratio.

*Slash becomes a less dangerous fuel as it ages because its surface area is drastically reduced.* In the Douglas-fir slash described above, needles made up only 35 percent of the weight but 80 percent of the surface area. When needles fall, surface exposed for active combustion is reduced 73 percent. (Needles lying on the ground are assumed to have an exposed surface area equal to the area of ground covered.) Absence of needles from slash does not necessarily indicate a safe level of flammability. The surface area of branchwood may be several times that of fuel that existed before addition of slash.

### Change Due to Aging

**Foliage.** —Loss of foliage is the most significant change in slash during the first 3 years after cutting. Length of time needles are retained is a good index to flammability: the more needles on a limb or twig, the higher the flammability. Species fall into three distinct groups according to duration of foliage retention.

Western hemlock and Engelmann spruce needles fall as they dry. Actual time required varies with exposure to drying conditions and size of wood on which needles are growing, but neither species retains dry foliage after the season of cutting. Being small, needles fall through the network of branches and lose their identity as they become part of the forest floor.

Western larch, Douglas-fir, and grand fir generally lose their foliage the first winter after cutting, but exceptions occur. On cutover areas, 1-year-old Douglas-fir tops sometimes have their needles still attached. In 1956, on experimental plots, grand fir slash cut the preceding fall still retained at least 50 percent of its foliage, but slash cut in the fall of 1954 had lost nearly all its needles by August 1955. No instances have been observed of foliage persisting into the second summer after logging. Fallen needles sometimes form noticeable concentrations on the ground, especially where they are supported by twigs.

Foliage falls gradually from slash of the three pines and western redcedar. Most of it has dropped from very exposed small branches at the end of the first year, but the fallen needles and sprays, being large, are trapped and supported by branches and so remain high in the fuel bed. Three years after cutting, supported foliage is still an important fuel component, but it is nearer the ground than when it first fell. On experimental plots western redcedar showed more nearly complete loss of foliage and greater compactness of fallen fine material than the pines, although cedar slash is generally considered the most durable of all species.

**Twigs and branches.** — Most of the fine twigs and all larger branches are still intact at the end of 3 years. Pine branches, especially ponderosa, retain much of their arching habit. Hemlock branches curl conspicuously; some lift their twigs 4 feet above the ground. All other species lie increasingly flat with age.

**Bark.** — Bark disintegration is noticeable at the end of 2 to 3 years but has not progressed far. Early disintegration of bark is limited to branches larger than 3/8-inch in diameter. White pine loses the most bark in the first 3 years; ponderosa, the least. On plots, ponderosa was the only species appreciably attacked by bark beetles.

Table 2.--Proportional weights of foliage and branchwood of various diameters

| Species | Percent of total crown weight | | | | | | |
|---|---|---|---|---|---|---|---|
| | Foliage | Branchwood by diameter classes | | | | | |
| | | < 1/8" | 1/8"-1/4" | 1/4"-1/2" | 1/2"-1" | 1"-2" | > 2" |
| Western larch | 11.7 | 4.8 | 14.3 | 8.7 | 31.6 | 28.9 | -- |
| Lodgepole pine | 15.3 | .5 | 10.9 | 18.0 | 19.9 | 27.0 | 8.4 |
| Ponderosa pine | 21.2 | -- | 1.0 | 12.8 | 16.5 | 37.0 | 11.5 |
| Western white pine | 25.3 | 2.0 | 14.6 | 8.6 | 16.5 | 33.0 | -- |
| Douglas-fir | 26.8 | 7.2 | 4.7 | 6.0 | 22.9 | 32.4 | -- |
| Grand fir | 36.8 | 8.4 | 6.2 | 4.7 | 17.6 | 26.3 | -- |
| Western hemlock | 23.0 | 10.5 | 4.0 | 5.3 | 13.9 | 41.9 | 1.4 |
| Engelmann spruce | 29.6 | 9.0 | 5.8 | 5.2 | 12.1 | 27.9 | 10.4 |
| Western redcedar | 36.0 | ([1]) | 5.3 | 3.9 | 25.6 | 29.2 | -- |

[1] Included with foliage.

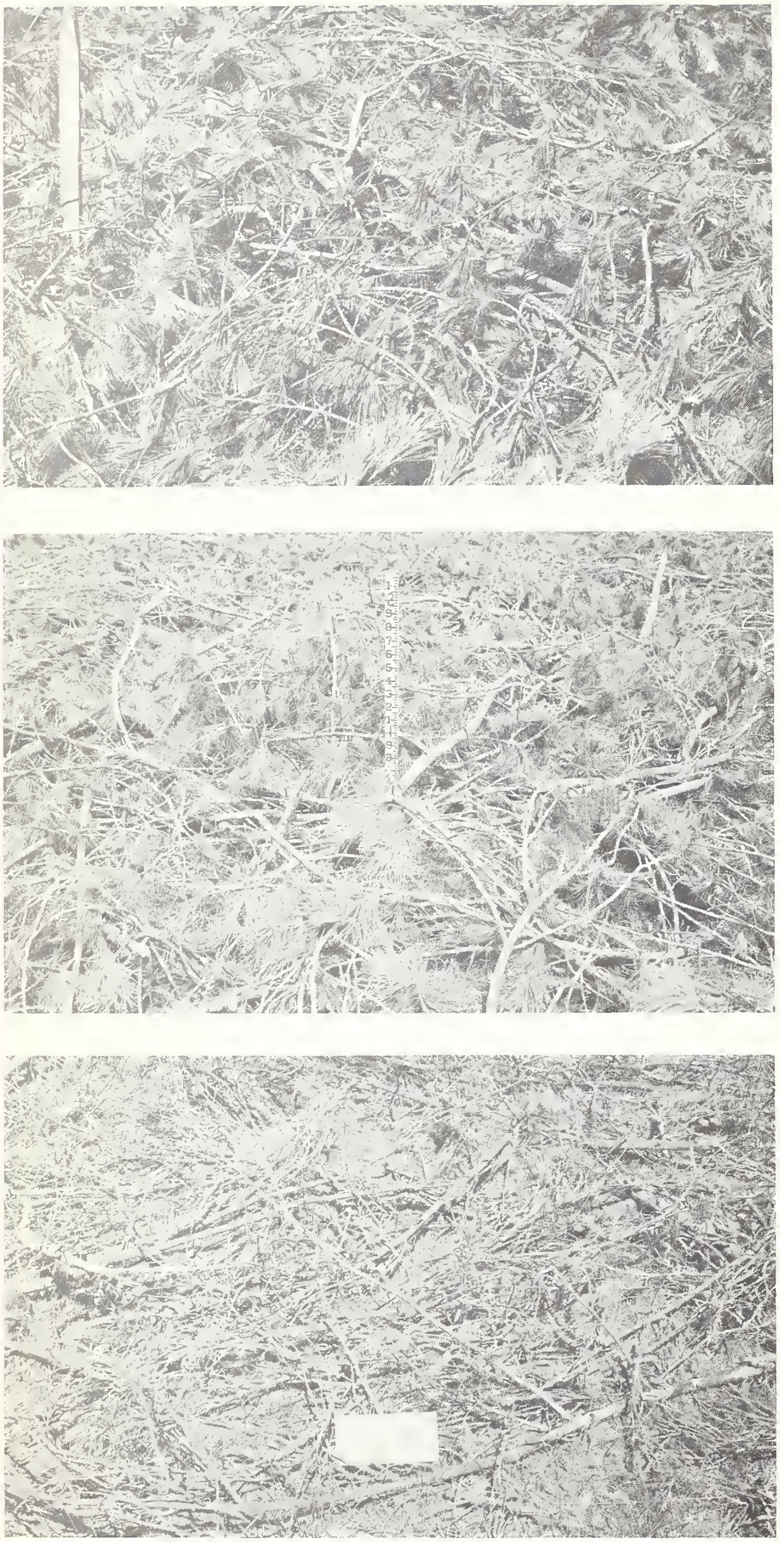


Figure 4. Slash of western white pine, which retains its needles 2 or more years after cutting (32.5 tons per acre). **Upper,** year of cutting; **middle,** 1 year after cutting; **lower,** 3 years after cutting.

**Wood.** — Butt ends of branches tend to split in drying, and surface checks occur where bark is lost. No evidence of decay was seen on plots at age 3 years.

## FUEL BED CHARACTERISTICS

As they occur in cutover forests, slash fuel beds are the products of many factors whose relative importance varies from logging job to logging job. Age, composition, and health of stand; type, size, and quantity of products cut; method of logging and care in its application — all these plus some minor considerations strongly influence the quantity, arrangement, and continuity of slash. Slash used in this study was not affected by the external factors that are at work on cutover areas. Therefore, experimental fuel beds reflected only species characteristics. Observation and measurement of slash on sample plots have provided information that leads to better understanding of slash flammability in the woods. The important observations and measurements are discussed here and are illustrated by figures 4 to 7 inclusive.

### Continuity

The effect of fuel continuity on fire behavior is somewhat controversial. The basic question is, "How far apart can fuel particles or fuel concentrations be and still produce continuous fire spread?" The biggest obstacle to answering this question directly is that fire spread depends not only on quantity of available fuel but also on fuel arrangement and weather conditions, and hence fire intensity. Fire spreads rapidly through continuous fine fuels; because of spotting, perhaps spread would be as rapid if the same amount of fuel were arranged in separated piles. This possibility should be considered carefully where a large quantity of fuel per acre would cause slash piles to be close together. Extreme situations have been observed where fires spread from pile to pile by heat radiation alone, independent of spotting. Figure 8 shows contrasting continuities of slash in which fire might spread at about the same rate.

This study does not analyze the large-scale effects of fuel continuity on cutover areas, but it does provide information on small-scale variations in continuity within the fuel bed as affected by species and quantity of slash. Although even these variations have not yet been measured, simply observing some of them gives a clue to expected fire behavior. Branching characteristics strongly affect continuity where quantity of slash is small. Short, uniformly leafy branches, as in western white pine, result in good continuity; the sparse branching habit and clumped needles of ponderosa pine, and the long, heavy branches of old hemlock cause fine components to be patchy. As quantity of slash increases, importance of branching habit decreases. On experimental plots fine fuel was continuous at 20 tons per acre in most slash with needles, but breaks large enough to affect fire spread occurred in ponderosa pine and species without needles. At 32.5 tons per acre, all kinds of slash were continuous. Figure 9 shows some of the variation in continuity that were observed.

### Depth and Density

Density, or volume of solid fuel per unit of fuel bed volume, is a measure of oxygen availability and distance between particles across which heat must be radiated to ignite additional fuel. Where quantity of slash per acre is known, depth is a direct measure of density. Aging decreases depth of fuel, hence increases density. Depth was measured annually at four points on each plot of experimental slash to determine initial density and changes caused by aging (table 3).

Compaction of the fuel bed usually reduces flammability. Availability of oxygen is reduced, fuel moisture is increased by shading and proximity to the ground, and efficiency of interradiation is decreased. It was obvious from the first that decreased depth of experimental slash would indicate reduced flammability. In some situations on cutover areas, however, the reverse appears to be true. In large Douglas-fir, hemlock, and spruce tops without foliage, fine fuels are so sparse and widely separated that they burn only with the help of underlying or adjacent fuels. Where these tops are lopped or crushed, the fine material forms a dense enough fuel bed to burn vigorously without outside assistance.

### Relation to Other Fuels

Some fuel is always present before slash is created. Superimposing even a small amount

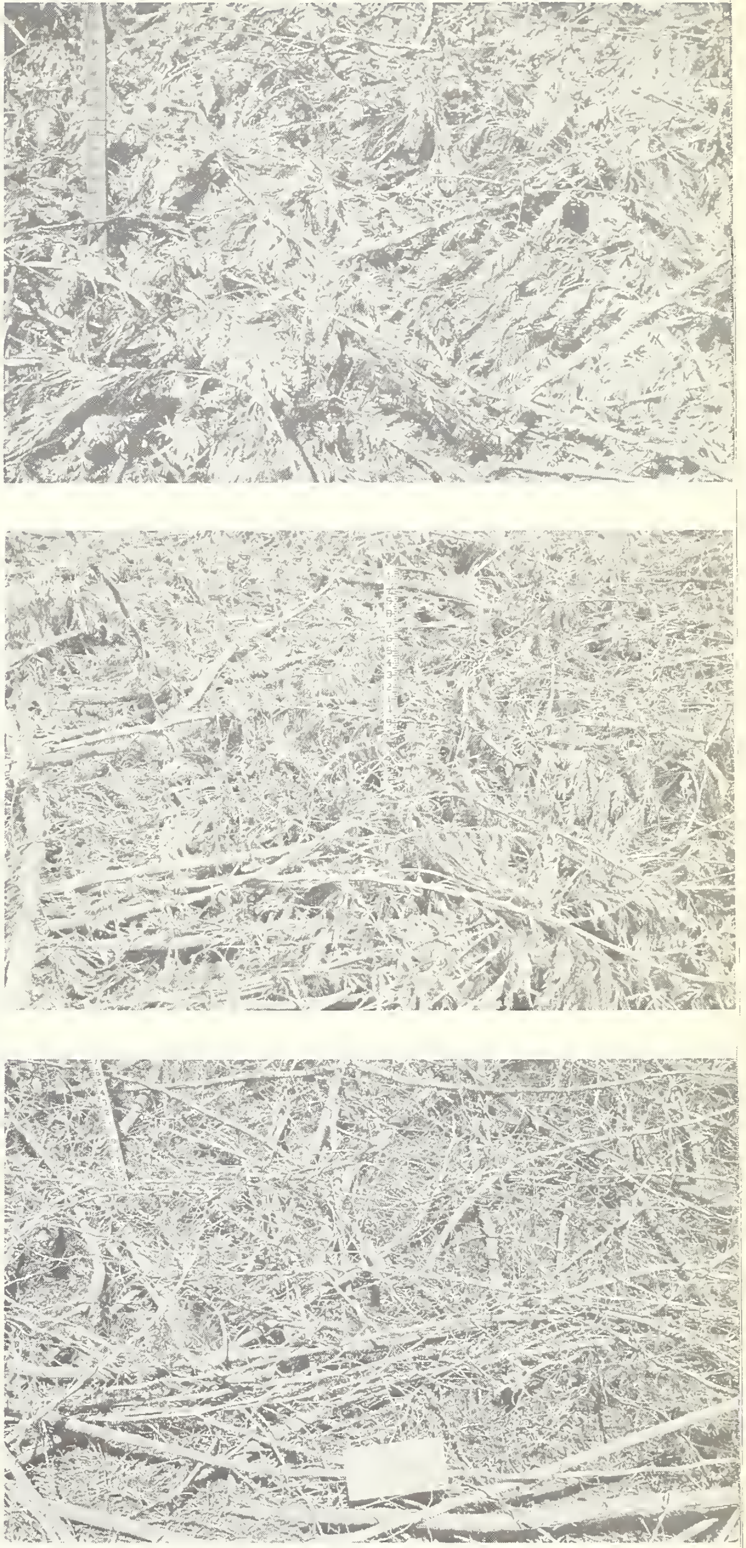


Figure 5. Slash of western redcedar, whose sprays disintegrate gradually in no set pattern (32.5 tons per acre). **Upper,** year of cutting; **middle,** 1 year after cutting; **lower,** 3 years after cutting.

of slash on natural fuels may produce an intolerable hazard where neither the slash nor the natural fuels alone would be serious. Slash under dense, young stands and tolerant, long-crowned trees draped with lichens results in a vertically continuous fuel bed as deep as the trees are tall. The disastrous McVay Fire in the Black Hills of South Dakota fed on pruned branches and thinnings in the young ponderosa pine. The same amount of slash under older trees would have been far less damaging. Where fires in light, flashy natural fuels, such as grass and ponderosa pine litter, would be fast, easy to control, and not very damaging, the presence of slash results in longer heat duration, greater resistance to control, and more damage to forest values. On the other hand, where natural fuels are predominantly coarse and slow-burning, slash may be just the kindling needed to produce a destructive, hard-to-handle fire.

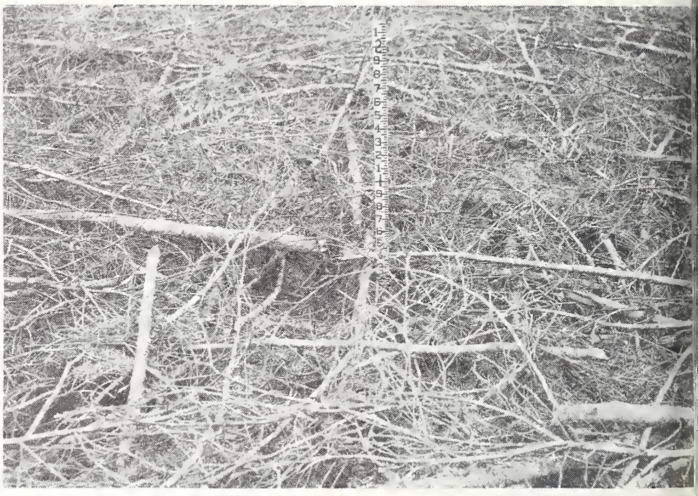


Figure 6. Slash of Douglas-fir, which usually loses its needles the winter after cutting (32.5 tons per acre). **Upper,** year of cutting; **middle,** 1 year after cutting; **lower,** 3 years after cutting.

Figure 7. Slash of western hemlock, which loses its needles while drying (32.5 tons per acre). **Upper,** year of cutting; **middle,** 1 year after cutting; **lower,** 3 years after cutting.

Figure 8. Slash fuel bed continuity as affected by method of logging. **Upper**, slash in windrows separated by nearly bare ground; **lower**, slash continuous over entire logged area.

Figure 9. Variation in continuity within the fuel bed. **Upper,** continuous fine fuel in western white pine slash due to moderately fine branching and even distribution of needles; **middle,** discontinuity in western hemlock slash due primarily to loss of needles; **lower,** discontinutiy in ponderosa pine slash due to coarse branching and tufted foliage (all species 7.5 tons per acre).

Table 3.-- Depth (in feet) of evenly distributed, lopped slash in relation to species, age, and weight

| Species | Years of cutting | | | 1 year old | | | 3 years old | | |
|---|---|---|---|---|---|---|---|---|---|
| | Tons per acre | | | | | | | | |
| | 7.5 | 20.0 | 32.5 | 7.5 | 20.0 | 32.5 | 7.5 | 20.0 | 32.5 |
| Western white pine | 0.51 | 0.80 | 1.00 | 0.32 | 0.54 | 0.78 | 0.35 | 0.55 | 0.72 |
| Lodgepole pine | .51 | 1.04 | 1.29 | .38 | .66 | .90 | -- | -- | -- |
| Ponderosa pine | .34 | .97 | 1.36 | .44 | .69 | .96 | -- | -- | -- |
| Western redcedar | .35 | .53 | .84 | .24 | .66 | .76 | .35 | .62 | .92 |
| Douglas-fir | .23 | .63 | .83 | .23 | .67 | .72 | .22 | .78 | .65 |
| Western hemlock | .30 | .62 | .92 | .31 | .71 | .88 | -- | .65 | 1.68 |
| Engelmann spruce | .49 | .92 | .96 | .40 | .58 | .88 | -- | -- | -- |
| Grand fir | .46 | .76 | .94 | .26 | .52 | .74 | -- | -- | -- |
| Western larch | .30 | .78 | .97 | .26 | .52 | .70 | -- | -- | -- |

# HOW SLASH DRIES

The rate at which slash dries determines how soon cutover areas become special forest fire hazards. Opening up the stand increases fire danger, and even green slash will burn under the right conditions. However, the full potential for fire occurrence, rate of spread, and intensity is attained only when moisture content, of fine fuels especially, has declined to a dangerous level. In the northern Rocky Mountains an average fine-fuel moisture content of 10 percent is dangerous, and 5 percent or below is critical. Coarse fuels contribute significantly to fire spread, intensity, and duration when moisture content of the peripheral inch approaches 10 percent.

Initial drying of slash involves change from the living to the dead state. It is not logical to expect freshly cut slash with a moisture content near 100 percent to dry to 10 percent as quickly as equally moist dead material of the same size. Initial moisture content and size of fuel particle are the important characteristics that affect rate of drying in slash just as they do in dead fuels. However, the influence of both these factors is modified by the presence of unbroken bark, especially on large slash components, and by the ability of fine twigs and needles to obtain moisture from the larger material to which they are attached. To get some idea of how soon slash becomes a serious fire hazard, initial moisture content of nine timber species has been investigated, and experiments have shown how rapidly slash of one species (Douglas-fir) dries in relation to size under three degrees of shade.

## MOISTURE CONTENT OF GREEN SLASH

Moisture content of freshly cut slash was measured for two purposes: (1) to find out how much drying would be required to cause high flammability and (2) to provide a basis for calculating the amount of green slash equivalent to a desired ovendry weight of experimental material. Some additional determinations were made in conjunction with crown dissection and classification. Material used included: needles, branchwood, mixed chips of needles and branchwood, and entire branches. Moisture content was determined by ovendrying and was expressed as percent of ovendry weight.

