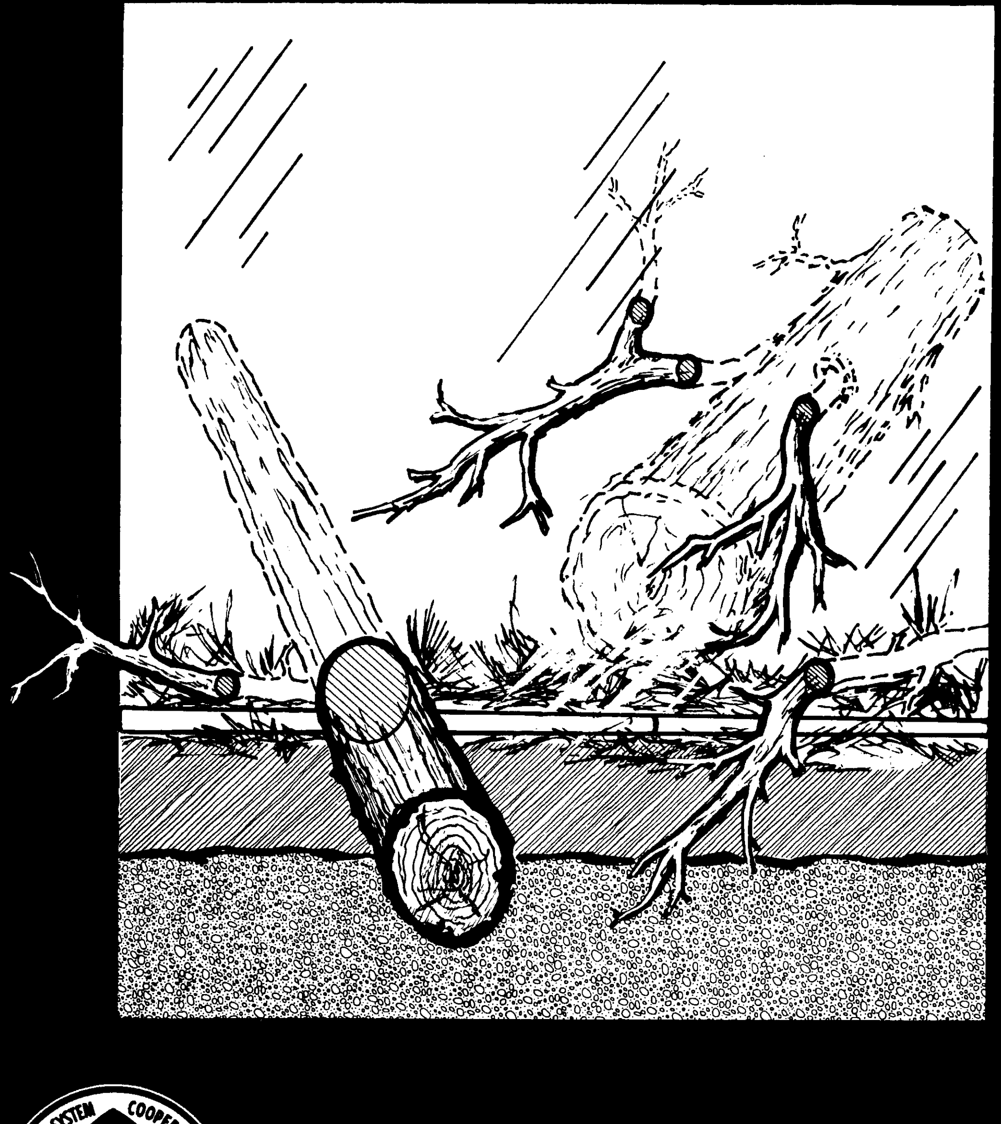
HANDBOOK FOR INVENTORYING DOWNED WOODY MATERIAL

James K. Brown



USDA Forest Service General Technical Report INT-16, 1974
INTERMOUNTAIN FOREST & RANGE
EXPERIMENT STATION
Ogden, Utah 84401

USDA Forest Service
General Technical Report INT-16
September 1974

HANDBOOK FOR INVENTORYING DOWNED WOODY MATERIAL

James K. Brown

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401
Roger R. Bay, Director

THE AUTHOR

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

CONTENTS

ABSTRACT

To facilitate debris management, procedures for inventorying downed woody material are presented. Instructions show how to estimate weights and volumes of downed woody material, fuel depth, and duff depth. Using the planar intersect technique, downed material is inventoried by 0- to 0.25-inch, 0.25- to 1-inch, and 1- to 3-inch diameter classes; and by 1-inch classes for sound and rotten pieces over 3 inches. The method is rapid and easy to use and can be applied to naturally fallen debris and to slash. The method involves counting downed woody pieces that intersect vertical sampling planes and measuring the diameters of pieces larger than 3 inches in diameter. The piece counts and diameters permit calculation of tons per acre.

