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Predicting Slash Depth for Fire Modeling

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PREDICTING SLASH DEPTH FOR FIRE MODELING

Frank A. Albini
James K. Brown

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INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
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PREDICTING SLASH DEPTH FOR FIRE MODELING

Frank A. Albini and James K. Brown
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The proficiency of David L. Bunnell and J. A. Kendall Snell in locating study areas and conducting fieldwork greatly contributed to the success of this study.
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RESEARCH SUMMARY

Development of equations for predicting fuel bed depth (called "bulk depth" herein) appropriate for modeling fire behavior in slash is described. Bulk depth (y) was correlated with the expected number of 1/4- to 1-inch-diameter particle intercepts per foot of vertical plane transect (x) by regressions of the form y = a*x. Values of "a" suitable for use in fire models were 0.767 for high-lead harvest debris, 0.940 for precommercial thinning of pines, 1.22 for precommercial thinning in several other western conifers, 0.877 for ground-lead harvest debris in pines, and 0.542 for ground-lead harvest in other species. Lopping of slash reduced average depth 17 percent for harvest debris and 31 percent for precommercial thinning debris. Correlation of high intercept depth (maximum height of sampled fuel particles) with bulk depth showed that the bulk depth can be well predicted using 64 percent of the more easily measured high intercept depth.

Models for settling of slash, retention of foliage and fine twigs, and species mixing, useful in preparing data for fire models, are presented. Application of the models in a slash hazard appraisal computer program is illustrated.
INTRODUCTION

Slash or debris created by harvesting and thinning are a major fire management problem because these residues can create unacceptable fire behavior hazards. Treating slash to maintain an acceptable fire hazard is expensive and requires skillful decision-making. An inexpensive, "template-to-use, yet objective means of appraising the potential fire behavior of slash is called to aid decisions in managing slash. Knowledge of potential fire behavior can help determine treatment alternatives, the financing of slash treatment activities, and even determine whether the slash should be created.

This report describes a method for predicting depth of slash fuels for analytical modeling of fire behavior.

The capability to predict debris and to model fire behavior has made possible a quantitative system for appraising fire behavior potential. Rate of fire spread and flame front intensity can be mathematically modeled using Rothermel's (1972) fire model, which is the basis for computing spread and energy release indexes in the National Fire Danger Rating System (NFDRS). An area-growth-rate model by Anderson,\(^1\) crown scorch model by Van Wagner (1973), and flame length models by Byram (1969) and Thomas (1962) are also available. A method for assessing total heat release and period of flaming that incorporates large-diameter fuels has been theorized by Albinii.\(^2\) The fire models require fuel loading by size class and fuel bed depth as inputs.

Loading and depth of debris vary considerably by cutting prescriptions, therefore must be estimated for each individual cutting situation. Other fuel inputs such as particle density, heat content, silica-free ash content, and particle surface area-to-volume ratio tend to be species dependent and can be approximated from known values (Albinii 1976; Brown 1970b, 1974).

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\(^1\)Office memo of August 10, 1973, on file at the Northern Forest Fire Laboratory, Missoula, Montana. (Manuscript in preparation by Hal E. Anderson.)

\(^2\)Albinii (1976) outlines the total heat load computation; the computation of burning time is based on empirical work reported by Harmathy (1972) describing structure fires and pile burning, modified slightly to agree with single-particle burning times reported by Anderson (1969).

---

For Rocky Mountain conifers, loads of slash can be predicted from relationships between tree crown weight and tree characteristics such as d.b.h. and height (Brown 1978). In the USDA Forest Service Northern Region these relationships have been installed in a computer program that obtains input from tree inventories and predicts potential debris as output.\(^3\) In addition to predicting debris, a method to predict fuel depth is needed to appraise fire potential. The objectives of this study were:

1. Determine the relationship between fuel depth and loading of slash and the extent to which species, age of slash, method of skidding, logging, and other factors influence the relationships.

2. Determine the relationships between the easily measured high intercept depth and bulk depth.

When using analytical models such as Rothermel's (1972), fuel depth is a critical parameter because it determines bulk density of the fuel array for given fuel loadings. Rate of fire spread is very sensitive to bulk density (Williams 1977). Fuel depth is a measure of the vertical extent of fuel in the zone that is actively involved in the spreading flame front. Conceptually, the bottom of this zone is the forest floor and the top is the height where fuel ceases to exist or is too sparse to affect propagation of the flame front. Fuel depth that is compatible with fire modeling can be difficult to measure because locating the top of this hypothetical zone in the fuel array requires judgment.