Table 4 shows that moisture content varies widely with species and with size of material. Differences greater than 50 percent were found between needle samples from the same tree. Obviously, many samples would be required to provide reliable average moisture content figures for material collected at any one time. Such intensive sampling would be desirable for studying flammability of living vegetation in relation to season and site, but it has no practical value for the present investigation. Severity of drying conditions to which fuel material is exposed after cutting soon obscures effects of initial moisture content.

## LOSS OF MOISTURE

Loss of moisture begins as soon as a tree is cut. Change in moisture content is noticeable almost immediately in fine, detached material. Western larch needles stripped from their branches lost 6 percent in less than 30 minutes despite being shaded. Small detached branches in full sun turn brown and brittle in a few days. On the other hand, unlopped tops may remain green several weeks after cutting, especially on north slopes and in shade. An experiment in 1953 with Douglas-fir slash has provided a better understanding of how slash of different sizes dries in relation to its environment.

### Experimental Procedure

Loss of moisture was followed in the unlopped tops of 15 young merchantable Douglas-fir trees, cut especially for the purpose, and in three beds of branches lopped from the same trees. Nine tops were located in a clear-cut area receiving 96 percent of full sunlight, one in a partially cut area receiving 69 percent, and five in an uncut stand receiving only 22 percent. A bed of lopped branches was located in each degree of shade. The study area was on a southeasterly exposure at 3,000 feet elevation.

The study continued from July 9 to October 9, 1953. Rainfall during the period was 19 percent below average; July and September were

Table 4.--Moisture content of four types of fuel materials in freshly cut slash, by percentage

| Species | Needles | | Branchwood | | Mixed chips | | Whole branch | |
|---|---|---|---|---|---|---|---|---|
| | Samples | Moisture content | Samples | Moisture content | Samples | Moisture content | Samples | Moisture content |
| | | *Percent* | | *Percent* | | *Percent* | | *Percent* |
| Western white pine | 14 | 117.0 | 11 | 81.1 | 4 | 104.2 | 9 | 117.3 |
| Lodgepole pine | 1 | 178.6 | 1 | 95.5 | 18 | 90.0 | 9 | 82.2 |
| Ponderosa pine | 4 | 124.7 | 1 | 85.3 | 5 | 90.9 | -- | -- |
| Western redcedar | 14 | 113.7 | 11 | 87.1 | 4 | 74.6 | 6 | 101.8 |
| Douglas-fir | 13 | 95.3 | 10 | 79.1 | 4 | 81.0 | 9 | 90.1 |
| Western hemlock | 11 | 115.8 | 11 | 72.4 | 4 | 88.5 | -- | -- |
| Engelmann spruce | 8 | 117.6 | 5 | 70.1 | -- | -- | 9 | 98.0 |
| Grand fir | 2 | 148.1 | 1 | 83.9 | 4 | 87.3 | -- | -- |
| Western larch | 1 | 360.0 | 1 | 66.1 | 9 | 93.2 | -- | -- |

dry, but August was relatively wet. Departures from normal precipitation were not unusual for the region. Temperature and relative humidity were about average. Records from three weather stations on the study area were compared with each other and with records from a fire-danger station 1 mile away. Factors of fire danger varied in response to topographic location and degree of shade as had been indicated by earlier research (*16, 21, 22*).

Moisture content of fine twigs and needles attached to tops of unlopped branches and of trunkwood one-fourth and seven-eighths inch inside the bark was measured at intervals suited to detection of significant changes. Samples of fine material were collected and ovendried. Readings of trunk moisture content were made with a commercial lumber moisture meter (*6*) at points where the trunks of experimental tops were 2, 4, 6, and 8 inches in diameter. At the start and end of the experiment, moisture content of wood was checked by ovendrying disks sawed from the tops.

### Drying Rate of Fine Material

Needles and twigs on lopped branches dried faster than any other material. In full sun, moisture content dropped to 10 percent in 13 days and to 6.5 percent in 18 days. Thereafter it fluctuated between 5 and 13 percent, just as it did in dead fuels during the same period. In partial shade, moisture content dropped to 10 percent in 24 days; after that, it stayed 1 to 5 percent higher than in unshaded material. Heavily shaded fine slash attained a minimum moisture content of 12 percent after 25 days, and then stayed 7 to 20 percent more moist than unshaded slash. Figure 11 (upper) shows the rate of drying of lopped slash.

The initial drying rate of lopped slash was less than one-third that of dead fuels. After a 1.59-inch rain, ½-inch sticks at the nearby fire-danger stations dried from 43 to 8 percent moisture in 3 days. The same change required 11 days in the fastest drying experimental slash.

Needles and twigs on branches attached to the trunk dried slowly (fig. 11 lower). In full sun, moisture content dropped steadily, with minor interruptions, to 11 percent at the end of 42 days. Three weeks later, on September 11, a minimum of 8 percent was reached. The last

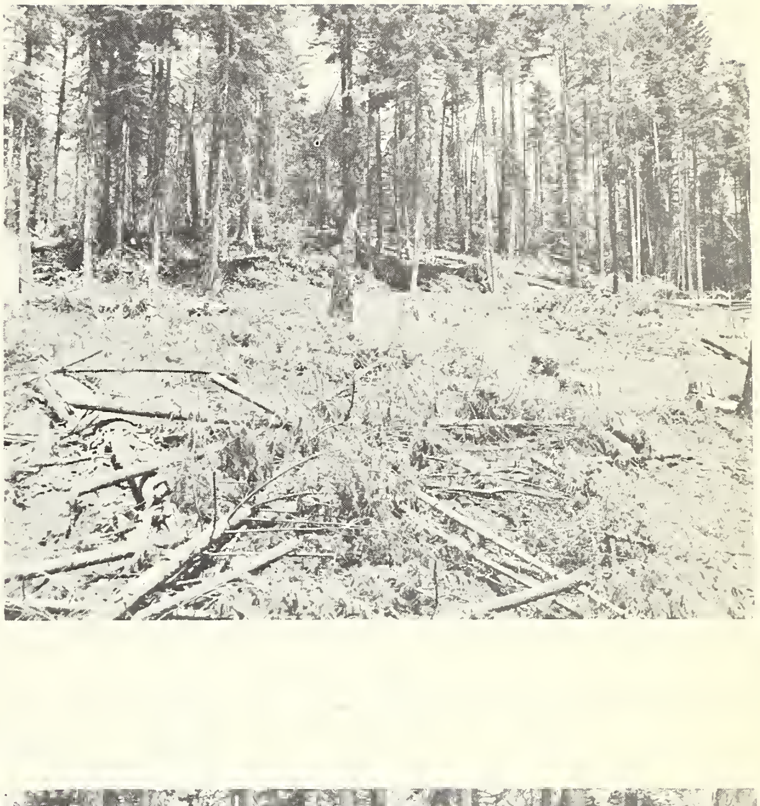
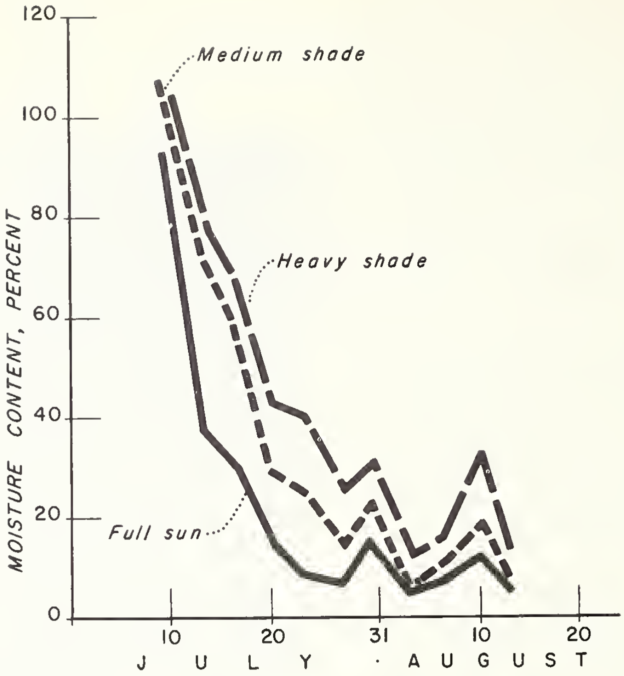


Figure 10. Conditions under which rate of drying was studied: **upper,** clear-cut area, with heavy partial cut in the background; **lower,** lightly cut area. Arrows point to weather stations and tops studied.



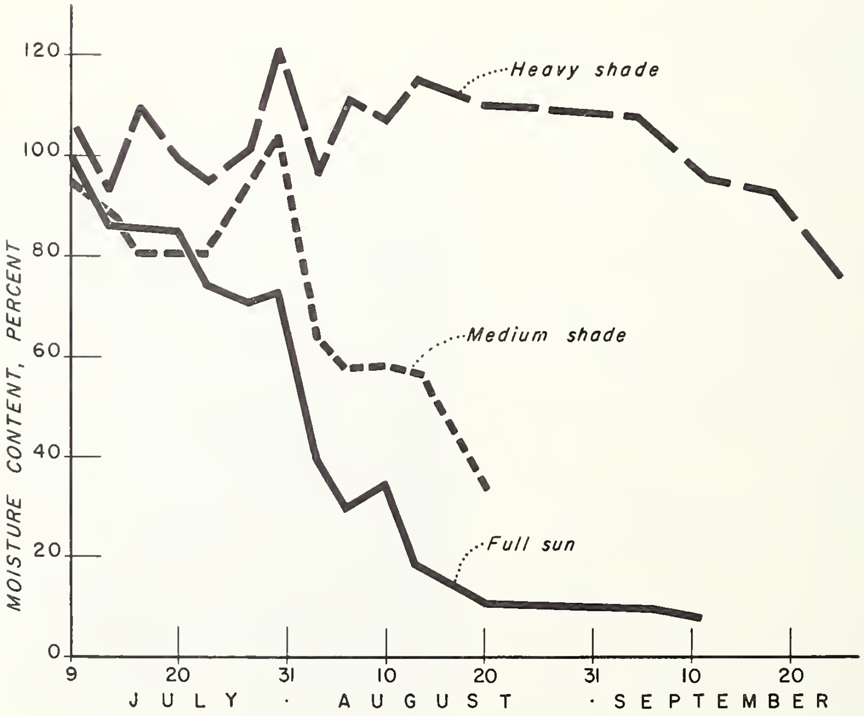


Figure 11. Drying rate of foliage and fine twigs: **upper,** on lopped branches; **lower,** on unlopped branches.

Table 5.--Moisture meter values at end of study for all trees in full sun and heavy shade

| Tree No. | Average meter reading | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1/4-inch depth | | | | 7/8-inch depth | | | |
| | Trunk diameter at point of reading (inches) | | | | | | | |
| | 8 | 6 | 4 | 2 | 8 | 6 | 4 | 2 |
| | *Tops in full sun* | | | | | | | |
| 1 | 27.0 | 20.0 | 16.9 | 11.0 | 22.0 | 19.7 | 17.3 | 13.0 |
| 2 | 21.0 | 21.3 | 20.3 | 17.0 | 20.3 | 21.0 | 22.0 | 22.0 |
| 3 | 24.3 | 23.2 | 22.3 | (1/) | 22.3 | 22.0 | 21.0 | (1/) |
| 4 | 22.3 | 23.0 | 14.7 | (1/) | 20.7 | 21.7 | 15.3 | (1/) |
| 5 | 21.7 | 21.7 | 18.7 | 17.0 | 21.0 | 20.7 | 19.7 | 18.0 |
| 7 | 19.3 | 22.3 | 16.7 | 12.0 | 19.3 | 21.3 | 17.3 | 16.0 |
| 8 | 27.7 | 26.7 | 19.7 | 21.0 | 25.3 | 24.7 | 19.7 | 22.0 |
| 9 | 23.7 | 19.3 | 21.0 | 17.0 | 23.0 | 20.3 | 20.7 | 22.0 |
| 10 | 21.0 | 19.0 | 19.7 | 14.0 | 21.7 | 20.3 | 19.7 | 16.0 |
| Mean | 23.1 | 21.8 | 18.9 | 15.6 | 21.7 | 21.3 | 19.2 | 18.4 |
| | *Tops in heavy shade* | | | | | | | |
| 11 | 37.7 | 34.7 | 33.0 | 31.0 | 27.0 | 29.3 | 30.7 | 31.0 |
| 12 | 39.7 | 34.7 | (1/) | (1/) | 28.3 | 30.0 | (1/) | (1/) |
| 13 | 34.3 | 32.3 | 33.3 | 36.0 | 28.7 | 29.7 | 31.3 | 34.0 |
| 14 | 33.3 | 36.0 | (1/) | (1/) | 31.3 | 36.3 | (1/) | (1/) |
| 15 | 35.3 | 31.0 | 33.3 | 28.0 | 27.7 | 27.3 | 28.3 | 27.0 |
| Mean | 36.1 | 33.7 | 33.2 | 31.7 | 28.6 | 30.5 | 30.1 | 30.7 |

1/ All missing values resulted from felling breakage of tops.

figure obtained for the one tree in partial shade was 33.5 percent on August 20.[2] The shape of the curve suggests that a moisture content below 15 percent might have been reached between September 5 and 10. After reaching its low point, slash moisture content in unshaded and partially shaded areas would be expected to fluctuate like that in other similarly situated dead fuels.

In heavily shaded tops, fine material did not dry to high flammability during the first summer. Average moisture content remained above 100 percent until shortly after a steady decline began on September 4. The minimum value, 76 percent, was recorded on September 25, when measurement was terminated.

Needles tended to drop off in approximately inverse proportion to the drying rate. Virtually all needles remained firmly attached to lopped slash exposed in full sun and partial shade, while needles on the tops in full shade had thinned noticeably by the end of the experiment. Probably selective loss of needles characterizes only Douglas-fir, and possibly grand fir; both species usually retain all of their foliage through the summer of the year in which they are cut, then lose their needles the following winter. Other species either lose all of their foliage in drying or retain all of it for a year or more regardless of the rate of drying.

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[2] This tree was moved and damaged when logs were skidded near it.

### Drying Rate of Wood

Moisture content of trunk wood samples, cut from the disks mentioned earlier and ovendried, averaged 140 percent in the outermost 1/2 inch, 102 percent in the 3/4- to 1 1/4-inch layer, and 30 percent at a depth of 2 to 3 inches. As would be expected, nearly all the initial moisture meter readings at the 1/4-inch depth were 65+, the maximum shown by the meter. Since most of the initial readings at the 7/8-inch depth were between 35 and 45, apparently a reasonably representative sample of heartwood moisture content was obtained.

Drying curves for shaded and unshaded material followed essentially the same pattern but differed strongly in response to depth of measurement. Figure 12 illustrates the drying process for 6-inch trunkwood. Apparently the initial rapid drying of the outer sapwood was accomplished largely through diffusion of moisture into the heartwood. At the end of the summer the moisture content of the experimental tops was still much greater than that of older, barkless logs at nearby flammability stations.

At the end of the study, average moisture meter reading at 1/4-inch depth at all diameters was 19.8 for tops in full sun and 33.7 for tops in heavy shade. Ovendried samples gave corresponding figures of 29.5 and 41.0 percent. At the 7/8-inch depth, terminal meter readings were 20.2 and 30.0 percent in full sun and heavy shade, respectively, as compared with ovendried sample values of 31.0 and 41.4 percent. Table 5 gives moisture meter readings on October 9, when the study of trunk moisture content was concluded. In spite of their final 7- to 11-percent minus error, the meter readings apparently gave an acceptable representation of the drying curves. A more accurate measure would be required for large fuel that might become dry enough to burn.

The final moisture content of about 30 percent for topwood in full sun indicates that only free water from the cell cavities is lost by the end of the first summer (2). Moisture content becomes essentially uniform throughout the peripheral inch and probably to the center of the trunk, presumably because the unbroken bark prevents rapid evaporation from the surface. Flammability of large slash with unbroken bark remains low throughout the first summer in comparison with that of older, barkless logs whose surface can be almost as dry as fine fuels late in the fire season.

## USES OF INFORMATION ON HOW SLASH DRIES

The time required for different kinds of slash material to reach high flammability under various types of cutting may be summarized as follows:

| | Type of cutting | | |
|---|---|---|---|
| **Material** | **Clear cut** | **Moderate partial** | **Light** |
| Lopped branches | 2 weeks | 3 weeks | 4 weeks |
| Unlopped branches | 6 weeks | 9 weeks | 3 months |
| Trunk wood | 2 summers | 2 summers | 2 summers |

This information has several practical uses. Although only one tree species (Douglas-fir) was investigated, results should be applicable to most other northern Rocky Mountain species. Parker (*33, 34*) has reported that ponderosa pine needles and twigs dry more slowly than those from Douglas-fir, but that needles and twigs of grand fir and western redcedar dry at the same rate. Observations made during other phases of the present study showed that ponderosa pine dried slowest of the nine species and that all the other eight species dried at about the same rate.

### Rating Fire Hazard on Cutover Areas

The information listed in the tabulation above applies directly to slopes and flats that are fully exposed to summer sun. Drying rate in clear-cut areas on protected sites, such as north slopes, approximates that tabulated for the partial cut. Moderate cutting in such locations results in a drying rate near that shown for the very light cut. On the lowest third of steep, north-facing slopes and in canyon bottoms, fuels dry more slowly than in any of the three types of drying area used in this study. Probably 5 to 7 weeks would be a realistic time allowance for lopped slash in these locations to dry, depending on the exact topographic situation and severity of cutting. Unlopped tops lying on north slopes are unlikely to dry significantly even when

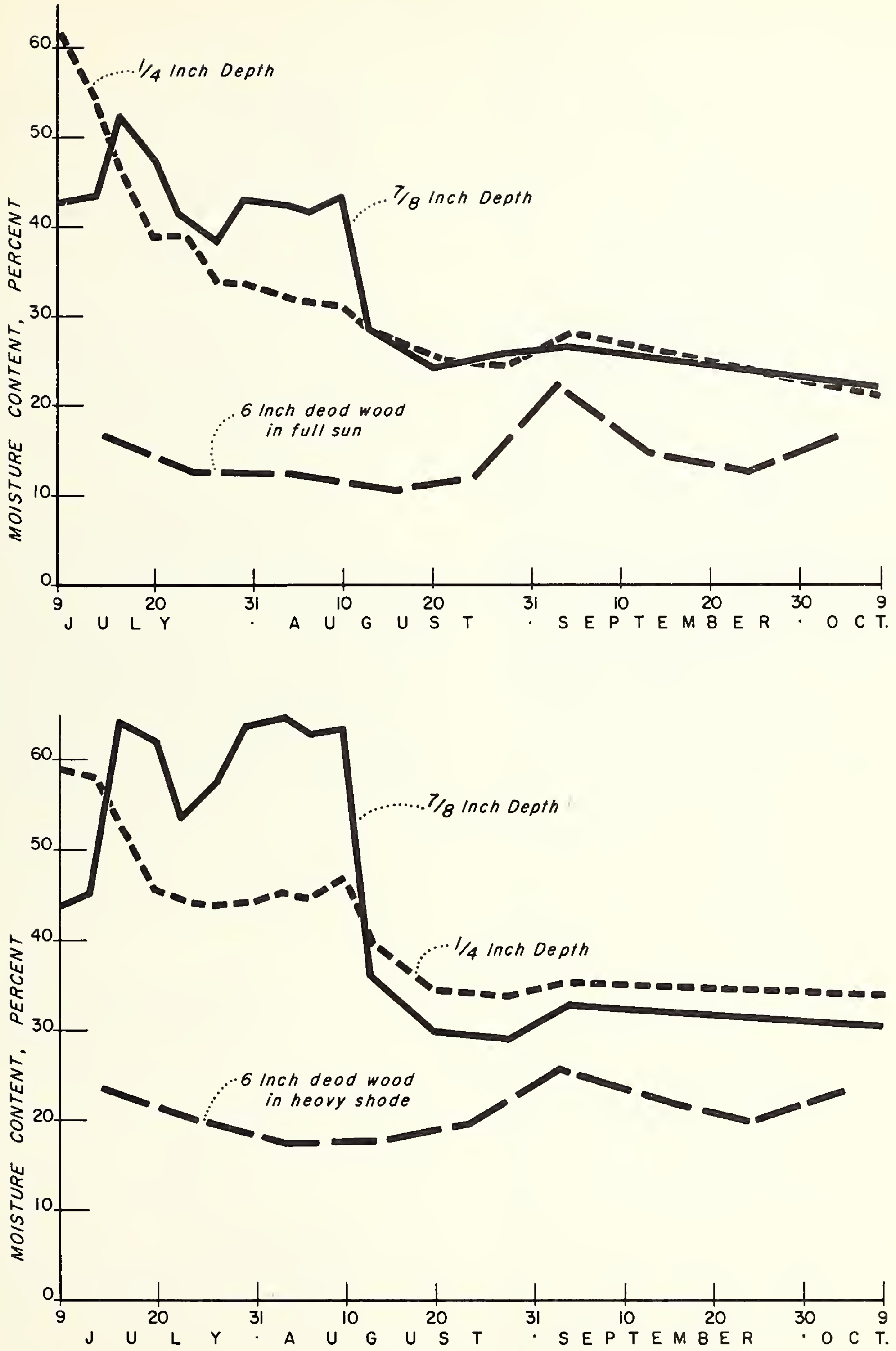

Figure 12. Drying rate of 6-inch wood of freshly cut tops, and comparison with older wood: **upper**, in full sun; **lower**, in shade.

exposed for the whole summer. However, moisture content of lopped and broken branches is the factor that controls flammability, since green tops burn if associated dry fuels supply enough heat; and concentrations of tops usually are accompanied by varying quantities of small, detached material.