OXFORD: 431
KEYWORDS: fire causes (forest), fuel inventory, forest fuels, debris, planar intersect method, sampling methods.

INTRODUCTION

This Handbook tells how to inventory weights, volumes, and depths of downed woody material. Downed woody material is the dead twigs, branches, stems, and boles of trees and brush that have fallen and lie on or above the ground. This material is usually called slash or logging debris if man creates it by cutting; it is called fuel, natural debris, or detritus if it accumulates without cutting.

Inventorying downed woody material can help land managers practice fuel management, plan for prescribed fire, and estimate utilization potential. For example, undesirable fuel hazards can be identified and plans made for hazard reduction. Fire behavior in wilderness areas can be predicted to aid in implementing let-burn fire policies. The volume of downed fiber can be estimated to plan for sales, removal, and utilization. Managers can communicate in exact terms about their debris problems.

The inventory can be done to provide all or any part of the following information:

1. Weights and volumes per acre of downed woody material for
    a. Diameter size classes of 0 to 0.25, 0.25 to 1, and 1 to 3 inches; and
    b. Diameters of 3 inches and larger for sound and rotten conditions.
2. Average diameter of debris larger than 3 inches.
3. Depth of fuel and forest floor duff.

This Handbook applies most accurately in the western United States because it contains average particle diameters for western conifers; however, the procedures are appropriate for forests everywhere. The inventory procedures are rapid and easy to use. For average amounts of downed debris, about 5 to 6 minutes per sample point are required for the measurements. More time is usually spent in traveling and locating sample points than in making the measurements. If only downed woody material is inventoried, a two-man crew can complete 20 to 40 plots a day, depending on how much debris is present.

The inventory of volumes and weights is based on the planar intersect technique (Brown 1971; Brown and Roussopoulos 1974), which has the same theoretical basis as the line intersect technique (Van Wagner 1968). The planar intersect technique involves counting intersections of woody pieces with vertical sampling planes that resemble guillotines dropped through the downed debris. Volume is estimated; then weight is calculated from volume by applying estimates of specific gravity of woody material. The planar intersect technique is nondestructive and avoids the time-consuming, costly, and often impractical task of collecting and weighing large quantities of forest debris.

Woody pieces less than 3 inches in diameter are tallied by size classes. Pieces 3 inches and larger are recorded by their diameters. Size classes of 0 to 0.25, 0.25 to 1, and 1 to 3 inches were chosen for tallying intersections because:

1. The class intervals provide the most resolution for fine fuels and are small enough to permit precise estimates of volume.

2. They correspond, in increasing size, to 1-, 10-, and 100-hour average moisture timelag classes for many woody materials (Fosberg 1970). [These are standard moisture timelags used in the National Fire-Danger Rating System (Deeming and others 1972).]

Inventory chosen areas as follows:

1. Decide on length of sampling planes and number of sample points.

2. Complete the fieldwork.

3. Calculate weight or volume, size, and depth of debris.

NUMBER AND SIZE OF SAMPLING PLANES

Choose sampling plane lengths from the following tabulation:

Downed material	*Diameter of debris*		
	0-1 in	*1-3 in*	*>3 in*
	Sampling plane (ft)		
Nonslash (naturally fallen material)	6	10-12	35-50
Discontinuous light slash	6	10-12	35-50
Continuous heavy slash	3	6	15-25

For any area where estimates are desired, 15 to 20 sample points should be located using the sampling plane lengths shown in the tabulation. This sampling intensity will often yield estimates having standard errors within 20 percent of the mean estimates. Areas larger than approximately 50 acres that contain a high diversity in amount and distribution of downed material should be sampled with more than 20 points. If material larger than 3 inches in diameter is scanty or unevenly distributed, the longer sampling planes in the tabulation should be used.

The amount and distribution of downed woody material vary greatly among and within stands. Thus, these sampling recommendations should be considered approximate because a greater or fewer number of plots may be required to furnish adequate precision for any given area. Sampling intensities are discussed further in Appendix I.