Fuel depth in slash and other downed woody material has been measured primarily on a high intercept basis (Brown 1974). In this procedure, the top of the fuel is defined by the highest particle to intersect a vertical plane about 1 foot wide. Although this procedure is easy to learn and to use, it does include large void spaces in the fuel array whenever they occur. This permits overestimation of an effective fuel depth and underestimation of bulk density required for fire modeling. A procedure for measuring effective fuel depth—called "bulk depth"—has been developed by William Frandsen (1974) at the Northern Forest Fire Laboratory. It allows observers to account for void spaces in the fuel arrays and provides a measure of effective fuel depth appropriate for fire modeling.

The merchantable top diameter relates to depth. Small top diameters result in more lopping of supporting branches and removal ofbolewood than large top diameters; hence, the slash is more compacted. Species may influence depth of slash due to differences in branch stiffness and branching habit. In a study by Roussopoulos and Johnson (1975), loading and depth of slash were directly related; however, as loading increased, depth increased at a reduced rate. Probably as more tree crowns are added to a fixed area, overlapping of branches occurs and the weight may cause compression. Methods of feiling and skidding trees should influence depth because the amount of trampling and breakage depends on if and how merchantable holes are removed.

Settling with age has a most significant influence on slash depth. For some western conifers over a 5-year period, depth of lopped and unlopped slash was reduced to one-half of the original value (Fahnestock and Dieterich 1962; Kil1 1968). Rate of settling varied; for some species, depth actually increased slightly during the second year before settling. In a study of piled slash over a period of 29 years, Nagener and Offord (1972) found that piles continued to settle; however, 50 percent of the settling occurred during the first 5 years.

\(^3\)Users' guide to debris prediction and slash hazard appraisal. 1977. USDA Forest Service Northern Region, Division of Fire Management, Missoula, Mont.
METHODS

Fieldwork

Sampling design.—The study was designed to provide data for four different skidding methods:

1. Ground lead.—Crawler tractor and rubber-tired skidder, entire log dragged.
2. Skypine.—One end of log elevated.
3. Helicopter.—Limited skidding.
4. Precommercial Thinning.—No skidding.

For each skidding method, two species groups were desired and for each species group, two age classes of slash. For each combination of skidding method, species, and age, we attempted to locate two study sites on areas representing different age loading levels: low (sparsely distributed), medium (nominally about half of ground covered by slash), and heavy (uniformly distributed).

Study sites were located in areas having different loadings to assure that any differences in skidding patterns due to loading would be reflected in the data.

Species were partitioned into the following two groups, based on similarity of lopped depths as observed by Fahnstock and Dieterich (1962):

1. Douglas-fir (Pseudotsuga menziesii [Mirb.] Franco)
   - Grand fir (Abies grandis [Dougl.] Lindl.)
   - Alpine fir (Abies lasiocarpa [Hook.] Nutt.)
2. Western hemlock (Tsuga heterophylla [Raf.] Sarg.)
   - Western larch (Larix occidentalis Nutt.)
   - Engelmann spruce (Picea engelmannii Parry)
   - Lodgepole pine (Pinus contorta Dougl.)
   - Ponderosa pine (Pinus ponderosa Laws.)
   - Western white pine (Pinus monticola Dougl.)

All slash was at least one-half year old and had existed through at least part of a winter. Two age classes were recognized: 0- to 1-year and 3- to 4-year. Some combinations of skidding, species, and age were not feasible because skyline and helicopter logging has received substantial use only recently in the Intermountain area, the 0- to 1-year and 3- to 4-year lodgepole pine and 3- to 4-year Douglas-fir were unavailable for sampling. Surprisingly, 0- to 1-year precommercially thinned stands other than pines were also unavailable. All other skidding, species, and age combinations were sampled.

Within study areas that were a minimum of several acres in size, two primary transects were established. Along each primary transect, a total of 50 or more sampling points were located at 2-foot intervals. Points without slash were not sampled.