### Setting Slash Disposal Priorities

Usually only slash cut the previous summer or fall in exposed locations is dry enough to require attention before about June 15. Since only dry, open sites are ordinarily accessible early in the season, spring slash disposal operations tend to be automatically directed against the worst hazard.

Current slash cut as late as August 10 in exposed areas may become dangerous before the end of the fire season. If the fall is dry, even slash cut in September can become a hazardous fuel. In sheltered situations, on the other hand, slash cut after the third week of July is unlikely to become highly flammable before the following summer. Data on slash drying indicate that disposal operations will be most effective if commenced as follows:

Before June 15:

Slash cut in the previous fall and winter in exposed locations

June 15 to September 1:

Current season's slash in exposed locations and slash cut before July 20 in sheltered locations

After September 1:

Current season's slash in areas likely to be least accessible next spring.

These suggestions are intended to be used in conjunction with the usual considerations of slash quantity and kind, fire risk, and values to be protected. Dates must be adjusted locally according to disappearance of snow and the start of fall rains.

### Preparation for Prescribed Burning

Since large tops require at least 6 weeks to dry, extensive felling in preparation for a prescribed burn the same year should be completed by about July 15. If this is impossible, partial lopping of felled trees will provide dry fuel if done while 2 to 4 weeks of drying weather can be expected. The suggested action is particularly important around planned ignition points and wherever dead ground fuels are sparse.

# MEASURING SLASH

To predict how any fire will burn, one must know the quantity, chemical composition, and arrangement of the fuel. Most of the solid and liquid fuels man uses are homogeneous and easily measured, and their characteristics can be adjusted to suit the purpose at hand. But forest fuels, including slash, are heterogeneous and very difficult to measure. Little progress has been made toward understanding forest fuels more than superficially. This section explains methods of measuring slash that will reduce the guesswork in estimating both the degree of fire hazard on cutover areas and the amount of work required to reduce this hazard to a tolerable level.

## BACKGROUND OF FUEL MEASUREMENT

### Fuel Type Classification

In the United States the need to measure forest fuels in order to make forest fire control more scientific was recognized by Gisborne and Hornby about 30 years ago. Their efforts produced the "fuel type" concept (*18*) and fuel type classification has been undertaken since then in all parts of the country. Probably the fuel type concept has been used most intensively in the northern Rocky Mountain region, primarily for fire control planning. Fuel type standards have been developed, and fuel types have been mapped on some 30 million acres of national forests.

Fuel types as now developed are an impressionistic, essentially qualitative measure of fuel quantity and arrangement. They do not actually measure fuel at all, but evaluate expected fire behavior in the various fuel complexes. Fuel type classification and mapping have been valuable tools for fire-control planning but have contributed little to the basic understanding of how fuel characteristics affect combustion. Moreover, keeping fuel type maps up-to-date has proved too expensive and complicated to be justified by the benefits they provide.

Experience has shown that the northern Rocky Mountain fuel type classification system had seriously underrated slash (*42*). Increasing area of recently cutover land, extending logging into zones of frequent lightning fire occurrence, and skyrocketing cost of slash disposal make a reevaluation of slash imperative. Learning to measure the fuel is one essential step toward reevaluation. Since slash is created by the one severe act of logging rather than by gradual accumulation, this fuel can be identified readily and measured directly.

### Measurement of Tree Crowns

In slash most of the fine fuel particles that burn rapidly are components of tree crowns — leaves, twigs, and branchwood. Coarse fuels — cull logs, broken chunks, long butts, etc. — can be tolerated in the absence of fine material that dries rapidly and acts as kindling. *Therefore, measurement of tree crowns is the most appropriate means of measuring slash.*

Weight and surface area of tree foliage have long interested students of tree physiology and forest influences. Several workers (*23, 25, 38*) have described methods of estimating leaf weight and area. Their work deserves close scrutiny by students of forest fuels, for both methodology and factual content. Kittredge's method, relating foliage weight to trunk diameter (*23*), has provided the basis for measuring slash described on the following pages.

In 1950, Olson, at the University of Idaho, attempted to measure volume of slash in place. But slash, as it lay after logging, varied so greatly in species composition, horizontal distribution, and compactness that meaningful measurement in place was impossible. Accordingly Olson concluded that the best procedure was to measure individual trees. After compiling and analyzing measurements of slash from crowns of felled trees before lopping, after lopping, and after piling, he could estimate the volume of slash per thousand board feet cut by species and d.b.h. (*29*). The weakness inherent in using volume as a measure of an unconsolidated fuel was partly overcome by determining the ratio of solids to voids in various slash fuel beds having a known volume per acre (*30, 39*).

At the same time, a group in California investigated the possibility of determining the dry weights of tree crowns by modifying Kittredge's method. Storey, Fons, and Sauer have since reported (*38*) estimates of total crown weight, and of the weight of needles and branchwood separated for 13 coniferous species.

They found a linear relation between the logarithms of crown length × weight and trunk diameter at the base of the crown. Although significant differences among species and species groups did occur, the general relation was surprisingly similar in all species. The Californians' method gives accurate results, but it has the serious drawback for practical application of using as a premise diameter at base of crown, a measurement that is difficult to obtain on standing trees. A further inconvenience is that weight × crown length rather than weight alone is presented as the dependent variable. The California method is desirable because it uses weight rather than volume as a direct measure of solid fuel quantity.

## CROWN WEIGHTS OF NORTHERN ROCKY MOUNTAIN TREES

In appraising the potential fire hazard of slash, one needs to predict what fuel situation will result from cutting given trees or stands. Any usable method of estimating must be reasonably simple and, if possible, based on measurements obtained in cruising or marking the timber. Such a method has been developed by modifying the California method to show crown weight (ovendry) as a function of the product of d.b.h. and crown length.

### Basic Crown Weight Relationship

During the 5-year period 1952 through 1956 crown weight relations were studied on 225 trees of nine species. Trunk diameter at breast height and base of live crown and length of live crown were measured, and all of the live crown exclusive of the trunk was weighed. Ovendry weight of crown was calculated by assuming average moisture content of green material to be 100 percent. Use of this assumption eliminated need for determining moisture content of every tree and, as shown by a check on two species, did not affect accuracy of subsequent calculations appreciably.

Analysis followed the form used by Storey, *et al.* (*38*), but for greater convenience of application the data were rearranged to make crown weight alone the dependent variable. A linear relation was found to exist between the logarithm of crown dry weight and the logarithm of the product of d.b.h. and crown length. Correlation coefficients were insignificantly smaller than those found when length × weight of crown was made dependent on d.i.b. at base of crown.

Species were classified into three groups on the basis of similarity of regression coefficients. Lodgepole pine alone formed one group, having considerably the largest regression coefficient, which was shown to differ significantly from those of all other species. Western redcedar and grand fir had closely similar coefficients at the opposite end of the scale; the other six species were intermediate. Statistical analysis showed that each of the latter two groups was homogeneous as to the regression coefficients of the species included. Statistical comparisons of individual species across group lines frequently failed to show significance; but classifications other than those used appear illogical, reduce within-group homogeneity, and increase errors of estimate.

Figures 13, 14, and 15 show the regressions for the several species and species groups. A single regression adequately represents both grand fir and western redcedar, since their adjusted mean crown weights do not differ significantly. Similarly one regression represents western hemlock, Douglas-fir, and Engelmann spruce in the intermediate group. Separate but parallel regressions are shown for the other three species, which have a common regression coefficient but significantly different means. Prediction equations are as follows:

lodgepole pine: $W = \frac{(hd)}{34.507}$

western white pine: $W = \frac{(hd)}{8.541}$

ponderosa pine: $W = \frac{(hd)}{2.525}$

western larch: $W = \frac{(hd)}{5.828}$

Douglas-fir, western hemlock, and Engelmann spruce: $W = \frac{(hd)}{3.811}$

western redcedar and grand fir: $W = \frac{(hd)}{1.278}$

W is ovendry weight of the live crown in pounds, h is length of live crown in feet, and d is d.b.h. in inches.

# ERRATA

Please attach the following correction to page 26 of LOGGING SLASH FLAMMABILITY by George R. Fahnestock, Intermountain Forest and Range Experiment Station Research Paper 58:

lodgepole pine: $$W = \frac{(hd)^{1.3789}}{34.507}$$

western white pine: $$W = \frac{(hd)^{1.0108}}{8.541}$$

ponderosa pine: $$W = \frac{(hd)^{1.0108}}{2.525}$$

western larch: $$W = \frac{(hd)^{1.0108}}{5.828}$$

Douglas-fir, western hemlock, and Engelmann spruce: $$W = \frac{(hd)^{1.0108}}{3.811}$$

western redcedar and grand fir: $$W = \frac{(hd)^{0.8301}}{1.278}$$

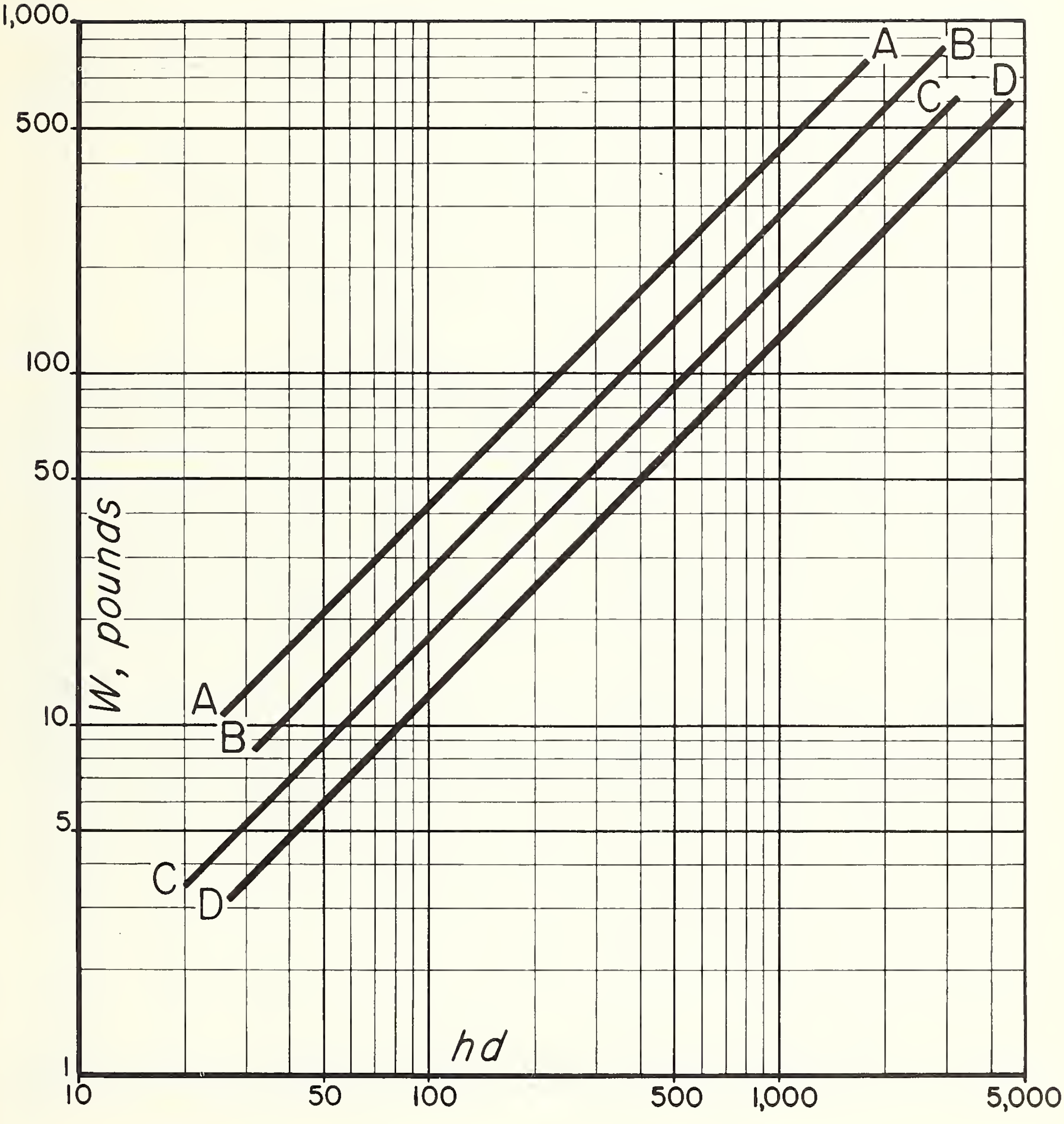

Figure 13. Crown weight, W, in relation to the product of d.b.h. and crown length, hd, for ponderosa pine (AA); Douglas-fir, western hemlock, and Engelmann spruce (BB); western larch (CC); and western white pine (DD).

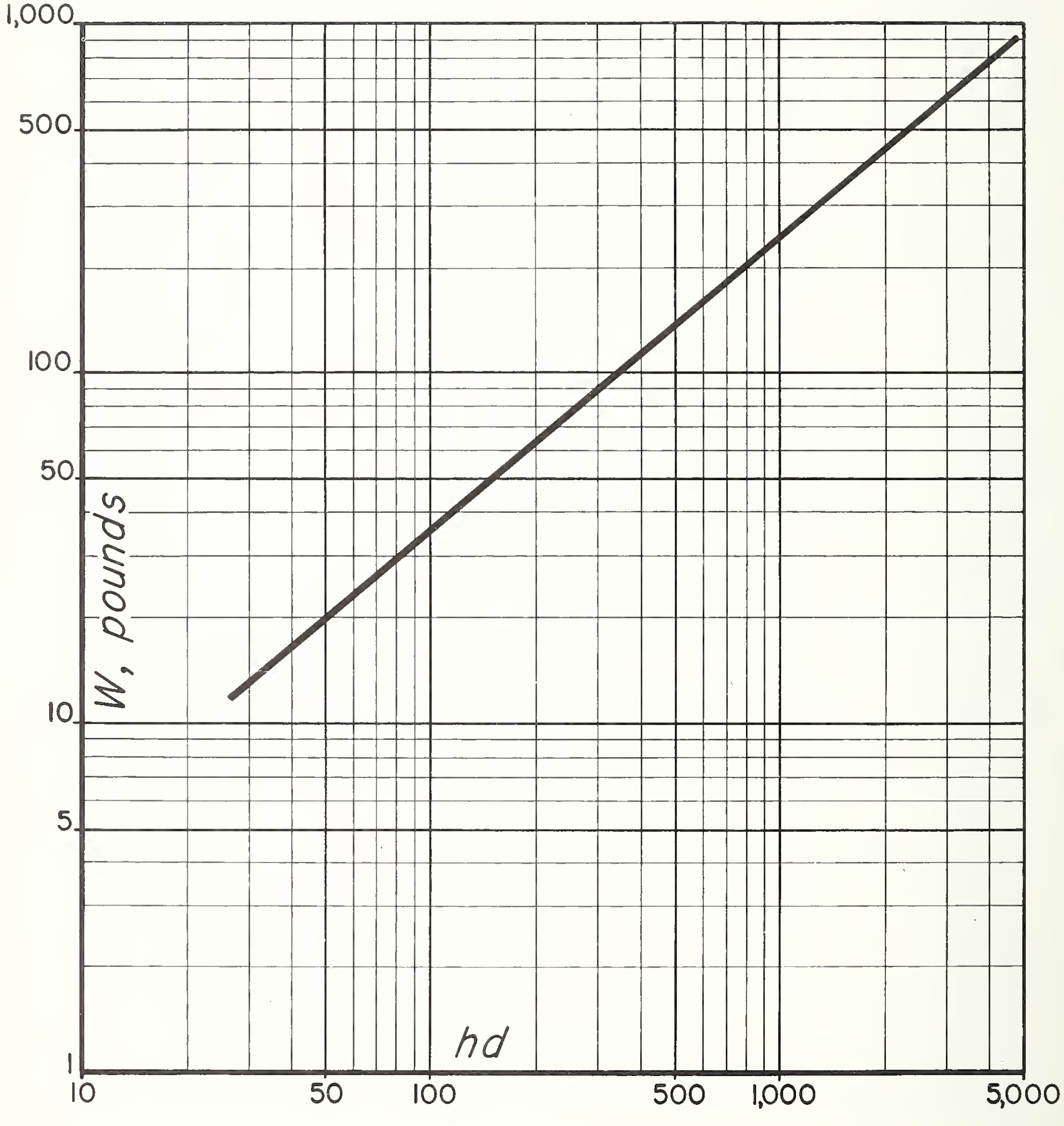

Figure 14. Crawn weight, W, in relatian to the product af d.b.h. and crawn length, hd, for grand fir and western redcedar.

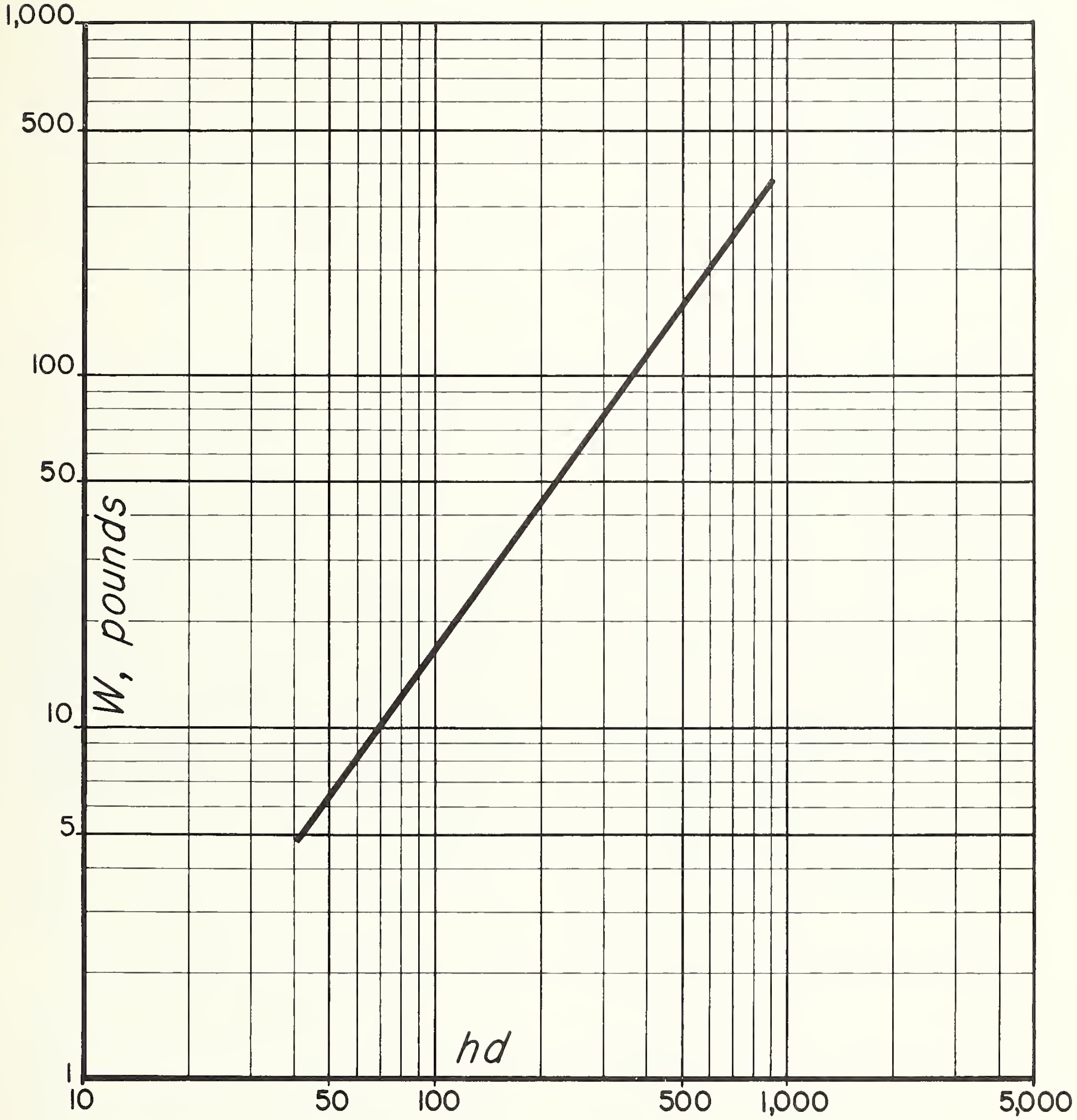

Figure 15. Crown weight, W, in relation to the product of d.b.h. and crown length, hd, for lodgepole pine.