FIELD PROCEDURES

Locating Sample Points

Locate plots systematically; two methods are:

1. Locate plots at a fixed interval along transects that lace regularly across a sample area (uniform sampling grid). For example, on a sample area, mark off parallel transects that are 5 to 10 chains apart. Then along the transects locate plots at 2- to 5-chain intervals.

2. Locate plots at a fixed interval along a transect that runs diagonally through the sample area. To minimize bias, have the transect cross obvious changes in fuels. Before entering the sample area, determine a transect azimuth and distance between plots.

Sample Point Procedures

Step 1: *Mark the sampling point* with a chaining pin (No. 9 wire or similar item). Avoid disturbing material around the point. Accurate estimates require measurements of undisturbed material. If standing tree measurements (d.b.h. and height) are a part of the inventory, measure downed material first.

Step 2: *Determine direction of sampling plane* by tossing a die to indicate one of six 30° angles between 0° and 150° (fig. 1). The 0° heading is the transect direction. Turn a fixed direction, such as clockwise, to position the sampling plane. As an alternative for indicating direction of the sampling plane, use the position of the second hand on a watch at a given instant. To avoid bias in placement of the sampling plane, do not look at the fuel or ground while turning the interval.

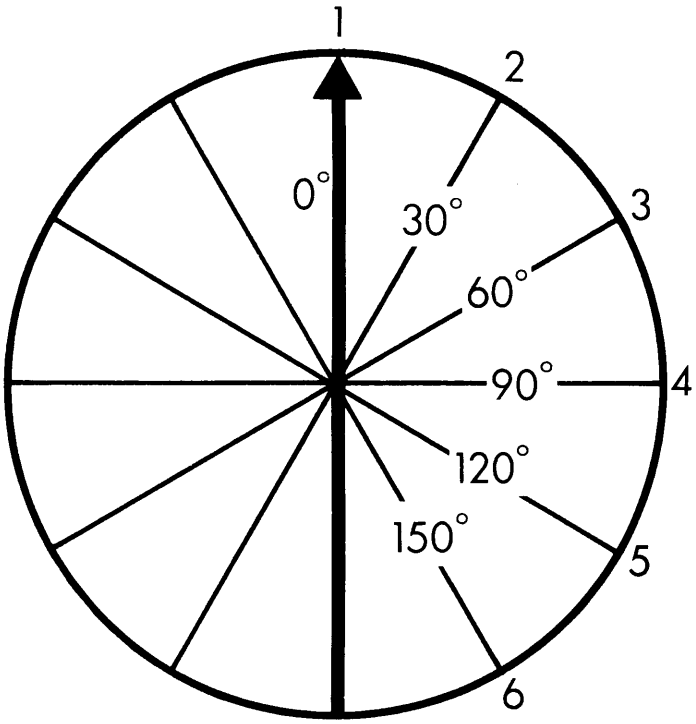


Figure 1.--Locating sampling plane by using die to pick one of six directions.

<u>*Step 3:*</u> *Denote position of the sampling plane* by running a tape or string out from the sampling point *parallel to the ground* in the direction determined in Step 2 (fig. 2). Extend the tape to the length of the longest sampling plane. A fiberglass rod or 1/2-inch aluminum tube placed along the string beginning at the sampling point facilitates counting pieces less than 1 inch in diameter. The rod should be 6 feet long, the length of sampling plane for small particles. The tape and rod fix the position of vertical sampling planes.