Loading measurements.—Using the planar intercept technique (Brown 1974; Brown and Roussopoulous 1974), loading was measured for at least 15 randomly preselected sample points along each primary transect. Sometimes the random selection resulted in more than 15 points out of 50 for measurement of loading. For 1/4- to 1-inch particles, two 2-foot planes, crossed perpendicularly, were vertically oriented and intersections counted. For 1- to 3-inch and greater than 3-inch pieces, the 2-foot planes were extended to 4 feet. Particles 0 to 1/4 inch were not tallied because of the counting work involved and the fact that the information appeared unnecessary to meet objectives.

Depth measurements.—High intercept and bulk depth measurements were recorded at each sampling point. High intercept depth was measured as the vertical distance from the bottom of the litter layer to the highest 0- to 3-inch diameter slash particle intersecting each 2-foot plane. Pieces greater than 3 inches in diameter were omitted in determining depth because they occur infrequently as the highest particle and have considerably less influence on rate of spread than smaller pieces.

Bulk depth was measured in each of four pie-shaped quadrants of a 2-foot diameter cylinder whose central axis was vertically oriented at each sample point. The two perpendicular sampling planes for tallying intersections of 1- to 3-inch particles, delineated the cylinder into quadrants. The top of fuel was the average height of an imaginary pliable sheet over the fuel particles. The bottom was at the base of the litter layer. Vertical gaps free of fuel for more than 1 foot were subtracted from each quadrant's depth. Caps of less than 1 foot were assumed to be vertical continuity of flames, thus were included in the depth measurements. Depths of the four quadrants were averaged to obtain a bulk depth estimate for each sample point.

Logging.—After loading and depth were measured initially, the slash along the transect was lopped so that all branches were within 2 feet of the ground and boles within 1 foot. High intercept and bulk depths were remeasured at all sample points where depth had changed.

Analysis

To understand the rationale behind the method of analysis applied here, hear in mind the objectives of the effort and the nature of the variables. The first objective was to establish an equation that can be used to predict fuel bed from quantities that describe the amount of slash on the area. The sampling procedure provided an estimate of the bulk depth and the variables for quantifying the slash fuel bed at each sample point: the number of intercepts of 1/4- to 1-inch and 1- to 3-inch-diameter fuel particles. The expected number of such intercepts can be predicted from slash loading, tree species, and d.b.h. simply by parsing the loading according to the fractional weight distribution of the individual tree crowns (Brown 1978). But the number of intercepts (regardless of size class) is subject to great sampling variability, since it should be approximately Poisson distributed.

A Poisson-distributed variable has a variance equal to its mean, so if N is its expected value, samples from N ~ N through N ~ N should occur with approximately equal frequency. This intrinsic variability makes it impossible to distinguish with certainty between a change in the mean value of the number of intercepts and simple data scatter when moving from one sample point to the next. To alleviate this problem, the data can be aggregated, combining measurements that lie within a range ±3 of each other. We can use the average values to discern the underlying trend of the average bulk depth with the average number of intercepts; otherwise, the trend would be largely obscured due to the great scatter in the individual samples. Sampled bulk depths also exhibited significant scatter, indicating a need to aggregate data.
Fuel bed depth was related to the expected number of intercepts of 1/4- to 1-inch-diameter fuel particles per foot of planar intersect by fitting regressions through aggregated data points. The 1/4- to 1-inch particles served as a proxy for the loading of debris fuel under 3 inches in diameter. The fitting of data points resulted from a three-step averaging process as described below:

1. For each study area, the data from the two transects were treated as a single set. Only sample points at which intercepts were counted were assembled in the data set, so the "unit" of sample information consisted of a triplet of numbers—the bulk depth, in inches; the total numbers of intercepts of 1/4- to 1-inch size class fuels in the two crossed sample planes; and the number of intercepts of 1- to 5-inch size class fuels in the same two (extended) planes.

For inspecting these triplets of numbers, they were aggregated and displayed in five categories, according to the number of 1/4- to 1-inch intercepts: 0-2, 3-6, 7-13, 14-22, and 23 or more intercepts. The display (table 1) consisted of the following descriptors for each subset:

- a. Average bulk depth
- b. Average 1/4- to 1-inch intercept count
- c. Number of sample triplets in the subset
- d. Mean square bulk depth
- e. Mean square 1/4- to 1-inch intercept count.