Table 6 gives fiducial limits of the regression values for each species. The probability is only 1 in 20 that calculations based on another sample comprising an equal number of trees would yield predicted values outside these limits. Thus average or total crown weight for a moderate-to-large number of trees can be estimated with reasonable accuracy. For an individual tree, however, actual crown weight may differ greatly from the regression value.

### Crown Length

To estimate crown weight by the method just described, d.b.h. and crown length must be known. D.b.h. is regularly measured in cruising and sometimes in marking, but crown length is not commonly measured and is difficult to obtain. Therefore, an effort was made to learn what general relations might exist between crown length and species, site index, crown class, and stand density. Crown length data were available for the 225 trees used in weight determination. To supplement this information, 1,945 crowns were measured on 40 sample plots in the western white pine, ponderosa pine, and western larch--Douglas-fir types.

Crown length for trees up to 30 inches in diameter bore a linear relationship to d.b.h. Differences among species were unexpectedly small. Statistical comparisons showed that for dominant and codominant trees species could be divided into two groups. Western white pine and the four very tolerant species had significantly longer crowns than the rest; also, their crown length increased more per inch of increase in diameter. For intermediate and suppressed trees the groupings were not so clear cut on purely statistical grounds. Western white pine definitely joined the other intolerant species, however, and hemlock was retained in the tolerant group on the basis of judgment, although it was between the two main groups. Actually small variations in crown length make little difference in crown weight at the small diameters representative of intermediate and suppressed trees. Figure 16 shows the relation of crown length to d.b.h. for all crown classes. For curve A, $h = 7.5 + 3.12d$; for B, $h = 4.0 + 2.60d$, in which h is crown length in feet and d is d.b.h. in inches.

Crown length was expected to vary widely by site index and stand density. The 31 plots in the western white pine type afforded good opportunity to test this hypothesis. Site index at age 50 ranged from 20 to 76, and percent of normal basal area ranged from 38 to 143. Very large differences in site index caused differences in average crown length of western white pine that were statistically significant but too small to affect crown weight appreciably. No significant effect of stand density on crown length was found. The relation of crown characteristics to site and stocking is an interesting subject for further study, but more intensive consideration here would not significantly improve the technique of measuring slash.

### Crown Weight Tables

Figures 13 to 16 inclusive are the basis for constructing a table of crown weight by d.b.h. class and species. Multiplying d.b.h. by the corresponding crown length in figure 16 gives the value hd with which to enter the appropriate graph to obtain crown weight. For example, the entering value for a 24-inch western white pine is $24 \times 82.2 = 1{,}973$, and the corresponding crown weight, from figure 13, is 302 pounds. This process was used to arrive at the crown weight values shown in table 7. Each value is the probable weight of crown for a tree having average crown length for the specified diameter. Though the tabulated value may differ greatly from the actual weight of any given crown, the total weight of a large number of tree crowns should be estimated within reasonable limits by this procedure.

Data collected were inadequate for construction of a reliable crown weight table for intermediate and suppressed trees. Applying figures for dominants and codominants to all trees is not likely to introduce serious overestimates in most instances, since relatively few intermediate and suppressed individuals are harvested. Incidental slash, i.e., that broken from residual trees, which cannot be estimated accurately, probably will more than compensate for overestimates.

### A Warning

Use of estimated average crown length in estimating crown weight is not defensible statistically. A second error of estimate is superimposed on the first (table 6), and the total error

Table 6.--Fiducial limits of regressions of crown weight on the product of crown length and d.b.h.

| Species | No. trees sampled | Fiducial limits, percentage of regression value | |
|---|---|---|---|
| | | 10-inch trees | 30-inch trees |
| Western white pine | 31 | +13.5 to -11.0 | +13.9 to -12.2 |
| Lodgepole pine[1] | 51 | +13.9 to -12.3 | +20.0 to -16.4 |
| Ponderosa pine | 14 | +20.2 to -16.9 | +21.5 to -17.6 |
| Western redcedar | 17 | +18.6 to -15.6 | +21.6 to -17.8 |
| Douglas-fir | 23 | +9.9 to -9.1 | +11.3 to -10.1 |
| Western hemlock | 15 | +9.2 to -8.4 | +12.0 to -10.8 |
| Engelman spruce | 20 | +9.2 to -8.4 | +12.0 to -10.8 |
| Grand fir | 18 | +18.6 to -15.6 | +21.6 to -17.8 |
| Western larch | 36 | +12.6 to -11.3 | +13.0 to -11.5 |

[1] For lodgepole only, the limits are for 8- and 18-inch trees.

of estimate is not known. Since crown length varies with site index and stand health, and probably other factors as well, application of average figures to any given stand may result in large errors. To estimate crown weights with reasonable accuracy, enough crown lengths should be measured to determine whether the averages given here apply, and to construct a new curve of crown length on diameter if they do not. The next step is to calculate new values of crown length X d.b.h. for each d.b.h. class, enter figures 13 to 15 with these values, and find corresponding crown weights.

The curves of crown length on d.b.h. and the mean crown weights estimated by use of these curves provide bases for comparison. They also can be used as they are when crown length data are not available for a stand, a deficiency that is likely to be common until the value of calculating slash quantity within measurable limits of accuracy is generally realized. *Any objective method of calculating slash quantity is vastly superior to the guesswork used heretofore.* However, the goal should be to obtain measurements of crown length for individual stands during cruising or marking.

## PREDICTION OF SLASH QUANTITY

Inability to measure slash quantity has been the main hindrance to realistic appraisal of flammability on cutover forest areas. The preceding discussion provides means for removing this obstacle. Similar methods can be used to predict slash weight that is expected to result from cutting certain specified trees or total crown weight per acre of stands of given age, site index, and density. Both types of calculations are described below.

### Slash Weight from a Prescribed Cut

Accurate prediction of slash weight per acre is possible when a record is made of each tree marked. A summary tabulation is made by listing the number of trees in each species by d.b.h. classes and reducing tree numbers to a per-acre basis. Then the number of trees in each class is multiplied by the appropriate value from table 7. Table 8 shows such a calculation for a hypothetical 160-year-old western white pine stand on an excellent site in which a re-

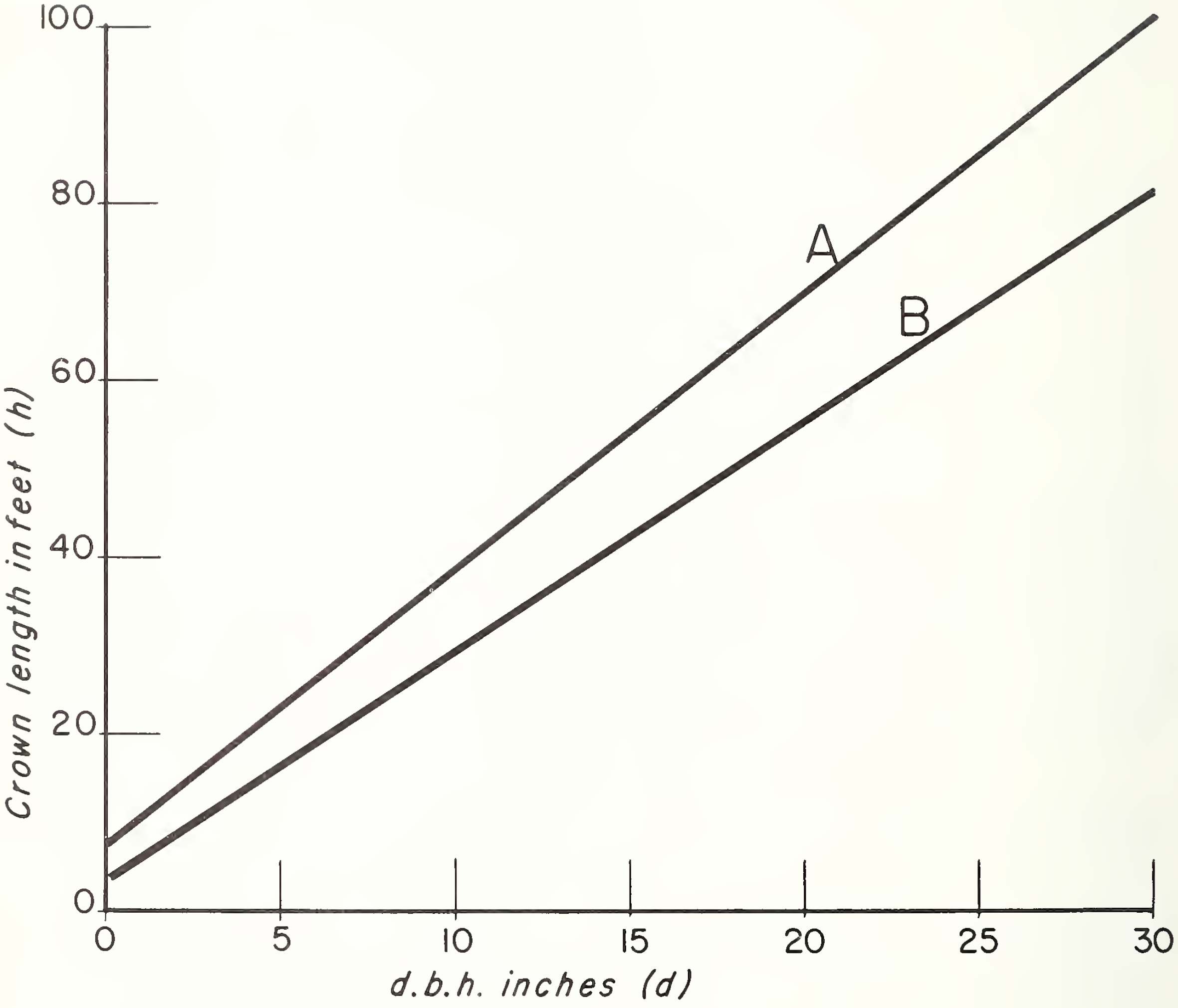

Figure 16. Crown length in relotion to d.b.h. for nine species of northern Rocky Mountain trees. Curve A represents western white pine, western redcedor, western hemlock, Engelmonn spruce, and grond fir; curve B represents lodgepole pine, ponderosa pine, Douglas-fir, and western larch.

Table 7. Crown weights of dominant and codominant trees by species and d.b.h. class

| D.b.h. class *(inches)* | Weight of live crown *(pounds)* | | | | | | |
|---|---|---|---|---|---|---|---|
| | Western white pine | Lodgepole pine | Ponderosa pine | Douglas-fir | W. hemlock E. spruce | W. redcedar Grand fir | Western larch |
| 2 | 3 | 2 | 7 | 5 | 7 | 13 | 3 |
| 4 | 10 | 7 | 23 | 15 | 22 | 28 | 10 |
| 6 | 19 | 20 | 48 | 31 | 43 | 52 | 21 |
| 8 | 32 | 42 | 82 | 54 | 72 | 79 | 36 |
| 10 | 48 | 75 | 126 | 84 | 108 | 110 | 55 |
| 12 | 68 | 120 | 178 | 118 | 152 | 145 | 77 |
| 14 | 91 | 178 | 237 | 157 | 203 | 184 | 103 |
| 16 | 116 | 256 | 310 | 205 | 260 | 226 | 134 |
| 18 | 144 | 353 | 391 | 259 | 324 | 270 | 170 |
| 20 | 177 | 464 | 478 | 317 | 397 | 320 | 207 |
| 22 | 212 | 596 | 574 | 381 | 475 | 371 | 249 |
| 24 | 251 | 776 | 684 | 454 | 564 | 427 | 297 |
| 26 | 293 | -- | 804 | 533 | 656 | 483 | 348 |
| 28 | 339 | -- | 927 | 615 | 760 | 545 | 402 |
| 30 | 387 | -- | 1,060 | 702 | 867 | 607 | 459 |
| 32 | 426 | -- | 1,187 | 786 | 955 | 658 | 514 |
| 34 | 470 | -- | 1,307 | 866 | 1,053 | 712 | 566 |
| 36 | 507 | -- | 1,416 | 938 | 1,136 | 759 | 613 |
| 38 | 540 | -- | 1,520 | 1,007 | 1,211 | 800 | 659 |
| 40 | 574 | -- | 1,619 | 1,073 | 1,287 | 840 | 702 |

Note: Values below heavy line are outside the range of data used in calculations.

Table 8.--Sample prediction of slash weight per acre in a 160-year-old western white pine stand

| D.b.h. class (*inches*) | Western white pine | | Western redcedar | | Grand fir | | Western larch | | All species | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Number trees | Total weight | Number trees | Total weight | Number trees | Total weight | Number trees | Total weight | Total trees | Total weight |
| | | *Pounds* | | *Pounds* | | *Pounds* | | *Pounds* | | *Pounds* |
| 8 | 5 | 160 | -- | -- | 3 | 237 | -- | -- | 8 | 397 |
| 10 | 6 | 288 | 5 | 550 | 3 | 330 | -- | -- | 14 | 1,168 |
| 12 | 8 | 544 | 8 | 1,160 | 2 | 290 | 3 | 231 | 21 | 2,225 |
| 14 | 9 | 819 | 11 | 2,024 | 2 | 368 | 4 | 412 | 26 | 3,623 |
| 16 | 8 | 928 | 6 | 1,356 | 2 | 452 | 4 | 536 | 20 | 3,272 |
| 18 | 6 | 864 | 3 | 810 | 2 | 540 | 4 | 680 | 15 | 2,894 |
| 20 | 5 | 885 | 2 | 640 | 2 | 640 | 2 | 414 | 11 | 2,579 |
| 22 | 4 | 848 | -- | -- | 2 | 742 | 2 | 498 | 8 | 2,088 |
| 24 | 3 | 753 | -- | -- | 2 | 854 | -- | -- | 5 | 1,607 |
| 26 | 2 | 586 | -- | -- | -- | -- | 1 | 348 | 3 | 934 |
| 28 | 1 | 339 | -- | -- | 1 | 545 | -- | -- | 2 | 884 |
| 30 | 1 | 387 | -- | -- | 1 | 607 | 1 | 459 | 3 | 1,453 |
| Total | 58 | 7,401 | 35 | 6,540 | 22 | 5,605 | 21 | 3,578 | 136 | 23,124 |

generation cut is to be made favoring pine. Approximately 60 percent of the pine volume in trees 14 inches d.b.h. and over is to be removed plus nearly all merchantable trees of other species. The dominant residual stand per acre will consist of 25 white pine, two redcedar, and two larch more than 14 inches in diameter. It is assumed that all trees 8 inches and larger can be utilized either for pulpwood or poles, but 18 cedar 8 to 11 inches d.b.h. are left for value increment. Total calculated weight of slash per acre is 11.6 tons. This amount of slash produces very high flammability.

Most oldgrowth stands contain numerous trees larger than 30 inches in diameter. Too few of these large trees were measured to permit determination of a crown length—d.b.h. relation. For the present, on-the-spot measurement of a representative number of crowns must be made to provide the necessary information. This can be accomplished when heights are checked by Abney level during cruising or marking. Then diameter can be used in conjunction with the appropriate curve from figure 13, 14, or 15 to obtain crown weight.

Approximate slash weight per acre can be calculated if number of trees of each species to be cut and their average diameters are known. Crown weight for the tree of average d.b.h. in each species is multiplied by the number of trees per acre that will be cut. The accuracy of this method is unknown; it probably varies considerably with species and tree size. For the example given in table 8, use of average d.b.h. and number lowers the estimate of slash weight per acre by 9 percent. By species, the underestimate varies from only 1 percent for western redcedar to 16 percent for western white pine.

Expected distribution of slash on large areas can be mapped approximately in the office if tallies are kept separate by timber type or other appropriate land subdivision. Slash distribution maps show where slash disposal is needed to reduce hazard to a favorable level. Map presentation of slash concentrations with respect to improvements, roads and natural firebreaks, high risk areas, and topographic features can help in determining the location, method, intensity, and cost of slash disposal and extra protection.

### Total Crown Weight Per Acre

In clear cuttings to a low diameter limit (e.g., lodgepole pine pulpwood cuts), virtually the total crown weight per acre becomes slash. Even where lighter cuts are to be made, advance consideration of the potential maximum slash tonnage has some value. The relation of crown weight to forest type, site, age, and stand density may also be interesting to tree physiologists and students of forest influences. To get an indication of these relations, total crown weight per acre was calculated for the 40 plots used in crown length determinations, for four additional plots in older age classes, and for a lodgepole pine stand in central Montana. Some of these findings are summarized in table 9.

Information from many more plots is needed before a clear relation can be shown for the response of crown weight per acre to the various factors affecting it. At present, enough data pertaining to 60- to 80-year-old western white pine stands are available to indicate what may be expected. Statistical tests on these data showed that total crown weight was correlated significantly with number of tolerant stems larger than 3 inches d.b.h. and with stand density expressed as percent of normal basal area, but not with site index. The absence of correlation with site index was surprising and will bear further investigation. Apparently the most useful relation is found with stand density, which can be expressed by the equation $W=0.143\ A$, where W is crown weight in tons per acre and A is basal area expressed as percent of normal. Thus a given increase in basal area results in a proportional increase in crown weight. Departures from this rule appear to result primarily from variation in the number of tolerant stems large enough to contribute significantly to total crown weight. The number and size of these stems vary with age and average diameter of the stand; hence the relation is rather difficult to interpret.

Some idea of the effect of age was obtained by a theoretical calculation based on Haig's and Meyer's stand tables for western white pine and ponderosa pine, respectively (*14, 26*). Crown weights per acre were calculated for pure stands at 20-year intervals up to 160 years.

The calculated weights were not very consistent, especially for younger stands, probably

Table 9.--Total crown weights per acre for five major species on sample plots in Idaho, Montana, and northeastern Washington

| Forest type | Location | Age | Site | Density (percent of normal) | Weight |
|---|---|---|---|---|---|
| | *County* | *Years* | | | *Tons/acre* |
| Western white pine | Shoshone (Idaho) | 62 | 43 | 134 | 24.4 |
| | Shoshone | 67 | 40 | 101 | 9.6 |
| | Bonner | 67 | 54 | 38 | 5.3 |
| | Bonner | 95 | 62 | 136 | 18.3 |
| | Shoshone | 107 | 59 | 111 | 18.8 |
| | Shoshone | 107 | 55 | 82 | 11.7 |
| | Clearwater | 130 | 60+ | 83 | 13.5 |
| | Clearwater | 150 | 70 | 71 | 15.3 |
| | Kootenai | 170 | 65 | 65 | 14.0 |
| Western redcedar | Bonner | 87 | -- | -- | 26.0 |
| Douglas-fir | Bonner | 90 | -- | -- | 18.7 |
| Ponderosa pine | Pend Oreille (Wash.) | 90 | III | 52 | 12.0 |
| | | 110-125 | IV | 50 | 11.0 |
| Lodgepole pine | Meagher (Mont.) | 200+ | -- | -- | 9.7 |

because no method was available to account for the lighter crowns of intermediate and suppressed trees. However, total crown weight per acre appeared to become constant at 60 to 80 years for both species. Total weight for site 100 (100 years) ponderosa pine was calculated to be approximately 25 tons per acre. The corresponding value for site 60 (50 years) western white pine is 17 tons per acre. The occurrence of heavy-crowned, tolerant species in mixture with white pine conceivably could result in almost doubling the above figure, which is for pure white pine.

### Slash Weight Per M Bd. Ft.

In lieu of a more satisfactory method of measurement, slash is usually appraised in terms of timber volume cut per acre. Olson and Fahnestock have shown, however, that quantity of slash varies with species and size of tree (*29, 31*). Olson's figures were based on slash volume. This section shows the relationship of slash weight per M bd. ft., Scribner rule, to size of tree for trees from 8 to 30 inches in diameter.

A total-height-on-diameter curve was constructed for each species or group of similar species, based on heights of the same trees for which crown lengths were measured. Tree volume at each d.b.h. was determined by use of the height curve and Haig's volume tables (*14*). Crown weight per M bd. ft. was determined by dividing crown weight by $\frac{\text{tree volume,}}{1,000}$ as shown in figure 17.

Crown weight, hence slash weight, per M bd. ft. at any d.b.h. depends on tree height and form class, crown characteristics, and utilization. Since western white pine usually is tallest for its diameter, tapers very gradually, is most completely utilized, and has the lightest crown of any species, slash weight per M bd. ft. is low--only 250 to 300 pounds for trees 18 inches d.b.h. and larger. Western larch, though similar to white pine in height and form, has thick bark and is utilized less fully. Therefore, slash weight per M bd. ft. is relatively high in the smaller diameters but approximates that for white pine in trees 24 inches d.b.h. and larger. The high and nearly constant weight per M bd. ft. found for lodgepole pine is surprising for a tree commonly considered to have a small crown. It appears to be caused by (1) the very heavy crown of lodgepole in relation to d.b.h. and crown length and (2) the slight variation in height among trees of merchantable size.