Scrutiny of such tables quickly revealed sample points that were obviously not representative, so they could be culled from the data set. The mean square depth figures served well to permit the "outlaw" points to be identified. Fewer than 10 points were discarded from more than 1,500 collected.

2. These data were analyzed in many ways in attempting to discover trends and correlations. One fact that soon became evident was that no substantial dependence of bulk depth on the 1- to 3-intercept count could be established, whether or not the 1/4- to 1-intercept count was included. This allowed further simplification by combining data for all 1- to 3-intercept counts. Table 2 displays this simplified data aggregation. An asterisk indicates that a sample point has been discarded in computing the averages shown, and two asterisks indicate the discarding of two data points. These data form the basis for the regression relationships between bulk depth and number of 1/4- to 1-inch intercepts.

3. Data in table 2 were grouped by combinations of skidding method, species, and age of slash. Constrained regressions were applied to the data because logically if no 1/4- to 1-inch fuel particles exist there should be no bulk depth. Analysis using unconstrained regressions supported this approach in that the constant terms were small and often statistically nonsignificant.

In deriving the regression equations, the data from all units aggregated were averaged. That is, all the bulk depth-intercept count pairs in the intercept count range 0-2 were averaged, all those in the range 3-6 were averaged, etc. Then the regressions were formed by weighting each resultant aggregate data point by the number of its supporting measurements.

Scatter diagrams of these "grand average" points showed a fraction power law form, so we chose to regress the average bulk depth against the square root of the average number of 1/4- to 1-inch intercepts.

Table 1—Sample table of aggregated data from one area used for establishing the relationships between bulk depth and number of particle intersections

<table>
<thead>
<tr>
<th>Intercept count range</th>
<th>Average</th>
<th>1/4 to 1 inch intercept count</th>
<th>No. points</th>
<th>Mean depth</th>
<th>Mean square depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2</td>
<td>1.453</td>
<td>1.500</td>
<td>0.00</td>
<td>2.367</td>
<td>0.0</td>
</tr>
<tr>
<td>0-2</td>
<td>1.335</td>
<td>1.500</td>
<td>0.00</td>
<td>1.667</td>
<td>0.0</td>
</tr>
<tr>
<td>0-2</td>
<td>2.250</td>
<td>2.500</td>
<td>0.00</td>
<td>6.710</td>
<td>0.0</td>
</tr>
<tr>
<td>0-2</td>
<td>2.000</td>
<td>5.000</td>
<td>0.00</td>
<td>3.000</td>
<td>0.0</td>
</tr>
<tr>
<td>3-6</td>
<td>7.475</td>
<td>1.867</td>
<td>0.00</td>
<td>3.050</td>
<td>0.0</td>
</tr>
<tr>
<td>3-6</td>
<td>4.750</td>
<td>5.667</td>
<td>0.00</td>
<td>4.500</td>
<td>0.0</td>
</tr>
<tr>
<td>3-6</td>
<td>9.957</td>
<td>4.127</td>
<td>0.00</td>
<td>9.365</td>
<td>102.4</td>
</tr>
<tr>
<td>3-6</td>
<td>23.75</td>
<td>14.33</td>
<td>22.50</td>
<td>22.50</td>
<td>0.0</td>
</tr>
<tr>
<td>7-13</td>
<td>4.650</td>
<td>4.833</td>
<td>4.075</td>
<td>3.300</td>
<td>3.433</td>
</tr>
<tr>
<td>7-13</td>
<td>10.00</td>
<td>9.333</td>
<td>9.000</td>
<td>12.00</td>
<td>7.667</td>
</tr>
<tr>
<td>7-13</td>
<td>21.47</td>
<td>27.08</td>
<td>18.60</td>
<td>10.89</td>
<td>18.43</td>
</tr>
<tr>
<td>7-13</td>
<td>109.0</td>
<td>91.33</td>
<td>83.50</td>
<td>144.0</td>
<td>59.00</td>
</tr>
<tr>
<td>14-22</td>
<td>6.800</td>
<td>7.150</td>
<td>6.000</td>
<td>0.00</td>
<td>0.0</td>
</tr>
<tr>
<td>14-22</td>
<td>15.00</td>
<td>15.00</td>
<td>16.00</td>
<td>0.00</td>
<td>0.0</td>
</tr>
<tr>
<td>14-22</td>
<td>46.24</td>
<td>55.75</td>
<td>36.00</td>
<td>0.00</td>
<td>0.0</td>
</tr>
<tr>
<td>14-22</td>
<td>225.10</td>
<td>225.10</td>
<td>256.00</td>
<td>0.00</td>
<td>0.0</td>
</tr>
<tr>
<td>25</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.0</td>
</tr>
<tr>
<td>25</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.0</td>
</tr>
</tbody>
</table>
One penalty for using constrained regressions is that there is no widely accepted simple quantity that reflects the degree of agreement between the equation and the data, in the way that the "coefficient of determination," called $r^2$, does for unconstrained regressions. If $r^2$ represents a bulk depth data point to be fitted by regression, $y$, the value of the bulk depth predicted by the regression expression, and $y$ the average of the data points to be fitted, then, by a statistical theory expression for the coefficient of determination for a constrained regression should be