Figure 17 emphasizes clearly the effect of large numbers of tolerant trees on slash quantity. Western redcedar, western hemlock, grand fir, and Douglas-fir all produce from two to five times as much slash per M bd. ft. as the western white pine, with which they are commonly associated. The ratio is lowest for big, sound trees; it increases greatly when cull is heavy, as usually occurs in old-growth tolerant stands. Obviously weight of slash per M bd. ft. also is multiplied when tolerant understory trees are harvested or are broken in logging the overstory. Thus, cutting 2,000 feet of cedar poles per acre having an average d.b.h. of 12 inches would produce the same amount of slash as cutting 10,000 feet of western white pine 16 inches and larger.

## CALCULATING RELATIVE SLASH DISPOSAL COSTS

Once the decision is made that slash disposal is needed, quantity of slash is the chief measure of the physical job to be done and hence the cost if hand methods are to be employed. Collections for slash disposal per M bd. ft., therefore, should reflect the quantity of slash anticipated. Usually, however, little change in collections is made from one species and average tree size to another. The chief reason, perhaps, has been lack of the information incorporated in figure 17. Table 10 expresses this information as multiples of a standard quantity of slash, or of the cost of treating this quantity. The standard used is slash weight per M bd. ft. of western white pine 16 inches and larger.

Table 10 can be used in two ways. Direct use would simply assign slash disposal rates per thousand in proportion to the appropriate slash weight factor. Thus if $1.00 per M were considered adequate for disposal of slash from mature western white pine, the rate for cedar poles averaging 14 inches d.b.h. would be $3.30. On the other hand, if different rates are considered undesirable, a justifiable average rate for an area can be arrived at by prorating the slash weight factor according to relative volume cut. For example, assume that the year's cut in the western white pine type is expected to include:

| | **D.b.h. (inches)** | **Percent** |
|---|---|---|
| Western white pine | 16+ | 30 |
| Cedar poles | 12 | 10 |
| Tolerant species | 22 | 40 |
| Lodgepole pine | 12 | 5 |
| Western larch | 20 | 15 |

Then the average, or over-all, slash weight factor would be calculated as follows:

| | | | | | |
|---|---|---|---|---|---|
| Western white pine | 1.0 | X | 0.30 | = | 0.30 |
| Cedar poles | 5.6 | X | .10 | = | .56 |
| Miscellaneous species | 2.5 | X | .40 | = | 1.00 |
| Lodgepole pine | 3.4 | X | .05 | = | .17 |
| Western larch | 1.5 | X | .15 | = | .22 |
| Mean | | | | | 2.25 |

Thus if $1.00 per M would provide for satisfactory disposal of white pine slash, the flat rate for all species would need to be $2.25.

Actually the problem is more difficult than these illustrations show: the cost of hand disposal is affected by terrain, travel, time, and other factors. Nevertheless, the slash weight factors appear to be the best available indicators of the cost of treating slash by hand methods.

Machine treatment of slash depends much less on slash quantity than does hand treatment. Slope steepness, number of residual stems per acre, and quantity of brush and down timber may be more important than slash weight. Consequently, estimates of needed slash disposal collections are based on average cost per acre for similar jobs. Perhaps the accuracy of these estimates can be improved if approximate slash weight per acre is known. As yet, there has been no opportunity to find out.

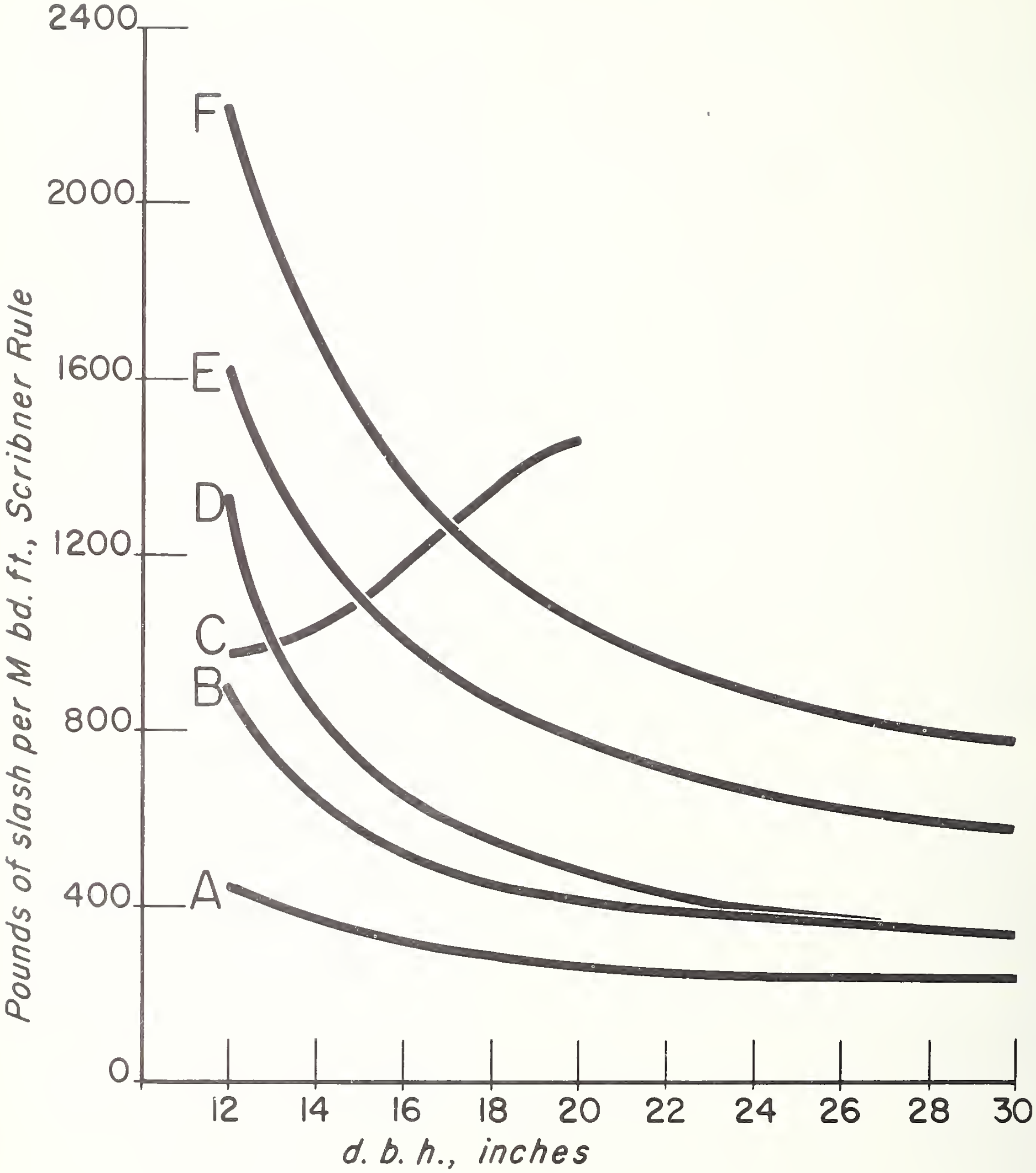

Figure 17. Relation of crown weight to gross board-foot volume by d.b.h. classes. (A) western white pine; (B) western larch, (C) lodgepole pine, (D) grand fir, (E) Engelmann spruce, (F) ponderosa pine. Douglas-fir, western redcedar, and western hemlock fall between (D) and (E).

Table 10. Relative quantities of slash per M. bd.ft. resulting from cutting stands of different species and average sizes

| Species | Slash weight factor, by d.b.h. classes | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 12 | 14 | 16 | 18 | 20 | 22 | 24 | 26 | 28 | 30 |
| Western white pine | 1.5 | 1.3 | 1.2 | 1.1 | 1.0 | 0.9 | 0.9 | 0.9 | 0.8 | 0.8 |
| Lodgepole pine | 3.4 | 3.6 | 4.2 | 4.7 | 5.1 | -- | -- | -- | -- | -- |
| Ponderosa pine | 7.7 | 5.8 | 4.9 | 4.1 | 3.7 | 3.4 | 3.1 | 2.9 | 2.8 | 2.7 |
| Western redcedar<br>Douglas-fir<br>Western hemlock<br>Engelmann spruce | 5.6 | 4.2 | 3.5 | 3.0 | 2.8 | 2.5 | 2.3 | 2.2 | 2.1 | 2.0 |
| Grand fir | 4.7 | 2.8 | 2.3 | 1.9 | 1.7 | 1.5 | 1.4 | 1.3 | 1.2 | 1.2 |
| Western larch | 3.2 | 2.2 | 1.8 | 1.6 | 1.5 | 1.4 | 1.3 | 1.3 | 1.2 | 1.2 |

## FIRE SPREAD IN SLASH

A direct measure of flammability was obtained by burning slash experimentally. Fuel bed characteristics were controlled, and weather was selected to give maximum uniformity in burning conditions. Even so, results varied sufficiently to make analysis difficult and the drawing of fine distinctions somewhat hazardous. The major effects of species, quantity, and age of slash could be evaluated, however, and the experimental burnings gave some interesting information about the influence of rising relative humidity on rate of fire spread.

### RESEARCH METHODS

#### Experimental Design

Experimental slash burning was done in the open on a flat area cleared of all other fuels (figs. 2 and 18). Slash of all nine species previously mentioned was cut especially and placed on square, 0.01-acre plots. Three weights per acre, 7.5, 20.0, and 32.5 tons, were selected as representative of what could be expected to result from light, medium, and heavy cutting, respectively, in heavy stands. The slash was scheduled to be burned (1) during the year of cutting, (2) 1 year after cutting, and (3) 5 years after cutting. Four replications were attempted in burning slash of each age, but unfavorable weather reduced the number to two in some instances.

#### Experimental Material

Thrifty dominant and codominant trees were cut to provide slash for experimental burning. Most were 90 to 100 years old. Some western hemlock, Engelmann spruce, grand fir, and western larch trees were older; but, except in ponderosa pine, few limbs were more than 2 inches in diameter. Entire branches were used whenever possible, but some breakage and cutting to facilitate handling were unavoidable. Slash was thoroughly mixed so that each plot received representative amounts of all size classes. Fuel was spread on plots for as complete and uniform coverage as possible. Differences in arrangement and continuity reflected characteristics of the slash itself.

#### Conditions for Burning

Plots were burned in August on days that met the following specifications:

1. Less than 0.2 inch of rain during preceding 5 days
2. No rain in preceding 2 days

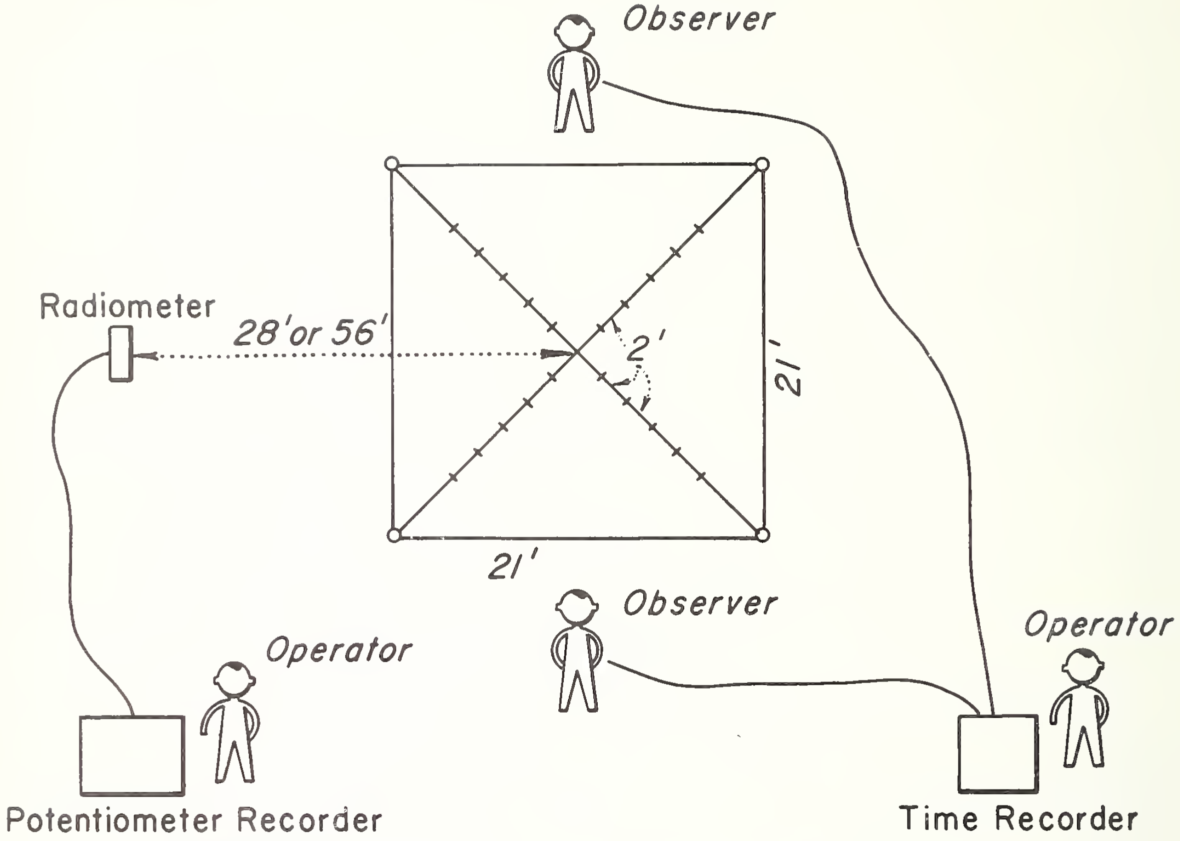

Figure 18. A sample plot ready for burning: **upper,** diagrammatic sketch of plot, personnel, and equipment; **lower,** plot No. 1, with 20 tons per acre of fresh Douglas-fir slash, prepared for ignition.

3. Midafternoon air temperature 70°F. or higher
4. Minimum 1/2-inch fuel-stick moisture content 8 percent or less
5. Minimum relative humidity 40 percent or less
6. Mean wind velocity at time of burning not more than 2 m.p.h.

Most of the slash was burned in the early evening. The rapid increase of relative humidity as temperature declined late in the day was accepted as a lesser evil than the stronger and capricious breezes in midafternoon. Fresh slash with needles attached was burned over a fairly representative range of relative humidity. Because they burned poorly or not at all at high relative humidities, most 7.5-ton plots and some 20.0-ton plots of slash that had lost its needles were burned at low humidities. This resulted in most 32.5-ton plots being burned at higher humidities, since only a few days each year were suitable for burning.

### Burning Procedure

One or two plots of slash were burned at the same time. Plots burned simultaneously or consecutively were separated by at least one cool plot--one that had burned long previously or was yet to be burned. Each plot was ignited at its exact center. Time elapsed following ignition was recorded when the fire edge passed successive markers at 2-foot intervals on four equally spaced radii extending from the plot center. Figure 18 shows a plot ready for burning.

Temperature and relative humidity were recorded twice: when each plot was ignited, and when recording of rate of spread ceased. Total air movement during the same period was measured with a portable, vane anemometer 4 feet above the ground surface about 50 feet from the plot being burned. Supplementary measurements included 1/2-inch fuel-stick moisture at the start and end of each day's burning, and slash moisture content as determined by oven-drying one or two samples from each plot.

The basic records from experimental fires were reduced to terms of seconds required for the fire edge to spread 1 foot radially. An average value was calculated for each plot, and these averages were used in subsequent analyses. The averages were based on from three to 16 time observations for 2-foot segments of plot radii. The six averages based on five or fewer observations were viewed somewhat doubtfully, but they were the best estimates available and appeared sufficiently consistent to be retained and used in analysis. Table 11 summarizes the basic data.

### Analysis

Preliminary exploration of the data disclosed an apparent linear relation between the logarithm of burning time in seconds per foot of radial spread and both relative humidity and tons of fuel per acre (*8, 10*). Furthermore, humidity and weight appeared to affect all species the same. Therefore, the data were subjected to multiple covariance analysis in which the two independent variables were relative humidity and weight per acre, and the dependent variable was the logarithm of burning time.

Separate analyses were made for fresh and 1-year-old slash. In both age groups the effects of both relative humidity and weight were found to be highly significant. The prediction equations are:

$$Y_0 = 1.7742 + 0.004931X_1 - 0.022293X_2,$$

for fresh slash, and

$$Y_1 = 1.8561 + 0.008677X_1 - 0.022522X_2,$$

for 1-year-old slash,

in which Y is the common logarithm of burning time, $X_1$ is relative humidity, and $X_2$ is weight.

Rate of fire spread is commonly given as chains of increase in perimeter per hour. If Y is expressed in these terms, the prediction equations become:

$$Y_0 = 0.7607 - 0.004931X_1 + 0.022293X_2,$$

and

$$Y_1 = 0.6788 - 0.008677X_1 + 0.022522X_2,$$

Statistical comparisons of rates of spread determined experimentally were calculated in terms of burning time but are expressed hereafter as chains per hour to be consistent with fire control usage. Because of the big differences in the effect of humidity, as indicated by the partial regression coefficients, separate prediction equations for the two ages of slash fitted the data significantly better than a single equation covering both ages. Therefore, com-

Table 11.--Results of experimental slash burning, by weight of slash per acre, age, and species, before analysis and adjustment

| Age and species | Weight of slash (tons per acre) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 7.5 | | | 20.0 | | | 32.5 | | |
| | Plots | Range of relative humidity | Mean rate of spread | Plots | Range of relative humidity | Mean rate of spread | Plots | Range of relative humidity | Mean rate of spread |
| Fresh slash: | | | *Seconds per foot* | | | *Seconds per foot* | | | *Seconds per foot* |
| Western white pine | 3 | 58-62 | 80.3 | 3 | 34-86 | 32.3 | 3 | 30-65 | 18.0 |
| Lodgepole pine | 2 | 74-83 | 141.0 | 2 | 84-88 | 48.5 | 2 | 52-64 | 17.5 |
| Ponderosa pine | (1/) | -- | -- | 2 | 60-85 | 71.5 | 2 | 54-91 | 33.0 |
| Western redcedar | 3 | 28-56 | 73.3 | 3 | 36-81 | 52.7 | 3 | 42-73 | 24.3 |
| Douglas-fir | 3 | 33-50 | 64.3 | 3 | 39-72 | 41.3 | 3 | 52-70 | 20.7 |
| Western hemlock | 2 | 51-67 | 87.0 | 3 | 47-74 | 40.7 | 3 | 27-66 | 28.3 |
| Engelmann spruce | - | -- | -- | 3 | 38-74 | 50.0 | 3 | 68-82 | 35.0 |
| Grand fir | 2 | 54-70 | 77.5 | 2 | 60-80 | 51.5 | 3 | 50-94 | 28.7 |
| Western larch | 2 | 76-77 | 67.5 | 2 | 62-68 | 24.0 | 3 | 70-82 | 18.7 |
| All species | 17 | 28-83 | 82.3 | 23 | 34-88 | 45.2 | 25 | 27-94 | 25.7 |
| 1-year-old slash: | | | | | | | | | |
| Western white pine | 3 | 26-90 | 81.7 | 3 | 80-91 | 62.3 | 3 | 71-90 | 26.3 |
| Lodgepole pine | 3 | 28-31 | 120.3 | 4 | 73-92 | 88.8 | 4 | 54-93 | 33.5 |
| Ponderosa pine | 2 | 28-30 | 153.5 | 4 | 66-85 | 129.0 | 4 | 71-83 | 83.8 |
| Western redcedar | 2 | 26-67 | 117.0 | 3 | 34-71 | 52.0 | 3 | 63-82 | 46.0 |
| Douglas-fir | - | -- | -- | 2 | 25-28 | 45.0 | 3 | 61-70 | 70.0 |
| Western hemlock | 2 | 28-30 | 43.5 | 3 | 44-81 | 58.7 | 3 | 64-82 | 74.0 |
| Engelmann spruce | - | -- | -- | 2 | 57-82 | 95.5 | 2 | 72-82 | 57.5 |
| Grand fir | 2 | 30-31 | 130.0 | 4 | 60-78 | 228.7 | 4 | 54-89 | 123.8 |
| Western larch | 1 | 30 | 109.0 | 4 | 64-86 | 215.2 | 4 | 55-87 | 97.5 |
| All species | 15 | 26-90 | 106.9 | 29 | 25-92 | 118.9 | 30 | 54-93 | 70.6 |

1/ Absence of data indicates that plots did not burn sufficiently to provide rate-of-spread measurements. In all, the following plots did not burn:

Fresh, 7.5-ton - - - - - - - 6
1-year-old, 7.5-ton - - - - 9
1-year-old, 20.0-ton - - - - 1

parisons among species were made within age groups. In order to test the effect of age within a species, however, the two groups were combined. The combined prediction equation is:

$$Y_{0+1} = 0.7859 - 0.007259X_1 + 0.021516X_2,$$

with $Y_{0+1}$ expressed in chains per hour. Combining ages affected the adjusted mean rates of spread very little, since the mean relative humidities of the two age groups differed by only 2 percent.

Comparisons between species within ages and between ages within species were made by Scheffe's method (*32*). Results of the comparisons are discussed in subsequent sections.