$$r^2 = 1 - \frac{\sum (y_i - \hat{y}_i)^2}{\sum (y_i - \bar{y})^2}.$$

This quantity is, however, a poor measure of the "goodness" of the regression equation. So we have used, in this presentation, a nonrigorous but intuitively more appealing measure of the suitability of the regression description:

$$s = 1 - \frac{\sum (y_i - \hat{y}_i)^2}{\sum (y_i - \bar{y})^2}.\tag{7.1}$$

This parameter compares the variance about the regression to the variance about the mean, as does $r^2$ for an unconstrained regression, but it is not limited numerically to the range 0 to 1. It is restricted only to be less than unity, and can be negative.

**RESULTS and DISCUSSION**

**Regression results for all of the skidding, species, and age combinations obtained in the study are shown in table 3. The relationships for skline and helicopter skiding were similar; so they were combined and called "high-lead." The high-lead of the fit descriptor, $s$, are largely due to the manner of aggregating data. Examples of fit are shown in figures 1, 2, and 3. Because of the data aggregation, tests for differences among the slash groups seem irrelevant. However, recognizing the large amount of variation among sampling points and the similarity of some of the regressions in table 3, the equations in figure 4 are recommended for application to fire modeling. To obtain the equations for initial depth shown in figure 4, some of the results in table 3 had to be adjusted to age 1 year.**
Table 1.—Constrained regressions through aggregated data points relating average bulk depth, \( y \) (inches) to average number of intercepts \( I/4 \) to 1-inch debris fuel in six crossed 3-foot sample planes, \( z \)

<table>
<thead>
<tr>
<th>Type of cutting</th>
<th>Dominant debris species</th>
<th>Sample included for data averaging</th>
<th>Regression equation</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground-lead harvest, 6-in top</td>
<td>DF, mix</td>
<td>1975</td>
<td>( y = 3.16x )</td>
<td>.66</td>
</tr>
<tr>
<td>Ground-lead harvest, 6-in top (flush after harvest removed)</td>
<td>DF</td>
<td>2, 5</td>
<td>1975</td>
<td>( y = 3.12x )</td>
</tr>
<tr>
<td>Ground-lead harvest, 6-in top (flushed after harvest removed)</td>
<td>DF</td>
<td>1</td>
<td>1975</td>
<td>( y = 3.18x )</td>
</tr>
<tr>
<td>Ground-lead harvest, 6-in top</td>
<td>DF</td>
<td>3</td>
<td>1975</td>
<td>( y = 1.45x )</td>
</tr>
<tr>
<td>Ground-lead harvest, 5-in top</td>
<td>LP, mix</td>
<td>1, 3</td>
<td>1975</td>
<td>( y = 3.05x )</td>
</tr>
<tr>
<td>Ground-lead harvest, 6-in top DF, mix</td>
<td>1, 2, 3</td>
<td>1975</td>
<td>( y = 2.27x )</td>
<td>.95</td>
</tr>
<tr>
<td>Ground-lead harvest, 5-in top</td>
<td>LP</td>
<td>1</td>
<td>1976</td>
<td>( y = 4.51x )</td>
</tr>
<tr>
<td>Precommercial thinning</td>
<td>PP</td>
<td>4</td>
<td>1976</td>
<td>( y = 1.35x )</td>
</tr>
<tr>
<td>Precommercial thinning</td>
<td>LP</td>
<td>4</td>
<td>1976</td>
<td>( y = 1.22x )</td>
</tr>
<tr>
<td>Precommercial thinning</td>
<td>DF</td>
<td>3, 4</td>
<td>1975</td>
<td>( y = 4.75x )</td>
</tr>
<tr>
<td>Precommercial thinning</td>
<td>LP, PP</td>
<td>1</td>
<td>1976</td>
<td>( y = 5.58x )</td>
</tr>
<tr>
<td>High-lead harvest, 6-in top</td>
<td>Mix</td>
<td>1</td>
<td>1976</td>
<td>( y = 4.60x )</td>
</tr>
<tr>
<td>High-lead harvest, 6-in top (flushed by harvest crew)</td>
<td>Mix</td>
<td>1</td>
<td>1976</td>
<td>( y = 4.60x )</td>
</tr>
</tbody>
</table>

These units are not typical of current practice, as trees of large d.b.h. were thinned. The relationship developed was not used for model purposes for this reason.

---

Figure 1.—Aggregated data for bulk depth as a function of intercept count (1/4- to 1-inch particles per 4 feet of transect) for precommercial thinning. Analysis is shown in table 3.

Figure 2.—Aggregated data for bulk depth as a function of intercept count (1/4- to 1-inch particles per 4 feet of transect) for ground-lead skidding. Analysis is shown in table 3.
Bulk Depth Versus High Intercept Depth

Measurement of bulk depth is time consuming and subject to personal interpretation. However, the simpler to measure "high intercept depth" (Brown 1974) tends to underestimate fuel bed compactness, resulting in a systematic overestimation of the rate of fire spread and reaction intensity by Rothermel's (1972) model (Brown 1972; Bevins 1976; Hough and Albini 1978). But because it is rapid, reliable, and widely used, we determined the regression relationship between high intercept depth and bulk depth to provide a formula that can be used to reduce the high intercept measurements for use in the Rothermel fire spread model. The analysis was made on pairs of bulk depth and high intercept depth measurements taken at each point.

Examination of a large number of regressions for various combinations of skidding species, and age revealed no substantive differences between the regression coefficients. Also, all the regression lines passed very nearly through the origin. For example, treating all debris of age 2 years and less as one set and all debris older than 2 years as another set gave the following relationships:

\[
\text{Bulk} \rightarrow \text{High Intercept Depth}:
\]

\[
\begin{align*}
\text{Age 2} & : y = 0.542 + 0.503X \\
\text{AGE 2} & : y = 0.303 + 0.602X
\end{align*}
\]

where

\[
y = \text{bulk depth (inches)}
\]

\[
x = \text{high intercept depth (inches)}.
\]

Variation among regression coefficients was restricted as shown by the histogram of ratios of bulk depth-to-high intercept depth computed for 118 transects (fig. 5). Sixty percent of the ratios were between 0.65 and 0.75. Regression coefficients pertaining to the major skidding species, and age groups are shown in table 4. Variability of coefficients within slash groups is comparable to variability among slash groups. Thus, the narrow range of variability and probable difficulty in establishing significant differences among slash groups seems to warrant application of one relationship between bulk depth and high intercept depth to all slash. Combining all measurement produced the regression:

\[
y = 0.638X
\]

\[
(s = 0.76)
\]

which simply states that bulk depth is 64 percent of high intercept depth. This compares with 52 percent observed by Bevins (1976) in studying Douglas-fir and hemlock slash in Washington.

Interestingly, the finding of 64 percent is consistent with fire spread verification studies (Brown 1972; Bevins 1976; Hough and Albini 1978) in which fuel bed depths that were reduced by factors in the range of 0.6 to 0.7 improved fire spread prediction by the Rothermel model.
### Table 4