## EVALUATION OF FACTORS AFFECTING RATE OF SPREAD

### Weight

Quantity of fuel was expected to affect rate of fire spread significantly, but the extent and nature of the effect were not known prior to the experimental burnings. Analysis of the first year's results for only four species indicated that in fresh slash, the effect of weight greatly overshadowed that of species (*8*). This preliminary analysis also indicated that the logarithm of rate of spread bore a straight-line relation to slash tonnage. However, relative humidity was not taken into account.

The present analysis, including all nine species at two ages, has confirmed the effect of weight found previously. The partial regression coefficients of rate of spread on weight, with relative humidity held constant, were 0.022293 and 0.022522 for fresh and 1-year-old slash, respectively. Thus, quantity of slash had the same effect in both ages of slash burned. The partial regression coefficients for weight are identical in the first three decimal places with the gross coefficient found in the earlier analysis.

Obviously fuel quantity consistently affects the rate at which fire spreads. Figure 19 shows that effect for all species of fresh and 1-year-old slash, with relative humidity at the respective means of 62.3 and 64.3 percent. Dashed lines are extrapolations that appear logical although they are outside the range of measured slash quantities burned. A rule of thumb for remembering the effect of slash quantity is that rate of spread increases approximately 6 percent for each ton increase in weight per acre.

### Species

Slash flammability is commonly considered to vary widely by species; foresters' opinions on how to rank the species likewise vary widely. Analysis of the first year's burning records for western white pine, western redcedar, Douglas-fir, and western hemlock failed to show interspecies differences in rate of spread for equal quantities of slash. Wide variation among species in quantity of slash per unit of log scale, coupled with the strong effect of fuel weight on rate of spread, suggests that opinion about relative flammability is based largely on observation of slash quantity. Nevertheless, variation in relative quantity of fine fuel components, shape of branches, persistence of foliage, and durability is sufficiently large that some significant differences among species have been found by the latest analysis.

Table 12 lists adjusted mean rates of spread and interspecies differences in fresh and 1-year-old slash. Values correspond to the all-species averages of 62.3 percent relative humidity and 21.5 tons of fuel per acre in fresh slash, 64.3 percent relative humidity and 22.5 tons per acre in 1-year-old slash. Table 12 shows plainly that species had little influence on rate of spread in fresh slash but was responsible for important variation in 1-year-old slash. Sensitivity of statistical comparisons was low because of the small number of plots supporting each adjusted mean. Examination of the calculations indicates that if about double the actual number of observations had been made, all differences of 2 chains per hour or more would have been found significant. This line of reasoning suggests the following conclusions:

1. In fresh slash, larch supports faster spread, ponderosa pine and spruce slower spread, than the other six species.
2. In 1-year-old slash, white pine supports the fastest spread, followed in order by a lodgepole — redcedar — hemlock group, a ponderosa — Douglas-fir — spruce group, and a grand fir-larch group; these last two groups are quite close together.

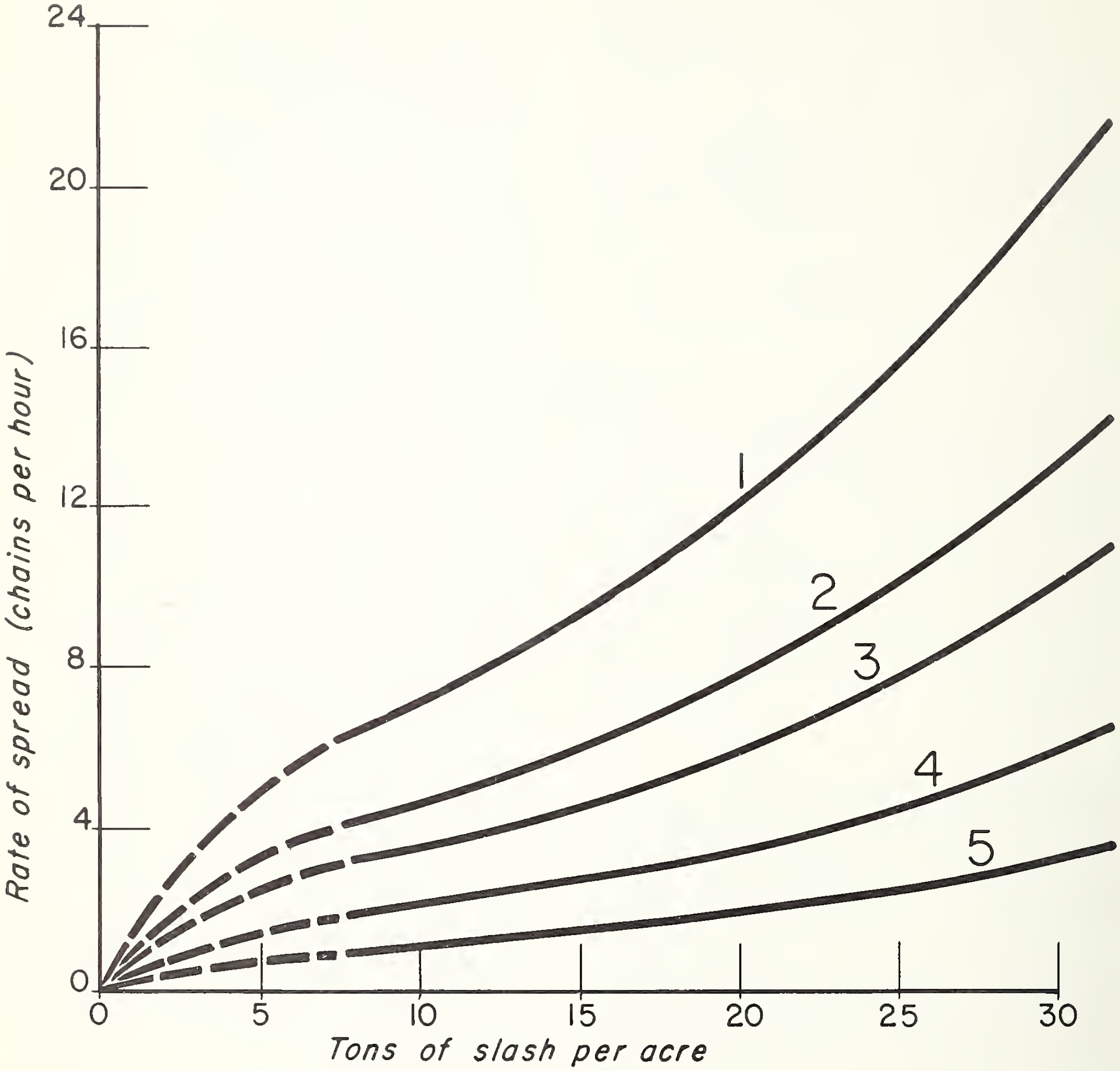

Figure 19. Rate of spread in relation to quantity of fuel by species and age groups. Curve numbers correspond with group numbers in the text.

Table 12.--Adjusted mean rates of spread and interspecies comparisons

*Chains per hour*

Fresh slash

| Species | Adjusted mean rate of spread | Differences between adjusted means 1/ | | | | | | | | | Adjusted mean rate of spread |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | WL | GF | ES | WH | DF | WRC | PP | LPP | WWP | |
| WWP | 9.6 | 3.6 | 1.2 | 3.0 | 1.6 | 0.7 | 1.7 | 3.2 | 1.5 | | 9.7 |
| LPP | 8.1 | 5.1 | .3 | 1.5 | .1 | .8 | .2 | 1.7 | | 3.9 | 5.8 |
| PP | 6.4 | 6.8* | 2.0 | .2 | 1.6 | 2.5 | 1.5 | | 2.5* | 6.4* | 3.3 |
| WRC | 7.9 | 5.3 | .5 | 1.3 | .1 | 1.0 | | 2.5 | 0 | 3.9 | 5.8 |
| DF | 8.9 | 4.3 | .5 | 2.3 | .9 | | 2.4 | .1 | 2.4 | 6.3* | 3.4 |
| WH | 8.0 | 5.2 | .4 | 1.4 | | 2.0 | .4 | 2.1 | .4 | 4.3 | 5.4 |
| ES | 6.6 | 6.6* | 1.8 | | 1.0 | 1.0 | 1.4 | 1.1 | 1.4 | 5.3 | 4.4 |
| GF | 8.4 | 4.8 | | 2.2* | 3.2* | 1.2 | 3.6* | 1.1 | 3.6* | 7.5* | 2.2 |
| WL | 13.2 | | .1 | 2.1* | 3.1* | 1.1 | 3.5* | 1.0 | 3.5* | 7.4* | 2.3 |

One-year-old slash

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1/ (*) Designates differences that are statistically significant.

Observation of how slash burns in the field and comparisons of physical characteristics among species indicate that the above groupings, based entirely on experimental results, may be somewhat unrealistic. Therefore the following regrouping is suggested:

1. Fresh western larch.
2. Fresh western white pine, lodgepole pine, western redcedar, Douglas-fir, western hemlock, and grand fir.
3. Fresh ponderosa pine and Engelmann spruce; 1-year-old western white pine, lodgepole pine, and western redcedar.
4. One-year-old ponderosa pine, Douglas-fir, western hemlock, and Engelmann spruce.
5. One-year-old grand fir and western larch.

Rates of spread for these species groups are shown in figure 19.

A few discrepancies between experimental results and field experience warrant special mention. Although the fastest rates of spread were measured in fresh larch slash, this species is generally considered the least dangerous. High experimental rate of spread in larch probably resulted from (1) presence of much more slash per acre than ever occurs naturally, and (2) compact arrangement of experimental slash which brought fine, dead needles close together and prevented them from falling to the ground as they normally would on cutover areas. Western redcedar burned less spectacularly than would be expected from its usual rating as the worst slash of all. General opinion is influenced by (1) the large quantity of cedar slash per unit of timber volume, (2) the presence (commonly) of large tops, small deadwood, and bark in areas cut for cedar, and (3) the great durability of cedar logging residues. The rather compact arrangement of cedar slash on plots reduced rate of fire spread below what might be expected in wildfires. Ponderosa pine slash also burned slower than had been expected. Possibly the apparent high flammability of ponderosa pine slash on cutover areas is due more to its occurrence on very dry sites and to the fact that it is usually intermixed with grass than to the characteristics of the slash itself.

### Age

Age, or time elapsed since cutting, causes a general reduction in flammability. The degree of reduction varies widely by species (table 13). This variation is an important factor in determining over-all species flammability ratings. A fuel that initially is highly flammable but becomes virtually nonhazardous after one winter obviously concerns foresters much less than one that deteriorates slowly.

Few of the tabulated reductions in flammability are very different from what was expected. Rate of spread in western white pine slash did not drop as much as was anticipated, but one such apparent inconsistency can be considered within the limit of experimental error. The close comparability of lodgepole pine and cedar indicates that the general great respect for cedar slash may be due as much to quantity and long-term durability as to inherently high flammability. Conversely, white pine slash may have been underrated somewhat because there is less of it per unit of timber volume. The big reduction in flammability of ponderosa pine slash is as surprising as the initial relatively low rate of spread in this species; this apparently low flammability may be offset by the long fire season and the very dry conditions typical of ponderosa pine sites.

As expected, rate of spread in Douglas-fir, grand fir, and larch slash dropped spectacularly after the first year because these species lost their needles over winter. The 90-percent reduction in flammability of larch placed this species at the bottom of the scale, where it had been thought to belong prior to the burning experiments. The change observed for Douglas-fir

Table 13.--Effect of aging 1 year on rate of fire spread in logging slash

| Species | Adjusted mean rate of spread[1/] | | Reduction in rate of spread after 1 year[2/] | |
|---|---|---|---|---|
| | Fresh | 1 year old | | |
| | *Chains per hour* | | *Chains per hour* | *Percent* |
| Western white pine | 9.2 | 9.3 | - 0.1 | -1.1 |
| Lodgepole pine | 8.7 | 5.6 | 3.1 | 35.6 |
| Ponderosa pine | 6.9 | 3.2 | 3.7 | 53.6 |
| Western redcedar | 7.7 | 5.8 | 1.9 | 24.7 |
| Douglas-fir | 8.5 | 3.6 | 4.9* | 57.6 |
| Western hemlock | 7.8 | 5.5 | 2.3 | 29.5 |
| Engelmann spruce | 6.9 | 4.7 | 2.2 | 31.9 |
| Grand fir | 8.9 | 2.2 | 6.7* | 75.3 |
| Western larch | 14.0 | 2.3 | 12.7* | 90.1 |

[1/] Based on analysis of data for the two ages combined; hence slightly different from values shown in table 12.

[2/] (*) Indicates change that is statistically significant.

and grand fir does not always occur; occasionally these two species retain much of their foliage through the first winter.

Hemlock and spruce had lost their needles before the first burn; so they showed relatively little reduction in flammability after aging 1 year. One-year-old hemlock slash has been grouped with the other species without needles despite the fact that the rate of spread determined experimentally for it closely approximated rates for lodgepole pine and cedar. Its large quantity of closely spaced, very fine twigs makes 1-year-old hemlock appear more dangerous than other species that have lost their needles, but it is less flammable than species with foliage still attached.

One block of plots, containing four species, was burned after aging 3 years. Results showed the following percentages of reduction in rate of spread:

| | |
|---|---|
| Western white pine | 54 |
| Western redcedar | 71 |
| Douglas-fir | 86 |
| Western hemlock | 82 |

The data were too scanty for analysis and are listed as tentative indications only. Their main value, when taken in conjunction with observations of slash characteristics, is to suggest that:

1. The big reduction in flammability of white pine slash, and probably lodgepole pine as well, comes in the third year.
2. Flammability of cedar slash declines rather steadily during the first 3 years.
3. Flammability of slash that loses its foliage in the first year following cutting declines very slowly after the first year and is of little consequence by the end of 3 years.

### Relative Humidity

Relative humidity was measured in order that its effect might be prevented from obscuring the effects of slash quantity, species, and age. Wind velocity and slash moisture content were recorded for the same reason; but wind velocity was held to a negligible quantity by careful selection of times for burning, and moisture content could not be determined reliably by the few samples obtained. Consequently the only extraneous factor included in the analysis was relative humidity. The values used were those corresponding to the midpoint of the time during which rate-of-spread records were being kept for each plot, as interpolated between psychrometric readings taken before and after each plot was burned.

Relative humidity had a highly significant effect on rate of fire spread. The apparent effect was much greater in 1-year-old slash than in fresh, as indicated by the respective partial regression coefficients, 0.008677 and 0.004931. Figure 20 illustrates this difference. Confounding of relative humidity with species and weight in 1-year-old slash may have caused part of the difference, but the major part appears to be a measure of the relative effect of atmospheric moisture on fire behavior in sparse as compared to abundant fine fuels.

The influence of relative humidity on rate of spread in experimentally burned slash is difficult to interpret. Since relative humidity increased rapidly while plots were being burned, fuel moisture could not reach equilibrium with atmospheric moisture. The behavior of a fire reflected the effect of the increase, over a period from a few minutes to nearly 2 hours, from the rather steady relative humidity of the afternoon to the transitory value determined for each plot.

From the data obtained, it is impossible to ascribe characteristic rates of spread to the various measured relative humidities. However, knowledge of how increasing humidity affected experimental slash fires provides some indication of what can be expected on wildfires and prescribed burns during the transition from afternoon to night. Figure 20 shows how rising humidity affected rate of spread in fresh slash and in 1-year-old slash. This relation prevailed regardless of quantity of fuel per acre. Given comparable weather and fuels, the behavior of any fire might be expected to conform to about the same rules. Wind would reduce the effect of increasing relative humidity and could nullify it completely. Topography would also have a modifying effect peculiar to each locality and existing weather pattern.

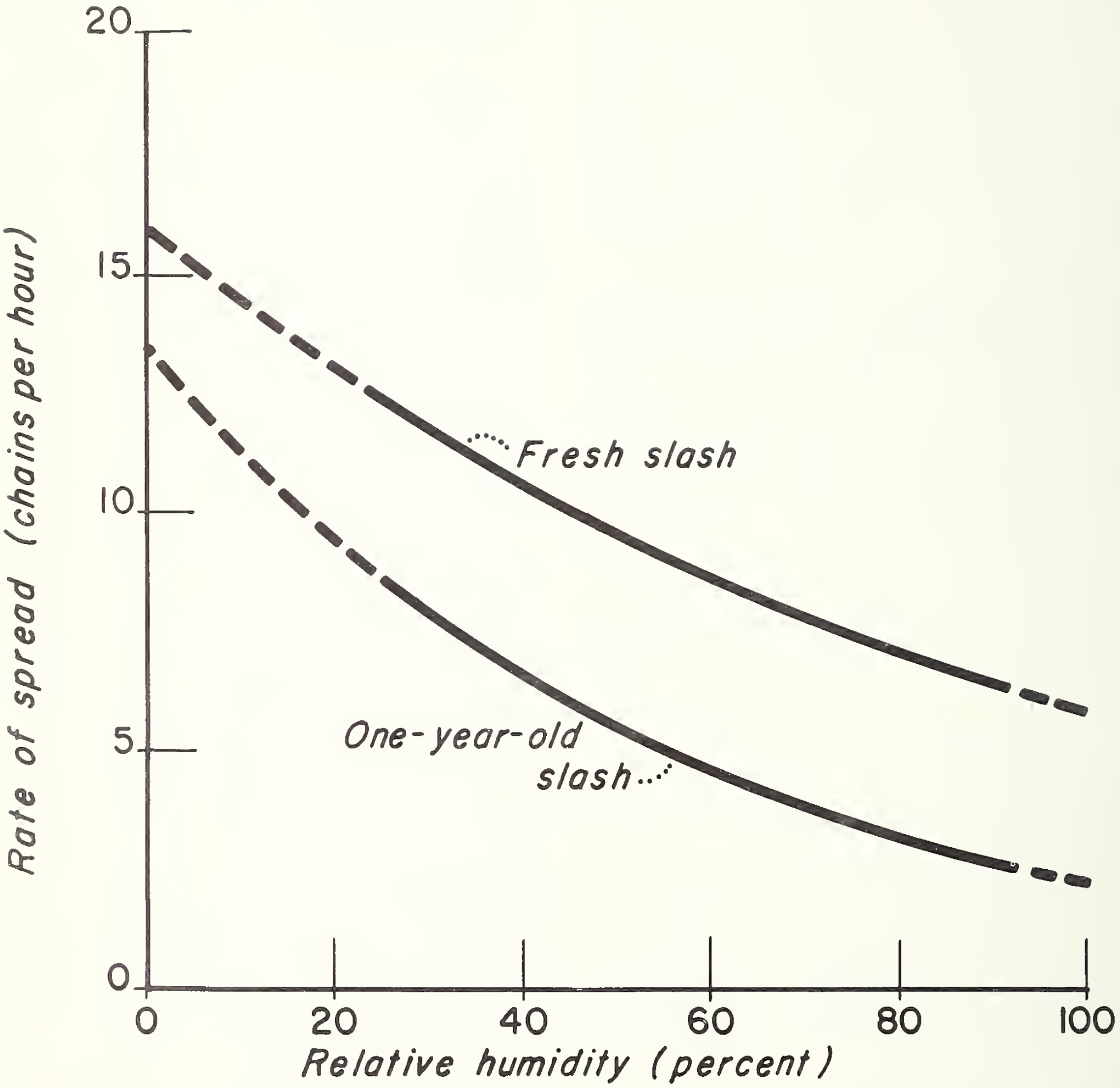

Figure 20. Effect of relative humidity on rate of spread in 20-ton-per-acre slash.

## INTERPRETATION OF FINDINGS ON RATE OF SPREAD

### Evaluation of Relative Flammability

Results of experimental burning, as summarized in figure 19, can be used for rating relative slash flammability to the extent that it is represented by rate of fire spread. A logical starting point is rate of spread for the most hazardous fuel at the probable maximum quantity per acre. If the high rate of spread in larch slash is discounted as being due to artificiality in the experiment, western white pine and its associates in Group 2 (fig. 19) emerge as the most dangerous. For calculating relative flammability, probable maximum quantity of available fine fuel per acre may be postulated as 25 tons. By coincidence, rate of spread of species in Group 2 corresponding to 25 tons per acre is 10 chains per hour, a convenient figure on which to base comparisons. Relative rate of spread, on the basis of 10 = probable maximum, can be read directly off the curves in figure 19 for any species or group and quantity of fresh and 1-year-old slash. A combination of species, with measured quantities for each, can be given a composite rating by the following procedure (refer to table 14):

1. Determine total weight of slash per acre (refer to MEASURING SLASH, pages 00 to 00) and percent of this total represented by each species as in "Tons per acre" and "Percent of total" columns under "Quantity" table 14. Total these columns.
2. From figure 19 record the factor for each species and age represented corresponding to the *total* tons per acre of slash for all species (20 T/acre in table 14); e.g. for fresh western white pine (Group 2) the factor taken from the curve directly above the 20 T/acre mark is 8.
3. Multiply the individual factors determined in step 2 above by their respective percentages from 1 above to get individual proportional ratings.
4. Sum the proportional rating product for fresh slash and for 1-year-old slash.
5. These totals are the proportional ratings on the basis of 10 = probable maximum. In the example (table 14) the flammability of the slash is 86 percent of the probable maximum while fresh, only 44 percent at the end of a year.