<table>
<thead>
<tr>
<th>Type of cutting</th>
<th>Age of dominant species</th>
<th>Areas included</th>
<th>b-coefficient</th>
<th>Average Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground-lead harvest</td>
<td>DF</td>
<td>0-1, 1975-2, 10, 11, 12, 13, 14, 20</td>
<td>0.610</td>
<td>0.050</td>
</tr>
<tr>
<td>Ground-lead harvest</td>
<td>DF</td>
<td>3-4, 1975-3, 5, 7, 8, 9</td>
<td>0.599</td>
<td>0.031</td>
</tr>
<tr>
<td>Ground-lead harvest</td>
<td>LP</td>
<td>3, 1975-23, 24, 25, 26</td>
<td>0.596</td>
<td>0.079</td>
</tr>
<tr>
<td>Ground-lead harvest</td>
<td>LP</td>
<td>1, 1976-3, 4, 23, 24, 30</td>
<td>0.608</td>
<td>0.036</td>
</tr>
<tr>
<td>Precommercial thinning</td>
<td>PP</td>
<td>4, 1976-10, 12, 13, 15, 16</td>
<td>0.592</td>
<td>0.107</td>
</tr>
<tr>
<td>Precommercial thinning</td>
<td>LP</td>
<td>3-4, 1976-1-2, 5, 6, 7, 17</td>
<td>0.653</td>
<td>0.066</td>
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<tr>
<td>Precommercial thinning</td>
<td>DP</td>
<td>3-4, 1975-4, 15, 16, 17, 18, 19, 21, 22</td>
<td>0.575</td>
<td>0.092</td>
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<tr>
<td>Precommercial thinning</td>
<td>PP</td>
<td>1, 1976-9, 11, 27, 28</td>
<td>0.713</td>
<td>0.059</td>
</tr>
<tr>
<td>Precommercial thinning</td>
<td>LP</td>
<td>1, 1976-29, 31</td>
<td>0.689</td>
<td>0.086</td>
</tr>
<tr>
<td>Skyline harvest</td>
<td>Mixed</td>
<td>1, 1976-14, 18, 19, 20, 21, 22, 25, 26</td>
<td>0.673</td>
<td>0.056</td>
</tr>
<tr>
<td>Helicopter harvest</td>
<td>Mixed</td>
<td>1, 1976-35, 36, 37, 38</td>
<td>0.631</td>
<td>0.048</td>
</tr>
</tbody>
</table>

### Effect of Lopping

The effect of lopping was evaluated by combining bulk depths determined before and after lopping, as a data pair for each study area and computing a linear regression constrained through the origin. The resulting equation is plotted over the scatter diagram shown in figure 6. Similarly, the data from all precommercial thinning areas were combined for regression (as shown in fig. 7). The quality of the relationships expressed by "$R^2"$ values of 0.91 and 0.69, respectively, was good. Note that the ratio of the regression coefficients in table 3 for lopped and unlopped high-lead harvest debris (5.60/4.60 = 0.78) is quite close to our result of 0.83 (fig. 6).

### HAZARD Model Application

To illustrate how this study has been utilized, sample printouts of fuel inputs (fig. 8) and fire behavior predictions (fig. 9) are shown for the slash HAZARD model now in use by USDA Forest Service Northern Region. This model affords managers the opportunity to assess the fire implications of tree cutting activities before debris is put on the ground. The fuel loadings required to run the HAZARD model are generated from tree inventories processed through a debris prediction model. The debris prediction model provides total potential debris for all trees on a site. Managers then tailor the total potential debris to specific cutting prescriptions and submit the data for processing by the HAZARD model. To ease checking of the transferred data, the HAZARD model prints out the input data (fig. 8).
Figure 8.—Sample printout of fuel inputs as produced by HAZARD program.
Factors for converting fuel inputs shown in Figure 9. A further discussion of model output and a guide to interpretation of the fire behavior numbers are in the Northern Region’s Users’ Guide.

Fuel Bed Depth Prediction

To predict fuel bed depth, predictions of slash in tons per acre are converted to number of 1/4- to 1-inch intercepts through two manipulations. First, weight per unit area is converted to number of 1/4- to 1-inch intercepts by species, using a constant multiplier that is inversely proportional to the product of wood density of the 1/4- to 1-inch slices and their mean square diameter (Brown 1974). Table 5 gives the conversion factors for 11 western conifer species.

Next, number of intercepts are combined for different species. Equations have been given that relate bulk depth to the count of 1/4- to 1-inch fuel intercepts in two crossed, 2-foot vertical planes (this relationship is the same as that for a randomly placed single 4-foot vertical plane). The equations for the pines and other conifers are different, so in some cases a method of combining them is necessary.