Table 14.--Sample calculation of relative rate-of-spread ratings for a combination of species and quantities of slash

| Species | Quantity | | Rate-of-spread rating | | | |
|---|---|---|---|---|---|---|
| | | | Fresh slash | | 1 year-old slash | |
| | Tons per acre | Percent of total | Factor | Proportional rating | Factor | Proportional rating |
| Western white pine | 5 | 25 | 8 | 2.0 | 6.2 | 1.6 |
| Western redcedar | 4 | 20 | 8 | 1.6 | 6.2 | 1.2 |
| Douglas-fir | 2 | 10 | 8 | .8 | 3.6 | .4 |
| Western hemlock | 4 | 20 | 8 | 1.6 | 3.6 | .7 |
| Grand fir | 2 | 10 | 8 | .8 | 2.0 | .2 |
| Western larch | 3 | 15 | 12 | 1.8 | 2.0 | .3 |
| Total | 20 | 100 | | 8.6   8.6 = Rating for area = 4.4 | | |

## Slash as a Fuel Type

Up to this point, discussion of actual rates of fire spread in slash has been avoided deliberately, but values are available in figure 19. Because the artificialities of the burning experiment were recognized, expression of flammability in relative terms appears to have more value. However, comparison of rates of spread in experimental slash with those that have been determined for fuels occurring naturally cannot and should not be neglected completely. This section attempts to interpret what happened on the experimental plots in terms that are familiar to foresters and fire control men.

A major obstacle to generalizations from results of experimental burning is the fact that slash on the plots had been distributed artificially. In the cutover forest such uniform distribution, both horizontal and vertical, would never be found. Unfortunately the effect of fuel arrangement (vertical) and continuity (horizontal) has never been measured satisfactorily. Barrows (*3*) and others have tried to express the effect of continuity but have not provided numerical values to represent their estimates. For slash the best assumption appears to be that the uniformity existing on the experimental plots adequately represents all other arrangements. Very large gaps in body of slash would result in the scattered islands of bad fuel being considered as separate concentrations, each to be rated on its own merits. During severe fire weather, spotting between rather widely separated concentrations occurs commonly and the resulting rate of spread may equal or even exceed that in continuous slash. Therefore the uniform fuel bed, which can be reproduced at will and visualized uniformly by everybody, is the best premise on which to base calculations.

A second difficulty in generalizing from the results of experimental burning is that in a forest some fuel besides slash is always present. For present purposes it is assumed that this "natural" fuel is a "low" rate-of-spread type. Barrows (*4*) indicates that average rate of spread in the "low" type is 2.5 chains per hour at Burning Index 40, the approximate average Burning Index that prevailed while the experimental slash plots were being burned. The further assumption is made that rates of spread measured on the plots would be increased in cutover areas by the rate characteristic of associated natural fuels. Therefore, to find the position of slash of different descriptions with respect to classified fuel types, 2.5 chains per hour are first added to the values shown in figure 19. The adjusted values are then compared with average rates of spread for northern Rocky Mountain fuel types. Table 15 classifies fresh and 1-year-old slash on this basis by species and quantity per acre.

Obviously the methods used in deriving table 15 are somewhat arbitrary. Nobody is sure at this time just how combining two dissimilar fuels affects rate of spread. However, it appears certain that fire would have spread through plots that did not burn if a duff-and-litter layer had been present. It appears equally certain that addition of even very small amounts of better aerated fuels would increase rate of spread roughly in proportion to the quantity of the additional fuel. Table 15 is the best available estimate of the resultant rates until more precise information becomes available.

The slash rate-of-spread type ratings in table 15 were derived directly from experimental results without application of judgment beyond that which led to grouping the species. Experience indicates that some of these ratings are probably too high, others too low. For example, fresh western larch slash almost certainly is rated too high, while redcedar, particularly 1-year-old and older, appears underrated. Like the general fuel-type ratings, those proposed for slash are suggested as guides to judgment, not substitutes for it. Local conditions must be considered, such as variations in weather patterns due both to climatic differences and topography. These variations commonly affect slash characteristics and especially slash deterioration with age. If table 15 is taken only as a rough guide, it can be useful; if taken as a precise measure of fuel type, it may cause confusion.

Apparently slash was seriously underrated by the U. S. Forest Service, Region 1, fuel type classification system developed in the 1930's (*42*). Of 19 fuel types involving recently cutover areas, only three were given an "Extreme" rate-of-spread rating, and two were actually rated "low." Table 15 shows no fresh slash in volumes greater than 4 tons per acre in any cate-

Table 15.--Equivalents of U.S. Forest Service rate-of-spread types for Montana and Idaho by species, quantity, and age

| Species | Rate-of-spread type | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Low and medium | High | Extreme | Flash | Low and medium | High | Extreme | Flash |
| | Fresh slash | | | | 1-year-old slash | | | |
| | Tons per acre | | | | | | | |
| Western white pine | <2 | 3-7 | 8-17 | >17 | <2 | 3-12 | 13-22 | >22 |
| Lodgepole pine | <2 | 3-7 | 8-17 | >17 | <2 | 3-12 | >12 | [1] -- |
| Ponderosa pine | <2 | 3-12 | 13-22 | >22 | <3 | 4-22 | >22 | -- |
| Western redcedar | <2 | 3-7 | 8-17 | >17 | <2 | 3-12 | 13-22 | >22 |
| Douglas-fir | <2 | 3-7 | 8-17 | >17 | <3 | 4-22 | >22 | -- |
| Western hemlock | <2 | 3-7 | 8-17 | >17 | <3 | 4-22 | >22 | -- |
| Engelmann spruce | <2 | 3-12 | 13-22 | >22 | <3 | 4-22 | >22 | -- |
| Grand fir | <2 | 3-7 | 8-17 | >17 | <7 | >7 | -- | -- |
| Western larch | <1 | 2-4 | 3-9 | >9 | <7 | >7 | -- | -- |

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[1] Blanks indicate that slash of species concerned does not occur in sufficient quantity to fall into indicated rate-of-spread type.

gories except "High," "Extreme," and "Flash." Apparently preoccupation with huge, unbroken expanses of bad fuels in old burns prevented adequate recognition of fuels as bad as or worse on smaller areas. *Evidence from both analysis of wildfires*[3]*and experimental slash burning indicates that henceforth slash should be recognized as an "Extreme" rate-of-spread type.*

## INTENSITY OF SLASH FIRES

Intensity is as important a characteristic of fire as rate of spread. Some fires spread very rapidly and grow large without causing much damage or being especially hard to control. Others, spreading at the same rate or slower, become unapproachable infernos. Usually the prime requisite for the occurrence of high-intensity fires is an abundant supply of finely divided, available fuel. Logging slash, particularly fresh logging slash, provides such fuel. Therefore information about the intensity of small experimental slash fires indicates what intensities might be expected when large volumes of slash burn uncontrolled.

Intensities of experimental fires were assessed chiefly by observing height and movement of flames and by measuring radiated heat. In addition, completeness of combustion, a further indicator of fire intensity, was determined for representative plots. Observations of flame characteristics were augmented by both still photographs and time-lapse movies. The preliminary analysis of fire intensity data thus far completed provides a measure of relative intensities of fires in fresh and 1-year-old slash as affected by species and quantity. Full-scale analysis of data on heat radiation in conjunction with measurements of flame area and convection column speed, obtainable from movies taken simultaneously, is expected to add significantly to the scanty existing knowledge of the heat budget of free-burning fires in dangerous fuels.

### FLAME CHARACTERISTICS

Because of the virtual absence of wind, each experimental slash fire tended to spread outward rather uniformly in all directions from the ignition point except where restricted by voids in the fuel bed. Immediately after ignition the flames roughly formed a cone that increased in height as long as all fuel within the periphery of the fire was burning actively. When fuel near the center of the burning area became depleted, the fire broke down into a ring of flames usually about half the maximum height of the earlier cone. The cone was most distinct and reached its greatest diameter in heavy concentrations of slash, especially if foliage was present. A strong central convection column and intense radiation from the entire burning area persisted after the flames had retreated from maximum height, sometimes until the fire reached the plot boundaries. In lighter concentrations of fuel, the cone was less well-developed and often short lived. Radiation from within the subsequent ring of flames was slight, and convection was weak and diffuse.

Height of flames varied greatly with quantity and type of fuel. On 7.5-ton plots of slash without needles, flames usually were less than 1 foot high, flaring higher only at an occasional cluster of fine twigs. At the opposite extreme, maximum heights of 15 to 20 feet were attained by flames on 32.5-ton plots of slash with needles attached. These heights surprised observers because mean depth of fuel seldom exceeded 1.5 feet, and wind speed was near zero. Fresh western white pine, lodgepole pine, and Douglas-fir slash burned with the highest flames and with apparently the greatest intensity. Flames from 1-year-old white pine and lodgepole slash were quite similar to those from fresh slash, but 1-year-old slash of other species burned with much lower flames than fresh slash. Figures 21, 22, and 23 show how flame size was affected by slash characteristics.

Detached ignitions, or flashes, occurred rather commonly in the convection columns above the hottest fires. Flashes result from de-

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[3] In testing an experimental rate-of-spread computer during 1951 and 1952 the author found that fires in slash areas consistently spread at rates characteristic of "Extreme" fuels for existing weather conditions.

layed ignition of flammable gases driven off by heating too rapidly for complete combustion with the available supply of oxygen. They are frequently observed in high-intensity fires. Figure 23 shows very high flames that are likely to have detached ignitions above them.

The flames of some very hot fires pulsated regularly in height at approximately 1-second intervals. No reference to or explanation of such pulsations has been found in the literature. Probably, like detached ignitions, they are related to a critical balance between rate of heating and available oxygen. Both phenomena usually occurred in completely calm air.

## HEAT RADIATION

Radiation was measured continuously during the burning of nearly every plot. The radiometer used in 1952 was suspended above the fire. Consequently it measured varying amounts of convectional heat together with radiation, with the result that the readings obtained were not reliable and could not be compared with those made in subsequent years. A directional radiometer was used in 1953, and a flat-plate total hemispherical one in 1954 and 1955 (*45*). Readings for the 3 years were adjusted mathematically to those expected for the flat-plate radiometer at the most commonly used distance, 28 feet from the plot center. Simultaneous readings with the two instruments on six plots indicated that corrected values were sufficiently accurate and consistent to support valid comparisons based on major differences in slash characteristics.

### Maximum Fire Intensities

Table 16 summarizes the usable radiation data for 20.0- and 32.5-ton plots. The few readings obtained from 7.5-ton plots were erratic and apparently depended more on location of the active fire edge than on intensity of radiated heat.

Although not conclusive, the data indicate several probable relations that can be used, pending final analysis, in estimating relative flammability:

1. On an average, fire intensity (as indicated by maximum heat radiation) is three times as high in 32.5-ton-per-

Figure 21. Effect of fuel weight on peak fire intensity in fresh western larch slash: **upper,** 7.5 tons per acre; **lower,** 32.5 tons per acre.

acre slash as in 20.0-ton. Thus, fuel quantity apparently affects intensity more strongly than it affects rate of spread.

2. Fire intensity declines more rapidly in the year after cutting than does the rate of spread. The reduction is about 60 percent for species that retain their needles and more than 80 percent for the others.

3. If quantity calculations, experimental rate-of-spread measurement, and field observations are considered, the following intensity groupings appear to be justified:

   **High intensity**--fresh and 1-year-old slash of western white pine, lodgepole pine, and western redcedar; fresh slash only of Douglas-fir, ponderosa pine, and grand fir.

   **Medium intensity**--fresh and 1-year-old slash of western hemlock; fresh slash of Engelmann spruce; 1-year-old slash of ponderosa pine.

   **Low intensity**--all ages of western larch slash; 1-year-old and older slash of Douglas-fir, Engelmann spruce, and grand fir. As with rate of spread, under field conditions the pound-for-pound comparison made here may be altered by the relation of quantity to species, by site conditions, and by the fuels that occur naturally with slash.

Peak radiation usually occurred after the initial cone of flame subsided, but while the interior of the fire was still very hot. The reduction in height of flames was more than offset by increases in thickness and in diameter of the fire. Radiation from fires in fresh 20.0- and 32.5-ton-per-acre slash tended to increase until fire diameter closely approached or actually reached its possible maximum of 20 feet. Diameter at maximum intensity was somewhat less in 1-year-old slash of the same weights because the flames were not so thick. When a fire quickly broke down into a thin ring of flame, the approach of the flames to the radiometer was the main factor affecting apparent intensity.

Figure 22. One year's aging considerably reduces peak intensity of fire in slash that loses its needles during the year after cutting (Douglas-fir, 32.5 tons per acre). **Upper,** current year's slash with needles attached; **lower,** 1-year-old slash with needles fallen.

Although flame temperatures of wood fires vary somewhat, variation in measured radiation from slash plots indicates differences in rate of heat transmission rather than in flame temperature. Differences in flame temperature probably were quite small, but differences in radiating flame area and in thickness of flames were large. Fire emissivities were calculated on the basis of an assumed flame temperature of 1,500°F. and an assumed shape of fire. Average maximum emissivity for fires in 32.5-ton per-acre lodgepole pine slash was 0.26, slightly below that quoted by Hottel for powdered coal flames (*19*). This appears to be a reasonably reliable figure because the actual shape of the flames closely resembled the assumed shape. Emissivities calculated for less intense fires ranged downward to 0.04, but these values are unreliable because of variation in the shape of the radiating areas.

### Intensity and Rate of Spread

Fire intensity is proportional to rate of fuel consumption, which may be regarded as the product of rate of spread and quantity of fuel available. Quantity of fuel was by far the dominant influence on the rate of spread of experimental slash fires. Therefore, rate of spread was almost a direct measure of rate of fuel consumption. Figure 24 shows that fire intensity bore the type of relation to rate of spread that would be expected under the circumstances.

The faster a fire spreads, the sooner the greatest possible quantity of fuel is burning simultaneously. Time to maximum intensity is an important consideration affecting speed and strength of initial attack. Figure 25 shows the intensity-time relationship for the three weights of lodgepole pine slash.

### Efficiency of Combustion

In 1955, unconsumed residues, including both ashes and charcoal, from 10 plots of 1-year-old slash were collected, ovendried, and weighed. Two 7.5-ton and four each of 20.0- and 32.5-ton plots were sampled. The 7.5-ton plots were grand fir and ponderosa pine; in addition to these two species, 20.0- and 32.5-ton plots included lodgepole pine and western larch. The small number of samples does not permit statistical comparisons between species. Fuel

Figure 23. Aging for 1 year only slightly affects peak intensity of fire in slash that retains its needles (western white pine, 32.5 tons per acre). **Upper,** current year's slash; **lower,** 1-year-old slash.

Table 16.--Average maximum radiation received by radiometers adjusted to instrument distance of 28 feet from plot center

| Species | Fresh slash | | | | 1-year-old-slash | | | |
|---|---|---|---|---|---|---|---|---|
| | 20.0 tons/acre | | 32.5 tons/acre | | 20.0 tons/acre | | 32.5 tons/acre | |
| | Plots | Heat | Plots | Heat | Plots | Heat | Plots | Heat |
| | | *Btu per sq ft /hr* | | *Btu per sq ft /hr* | | *Btu per sq ft /hr* | | *Btu per sq ft /hr* |
| Western white pine | -- | -- | -- | -- | 2 | 193 | 3 | 628 |
| Lodge pole pine | 2 | 523 | 2 | 2,003 | 3 | 317 | 3 | 885 |
| Ponderosa pine | 2 | 359 | 2 | 1,245 | 4 | 142 | 4 | 297 |
| Western redcedar | -- | -- | -- | -- | 2 | 138 | 2 | 279 |
| Douglas-fir | -- | -- | -- | -- | 2 | 98 | 2 | 156 |
| Western hemlock | -- | -- | -- | -- | 2 | 110 | 1 | 176 |
| Engelmann spruce | 3 | 245 | 3 | 317 | 2 | 130 | 1 | 60 |
| Grand fir | 2 | 263 | 2 | 902 | 3 | 49 | 4 | 216 |
| Western larch | 2 | 478 | 3 | 957 | 4 | 64 | 4 | 258 |
| Mean | | 362 | | 1,010 | | 136 | | 364 |

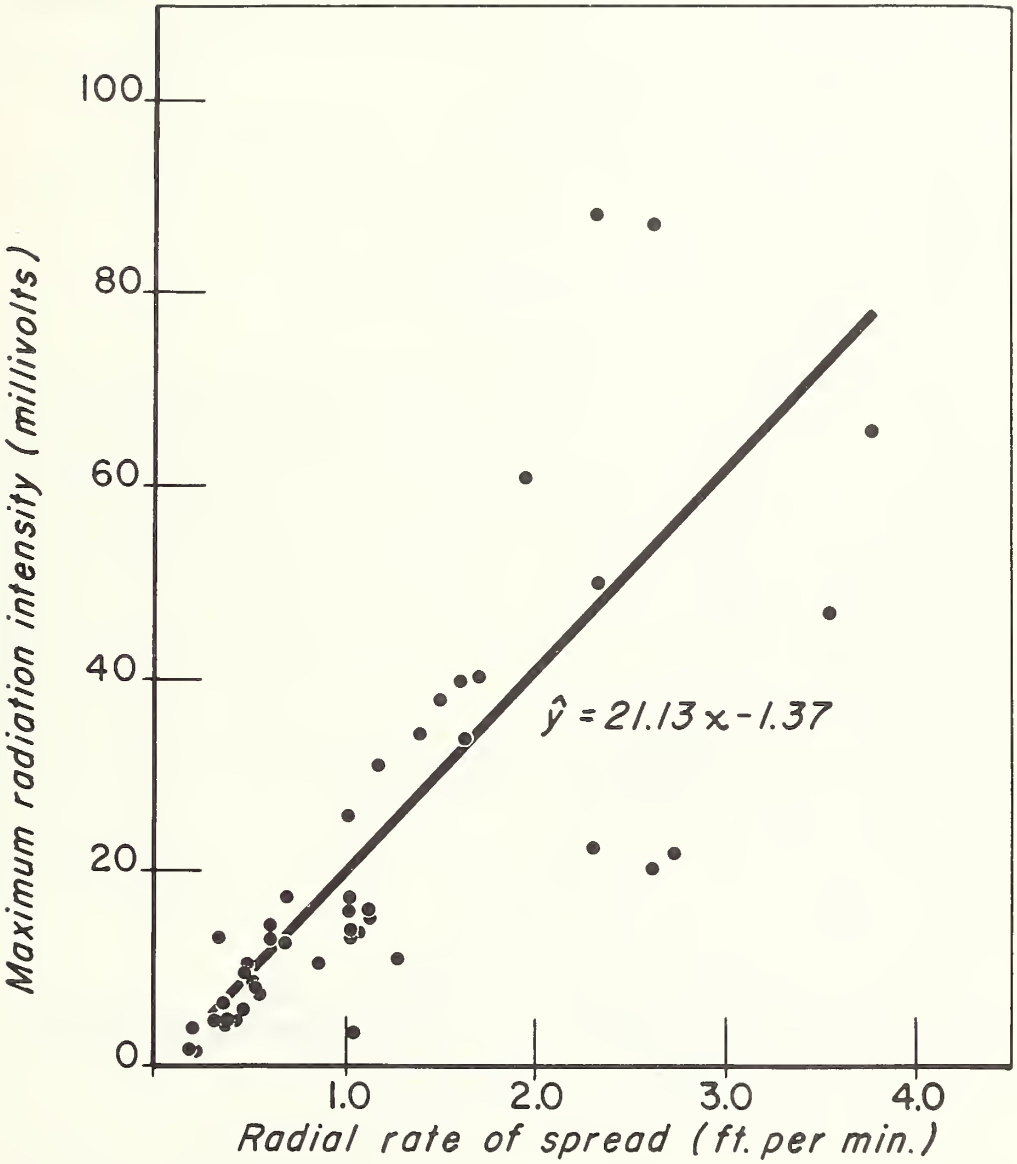

Figure 24. Fire intensity in relation to rate of fire spread in fresh and 1-year-old slash of lodgepole pine, ponderosa pine, grand fir, and western larch. **Basis:** 48 fires.

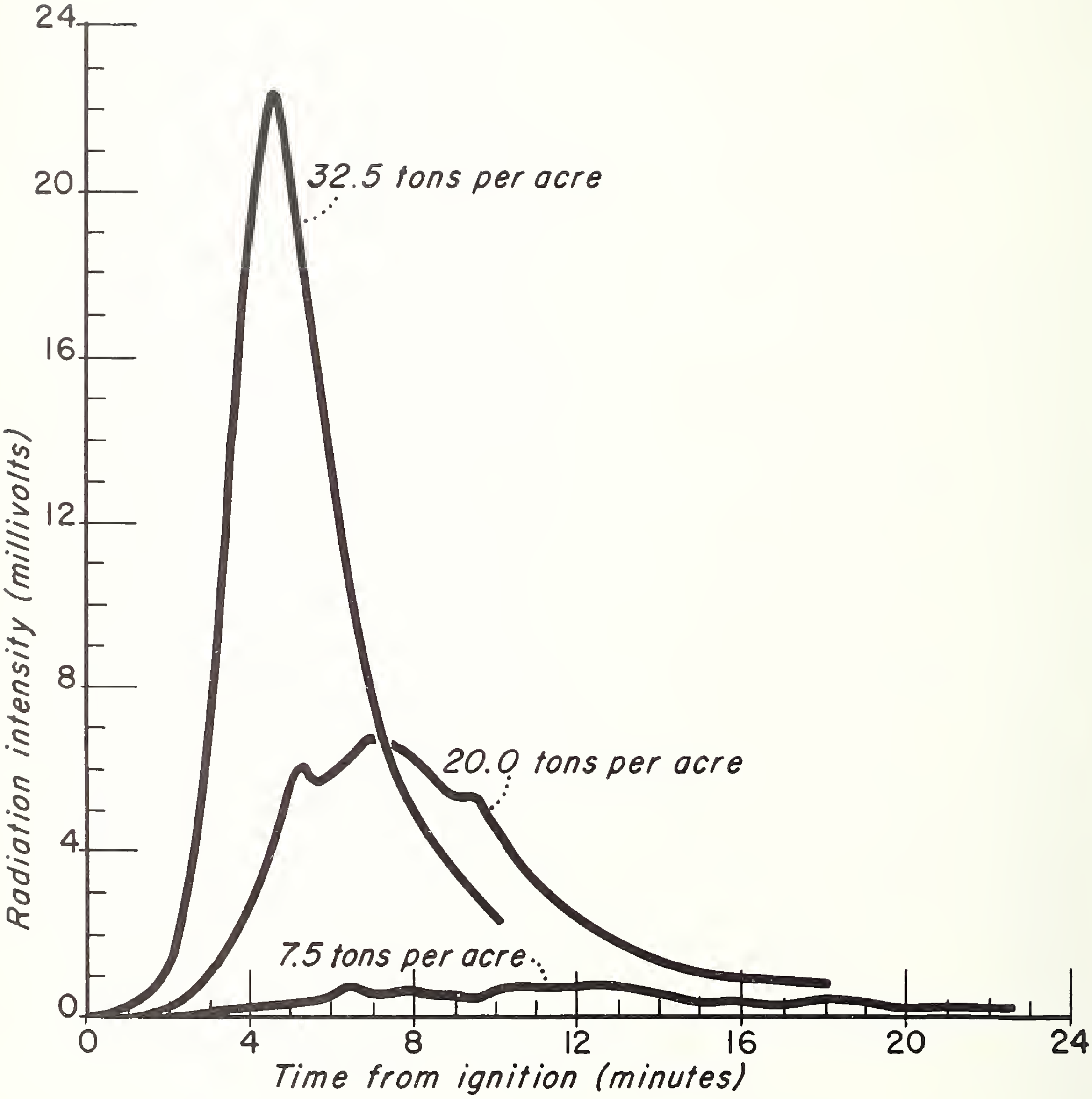

Figure 25. Radiotion intensity in relation to time from ignition for three weights per ocre of lodgepole pine slosh.

consumed for each weight of slash averaged as follows: 7.5 tons, 56 percent; 20 tons, 71 percent; and 32.5 tons, 79 percent.

Some of the increase in combustion efficiency with weight results from continued burning of more large material after the fast-spreading phase of the fire is over. It stands to reason, however, that increasing the amount of fine fuel causes more coarse material to burn during the early stages of the fire also, thereby further intensifying heat output.

### Use of Fire Intensity Data

Until combustion in free-burning fires is more fully understood, intensity data like those obtained by this slash flammability study can be interpreted and applied only very generally. Close agreement with rate-of-spread findings indicates that ratings based on rate of spread usually will represent adequately the fire-intensity factor of slash flammability. Flammability ratings of western white pine and lodgepole pine can be given a plus mark to indicate the high heat output and violent flame behavior that characterize fires in both fresh and 1-year-old slash. Rapid build-up of heat energy output also is a very important characteristic of the slash species that burned hottest experimentally.

# SLASH TREATMENT IN RELATION TO FLAMMABILITY

The preceding sections have described results of various phases of the logging slash research program and have suggested some specific ways of applying those results. Although these individual applications may help to provide a sound basis for selecting the best slash treatment for a particular situation, all pertinent information on slash flammability must be integrated and considered in conjunction with other factors. By "treatment" is meant any and all measures undertaken to offset the effects of increased flammability. Included under "treatment" are slash disposal, extra protection, modified cutting practices, and any other possible actions. Flammability rating will indicate whether individual slash areas require special attention, but other considerations probably will dictate the type and intensity of treatment.

## INTERPRETATION OF FLAMMABILITY

### The Flammability Rating to Use

The section on FIRE SPREAD IN SLASH shows how relative flammability ratings can be calculated for slash by species, quantity, and age. Slash treatment priorities are indicated more accurately by numerical flammability ratings than by estimated fuel type, which heretofore has been the basis for deciding whether to treat slash areas. Addition of quite small quantities of slash per acre produces a fuel type that warrants either disposal or extra protection. However, the variation of slash quantity, and hence the relative flammability rating, within each hazardous fuel type is large--more than 100 percent of the lower value in some types. Now this variation, which has long been recognized to some degree in practice, can be measured.

The flammability rating of fresh slash is not a satisfactory basis for selecting appropriate treatment. Slash is most hazardous and shows the least difference among species during the season of cutting; therefore, disposal should be accomplished then. However, this ideal is seldom attained. Furthermore, when extra protection is selected in lieu of disposal, the first fire season is only a small portion of the time during which protection must be provided. As a practical matter, slash disposal usually can be accomplished by the end of the year after logging if it is going to be done at all. Therefore, it appears realistic to base treatment priorities on relative flammability of 1-year-old slash, in which interspecies differences that appear likely to persist for several years can be recognized.

### Total Flammability Versus Fuel Flammability

Since all experimental burning was done in the early evening, when burning conditions were essentially the same in the open as in dense timber, only flammability of the fuel was measured. Arnold and Buck (*1*) showed that complete removal of forest cover reduces fuel moisture by as much as one-half and increases wind speed up to tenfold. In the northern Rocky Mountains these changes result in approximately doubling expected rate of fire spread under common, summer afternoon burning conditions. For northern Rocky Mountain fuel types, which take into account the effects of exposure to weather factors, the following relative rate-of-spread ratings have been found to exist among fuel types:

| | |
|---|---|
| Low and medium | 1 |
| High | 3 |
| Extreme | 5 |
| Flash | 15 |

However, it has been shown that addition of slash alone, without allowance for change in microclimate, is sufficient to place rate of spread in the "Extreme" class. Obviously, density of the residual stand must be considered in rating total slash flammability. Clear cutting results in maximum hazard by subjecting abundant fuel to severe burning conditions. When cutting is lighter, total flammability is proportionally lower because of both smaller quantity of fuel and greater density of the residual stand. When increases in both amount of fuel and severity of microclimate are considered, cutting that results in fuel flammabilities having the above 1-3-5-15 ratio may produce total flammabilities in a 1-6-10-30 progression.

## SELECTION OF SLASH TREATMENT

Several factors in addition to flammability help to determine the most appropriate slash treatment for a given situation. Although not subjects of the research described herein, these factors must be considered in order that their relation to flammability can be understood. In some instances flammability is a conditioning influence on another factor; in others there is little connection. No attempt is made here to discuss factors in order of priority, since priorities usually change from one situation to the next.

### Values to be Protected

All protection is undertaken because of the values involved. Very often no accurate measure of values is available. Nevertheless, consideration must be given both to the values themselves and to the amount of damage these values are likely to sustain. After logging, flammability rating expresses the potency of the damaging agency; physical and biological nature of the resource determines the degree of damage possible; social and economic considerations define the damage that can be tolerated. For a given flammability rating, slash treatment should be most intensive where values are highest and most subject to damage.

### Ability to Abate Slash Hazard

Both fuel flammability and total flammability must be considered in relation to available means of hazard reduction. In some instances adequate fuel reduction is out of the question with known techniques or reasonable expense; in others, the change from closed to open stand conditions may prevent fuel reduction from adequately abating total flammability. A realistic appraisal of ability to reduce hazard is an absolute necessity. There is no point in spending money for slash disposal if the effect of treatment will be insufficient to reduce appreciably the expense of protecting an area.

### Ability to Protect the Area Without Hazard Abatement

Fuel type is one important criterion of ability to provide effective protection. However, improved accessibility and advances in protection techniques and equipment permit protection of hazard areas that 10 years ago would have required major fuel reduction measures. Relative effectiveness of hazard reduction and extra protection must be reevaluated constantly to account for improvements in slash disposal methods and in the capabilities of the protection force.

### Relative Costs of Hazard Reduction and Extra Protection

Costs of slash disposal are relatively easy to determine; the cost of effective protection is not, but some estimate must be made. Availability of manpower and equipment for carrying out the two alternatives is an important consideration. Relative costs must be considered along with actual ability to abate hazard and to protect high hazard areas. Flammability studies indicate that slash that retains its needles more than 1 year should have top priority for disposal, and that extra protection has the best prospect of success in slash that loses its needles soon after cutting.

### Effect of Slash Treatment on Land Management Objectives

Values, both tangible and intangible, require consideration in connection with the effects of slash treatment as well as with the effects of wildfire. Sometimes drastic, expensive, and apparently damaging slash treatments fit well with management objectives and techniques; at other times less strenuous measures can largely destroy the values they are intended to protect. The latter situation sometimes justifies tolerating a serious hazard, especially if risk of wildfire occurrence is rather low. Observation of some areas raises the questions of whether a wildfire would have been more damaging than the slash disposal job. *The public is likely to be more tolerant of damage caused by wildfire than of damage caused by ill-conceived or poorly executed slash disposal.*

## NEED FOR FURTHER RESEARCH

Results of this study indicate numerous opportunities for further productive research. Continuation and extension of several studies described on preceding pages are necessary to develop techniques for more precise appraisal of flammability. However, the greatest need is to develop means of determining the most efficient methods of treating slash. This problem touches many phases of wildland management for which various subject matter specialists are best able to propose appropriate research. The purpose of this section is to suggest studies that will lead to greater competence in protecting cutover land from fire.

### EXTENSION OF PRESENT STUDY

#### Experimental Burning

Experimental burning of 5-year-old slash will be completed in 1960 to yield information on the effect of age on rate of spread and fire intensity. Depth measurements and descriptions of slash fuel beds will continue to provide information on compaction and rate of decomposition.

Experimental burning should be extended to obtain information on rate of spread and fire intensity under conditions not yet sampled. Small plots of fresh 20.0- and 32.5-ton-per-acre slash, like those described in this publication, should be burned at relative humidities below 30 percent to obtain fuller information how low humidity affects fire spread in heavy fuel concentrations. This burning should be done in a forest fire laboratory where effects of wind could be eliminated. Plots of 7.5-ton slash should be burned on natural duff beds to determine how fire spreads in light concentrations of slash when continuous, slow-burning, natural fuels are present.

Rather large-scale burning experiments are needed to test the effect of fuel arrangement on rate of spread. One very important and very controversial question to be answered is whether fire spreads faster where fuel is continuous or where it is concentrated in piles or "jackpots" that burn hot enough to throw brands capable of causing spot fires.

#### Check on Measurement

A basis for measurement of slash quantity has now been established. The next step is a field check for accuracy. This would consist of estimating total crown weight on a series of plots by methods described above under MEASURING SLASH, then cutting the trees and weighing the crowns. In addition to checking the accuracy of the weight estimation method, this project should be designed to yield information about how site index, stand density, and stand health affect crown weight per acre. A related study of slash measurement that may ultimately have economic value is determination of amount of raw material available for products not yet developed.

### Characteristics Of Slash

Better knowledge of the physical and chemical characteristics of slash will lead to better understanding of flammability. More intensive study of the moisture content of tree crowns is needed, especially to find out how moisture content varies with season of the year and variation in the precipitation pattern. Investigations of brush and herbaceous vegetation (*12*, *35*) have shown that moisture content varies enough to affect fire behavior strongly. Similar studies of living tree crowns might provide one gage of crown fire potential.

Although physical characteristics and moisture content appear to be the main attributes of slash that affect flammability, studies of chemical composition are warranted. Determination of the quantities and combustion characteristics of needle fats and oils should have first priority. Study of flash points of green and dry forest fuels has been elementary so far (*20*, *37*). Further research should give useful information applicable to both surface and crown fires.

## EVALUATION OF SLASH TREATMENT

The greatest current need of the slash disposal program in the northern Rocky Mountains is to determine whether the right measures are being employed with appropriate intensities in the problem areas. The questions to be answered are both technical and economic. Slash treatment must provide adequate fire protection, and must do it at acceptable cost. Slash measurement techniques and flammability ratings developed by the present study provide means for examining critically the need for slash treatment and the effectiveness of disposal operations, both of which are basic considerations in determining how much should be spent to combat the slash fire hazard effectively. The type of applied research required provides excellent opportunity for cooperative endeavor by research and administrative agencies. Because economic conditions change continually, need for evaluation of slash treatment programs will also continue.

### Technical Evaluation

The two most important things to be learned in studying the technical effectiveness of slash treatment are: (1) whether effort is being directed against hazards in proportion to their severity, and (2) whether the measures employed are accomplishing their purpose. Inspection of many cutover areas supports the opinion that the intensity of slash disposal practiced frequently is not in proportion to the need for it. Learning whether this is true may strongly influence the amount and allocation of funds collected for both slash disposal and extra protection. Measuring accomplishment is most important where slash has been piled by hand. Prescribed burning and bulldozer-piling usually eliminate slash almost completely on the area treated, but examination is necessary to see whether new hazards have resulted from escape of slash fires or mechanical damage to the residual stand.

If extra fire protection measures have been employed in lieu of slash disposal, evaluation will be especially difficult. In the first place, the presumed extra protection commonly is very difficult to measure and, indeed, even to identify as something distinct from the general fire control effort. In the second place, accomplishment can be measured only in terms of decreased frequency, size, and cost of fires, all of which are influenced by so many other factors that the effect of variation in fuel is extremely difficult to measure.

The most useful technical evaluation will result from on-the-ground study of recent slash disposal operations. One procedure should consist of determining, in the order given, (1) flammability after logging, (2) slash treatment applied, and (3) flammability after treatment. Initial postlogging flammability ratings can be calculated in the office from cruise or cutting records but should be corroborated by field examination to take into account features that are not recorded, such as number of snags and windfalls. Kind of treatment used usually is recorded, remembered, or obvious from evidence on the ground; but degree of treatment is difficult to measure except in terms of cost. Flammability after treatment is the crux of the whole problem, and it also is hard to measure. Thus within the larger study of the effectiveness of slash disposal as a measure for hazard reduction are two opportunities for development of research methods (1) for expressing slash treatment quantitatively, and (2) for rating flammability after treatment.

A second research procedure is examination of information available about fires that have burned in cutover areas. This type of study has been rather unfruitful in the past, possibly because of insufficient or inaccurate information both about the fires and about the physical conditions of the cutover areas before they burned. Nevertheless, periodic analysis of mass statistics and individual fire case histories remains a potential source of valuable knowledge and of leads to follow in starting other types of research.

### Economic Evaluation

Cost and accomplishment of slash treatment need to be tested against the least-cost-plus-damage criterion. The present annual cost of slash treatment in the Inland Empire is about $3.75 million, but the annual cost of suppressing slash fires and the damage sustained from these fires is much less. Possibly the total bill would be smaller if different treatments were applied. Technical evaluation of slash treatment will answer some financial questions, but economic analysis of the slash disposal field and of individual cases also is necessary.

The economics of slash treatment can be studied partially by compiling and analyzing fire reports and examining case histories of individual fires. Such studies should be pursued concurrently with the similar analyses of technical accomplishment mentioned earlier. Unfortunately, incomplete records of past fires, inadequate representation of important conditions, changing methods of fire control, and new facilities for fire control seriously complicate the interpretation of past occurrences in terms of future probabilities. Therefore statistical and case-history studies may only suggest what type of research is needed to provide definite answers. One possibility that should be considered is large-scale, long-term comparison of two or more similar areas on which the slash problem would be handled in different ways. The areas might need to be whole national forests; the duration of such an experiment should be 5 to 10 years.

Any attempted method of economic analysis will be impeded by lack of a satisfactory method of appraising fire damage. Without realistic damage appraisal, it will be difficult to compare the cost of slash treatment with that resulting from omitting treatment. Arbitrary guidelines and values can be used temporarily for research purposes, but economic analysis should help point the way to development of better methods of damage appraisal.

## DEVELOPMENT OF EQUIPMENT AND TECHNIQUES

Although this study of flammability was not directly concerned with slash treatment, it is impossible to think about slash without also theorizing about methods that might revolutionize present practice. Usually this theorizing revolves about "magic" chemicals that would decompose slash quickly or machines that would grind it up. Such dream-stuff is unlikely to materialize in the near future, but the whole operation of slash disposal offers virtually limitless possibilities for devising and perfecting machinery and techniques, an activity that seemingly should afford opportunity for highly productive use of slash disposal funds.

The bulldozer has come into its own for piling slash on favorable ground, but important and troublesome situations remain: (1) Some slopes are too steep or too erosive to permit use of bulldozers, and (2) some partially cut stands contain enough slash to require disposal and also a residual stand that would be harmed by use of fire or of heavy machinery. Full-tree logging might solve these problems. With this technique, now used rather extensively in Russia but barely tried in the United States (*24*), entire trees are skidded to the landing. There the desired raw products are cut, and the tops and limbs are burned or chipped. Full-tree logging appears to be an especially good technique for use on relatively small trees, such as those cut for poles, piling, and pulpwood. Obviously slash disposal or use will be facilitated if the slash is concentrated in one place; accurate comparative tests against conventional methods might reveal additional advantages.

Several possibilities have been suggested for development of slash disposal equipment; little work has been accomplished to date. One possibility that would apply to steep terrain is a lightweight winch equipped with a haul-back and some sort of grapple to skid slash up or down hill. For partially cut stands especially, a good chipper or brush chopper will become increasingly desirable. Experimental development should improve models now available by increasing their compactness and mobility and by incorporating self-feeding apparatus.

## USES AND EFFECTS OF FIRE

The chief purposeful use of prescribed burning in forests of the inland West is for slash disposal. After decades of experience, foresters still burn on the basis of experienced judgment rather than on proved fact and measurement. Rarely does a year pass without some slash fires escaping because of "unexpected" behavior at one extreme and excessive time being wasted on attempting to burn fuels that will not burn at the other. The findings on rate of spread and fire intensity in slash point toward development of a body of knowledge that can be expressed quantitatively and used as the basis for instructions or rules for burning.

One very important opportunity for improving use of fire is the extension of time during which prescribed burning can be done safely and effectively. Techniques of area ignition hold promise for the burning of relatively sparse or green fuels and for burning during damp weather. On the other hand, with proper precautions based on better knowledge of fire behavior, slash area preparation, and local weather, burning undoubtedly can be done safely in drier weather than is now usually selected. Both possibilities are promising enough to warrant testing even at the risk of sacrificing a few hundred acres of green timber.

Some practical questions that need answering relate to (1) minimum quantity of fuel that can be burned, (2) maximum quantity that can be burned safely under given conditions, and (3) precautions that are required for different combinations of topography and weather.

The whole subject of fire effects is ripe for pioneering research. Direct effects of heat on vegetation are particularly appropriate for study in connection with slash flammability because slash fires now damage many trees unnecessarily. Research is needed (1) to rate the various commercial species according to their fire resistance, (2) to measure what degrees of heat each can tolerate, and (3) to determine at what distance from slash fires damage occurs under varying weather conditions. Better knowledge of effects of heat on soil organisms could be used to advantage for prescribed burning to destroy *Ribes* seed in the duff of cutover western white pine stands.

## USES FOR SLASH

The best treatment for a troublesome waste product is use. Approximately 2 million tons of tree crown material are cut annually in Idaho and Montana alone. Technology has devised uses for all this raw material: chipped slash can be used for cattle bedding, soil amendment, and agricultural mulch; it can be burned for fuel, pressed into particle board, and pulped for fiberboard. Economically these uses are not yet feasible because other raw materials--sawmill residues, topwood, snags, and windfalls — are more readily available and easier to process. However, Europe's experience strongly suggests that product specifications will become less particular and that ultimately virtually 100 percent of the woody portion of every tree will have to be used. Research should start now to develop uses for fine slash components. Possibilities for productive studies range from means of concentrating and cleaning slash in the forest to complex processes of manufacturing. The incentive is twofold: removal of a fire hazard and utilization of what is now waste.

In continuation of work already begun as well as in the other lines of study suggested, the possibilities for productive research far exceed present prospects for accomplishing it. Direct applicability of results to pressing administrative problems makes research on logging slash an especially attractive subject for cooperative effort.

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