The depth prediction equation can be written for slash of one type species as:

\[ \delta = m \times \delta' \]

where

- \( \delta \) = initial bulk depth
- \( \delta' \) = expected number of intercepts of 1/4- to 1-inch fuel particles in a randomly placed 1-foot vertical plane.
The quantity $x$ is proportional to the average loading on the site of 1/4- to 1-inch fuel pieces. When only pines are present in the fuel bed, or when none are present, this formula provides a prediction of fuel bed depth for fire modeling. But when both types are present, the mixed species fuel bed depth will contain contributions for both types. The model for mixed type fuel bed depths used in the HAZARD model is as follows:

Let $x_1$ = expected 1/4- to 1-inch count per foot for pine types, and $x_2$ = expected 1/4- to 1-inch count per foot for other types.

If the two types are randomly distributed over the site, then the fraction of the total 1/4- to 1-inch size class loading that is pine type should be (ignoring particle density differences) $f_1$, where

$$ f_1 = x_1 / (x_1 + x_2) $$

and the fraction for other types is $f_2$, where

$$ f_2 = x_2 / (x_1 + x_2) = 1 - f_1. $$

Now, if the two types were segregated on the site, so that a fraction $f_1$ of the site is covered by pine species and $f_2$ by others, the expected intercept count in the pine-covered area would be $x_1/f_1$ and the bulk depth in the pine-covered area would be

$$ g^{(1)} = a_1 x_1 / f_1. $$

Similarly, the bulk depth of the other fraction of the area would be

$$ g^{(2)} = a_2 x_2 / f_2. $$

On such a segregated site, the average bulk depth would be $g_0$, where

$$ g_0 = f_1 g^{(1)} + f_2 g^{(2)}. $$

We take this latter expression to be the average fuel bed depth for the mixed type situation. This equation can be rewritten by substituting for the $f$ and $g_0$ values to give

$$ g_0 = (a_1 x_1 + a_2 x_2) / (x_1 + x_2). $$

Other factors that affect initial fuel bed depth are reflected in this formula by changing the values of $a_1$ and $a_2$ in accordance with the results discussed earlier (fig. 4).

**Foliage Loss and Settling**

The early effects of aging on debris fuels are settling of the fuel bed and loss of foliage and fine twigs to the forest floor. For modeling fire behavior in slash, it is necessary to quantify rate of settling and the loss of foliage and fine twigs. To operate the HAZARD model, data from Olson and Fahnestock (1955), Fahnestock and Dietrich (1962), Steele (1969), Wagner and Offord (1972), and Fromm (1970a) were integrated to describe loss of material (fig. 10). Not all foliage that drops from the branches was excluded from the fuel complex because some foliage remaining in the litter layer and suspended as mats in the slash is still available as fuel for a surface fire.

Settling of slash was modeled as a reduction in depth using table 3, Fahnestock and Dietrich (1962), and Kill (1968). This study, together with others cited, permitted construction of a settling model adequate for hazard appraisal (fig. 11).
SUMMARY

To aid in modeling fire behavior for appraisal of slash hazard, equations were developed for predicting fuel bed depth from the loading of 1/4- to 1-inch fuels. The depth equations differed among precommercial thinning, ground-lead ha-vesting, and high-load harvesting systems and between pines and other conifers. Settling of slash with age was weakly discerned; however, our findings, together with others, permitted inference of a rough aging model that distinguishes between harvesting and precommercial thinning.

Depth of unlogged slash was strongly related to depth of unlogged slash. A strong relationship was also developed between the "bulk depth," useful in fire behavior modeling, and the "high intercept" depth that is easily measured in the field. The influence of merchantable tip diameter on slash depth was evident, although it was not quantified. Accuracy of the depth relationships is probably adequate for most tree cutting activities in western mountainous areas, except perhaps west side slopes along the Pacific Coast. Here the large trees and methods of logging may result in depth/load relationships different from ours. Depth predictions should be verified in the Pacific Coast mountains before modeling fire behavior in slash.

When predictions of fuel depth are coupled with predictions of slash loading (by size class) from tree inventories, the depth models presented here allow prediction of fire behavior before the slash is created. Hopefully, this information will aid in timber sale planning and in management of slash fuels.

REFERENCES


Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field programs and research work units are maintained in:

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