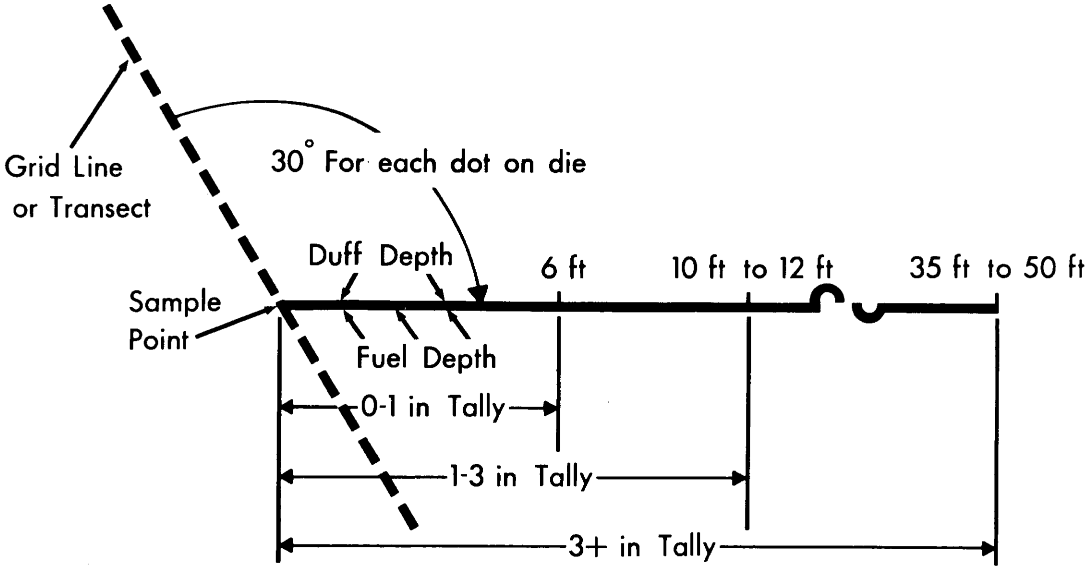


Figure 2.--Top view of sampling plane and location of fuel depth measurements.

Step 4: *Measure or estimate slope* by sighting along the sampling plane from the sample point using an Abney level or similar device. Ample precision is the nearest 10 percent, which can be coded using one digit (10 percent = 1, 90 percent = 9, etc.).

Step 5: *Tally the number of particles* that intersect the sampling plane by the following size classes:

0 to 0.24 inch (0 to 0.6 cm)

0.25 to 0.99 inch (0.6 to 2.5 cm)

1.0 to 2.99 inches (2.5 to 7.6 cm)

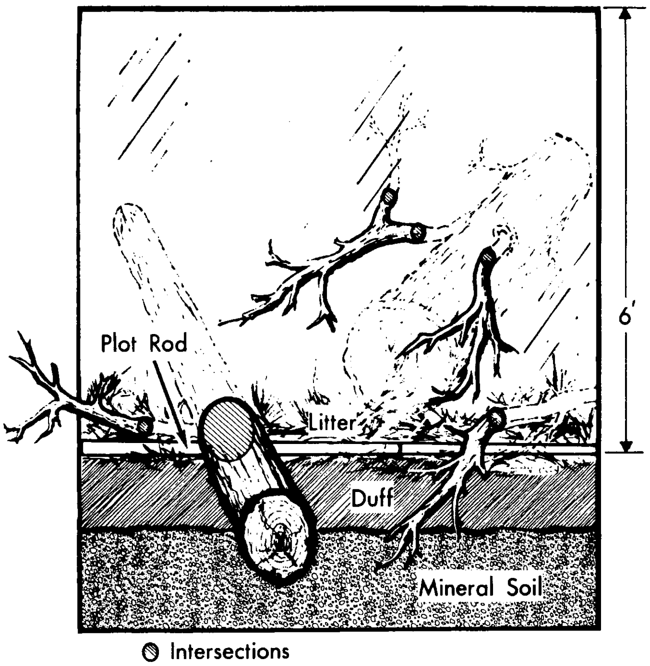
The intersections can be counted one size class at a time or "dot tallied," which takes slightly longer than counting (see sample data form, page 14).

The actual diameter of the particle at the point of intersection determines its size class. A go-no-go gage with openings 0.25 inch, 1 inch, and 3 inches works well for separating borderline particles into size classes and for training the eye to recognize size classes (fig. 3).

The vertical plane is a plot. Consequently, in counting particle intersections, it is very important to visualize the plane passing through one edge of the plot rod and terminating along an imaginary fixed line on the ground. *Once visualized on the ground, the position of the line should not be changed while counting particles* (fig. 4). See tally rules for qualifying particles.

Figure 3.--Diameter of the intersected twig is checked with a go-no-go gage. The plot rod marks the sampling plane.

Figure 4.--The sampling plane is exactly defined by one edge of the plot rod.



Step 6: *Take three measurements of dead fuel depth.* Record depth as the vertical distance from the bottom of the litter layer to the highest intersected dead particle for each of three adjacent 1-foot-wide vertical partitions of the sampling plane (fig. 5). Litter is the surface layer of the forest floor and consists of freshly fallen leaves, needles, twigs, bark, and fruits. Begin the vertical partitions at the sample point. Record to the nearest whole inch.

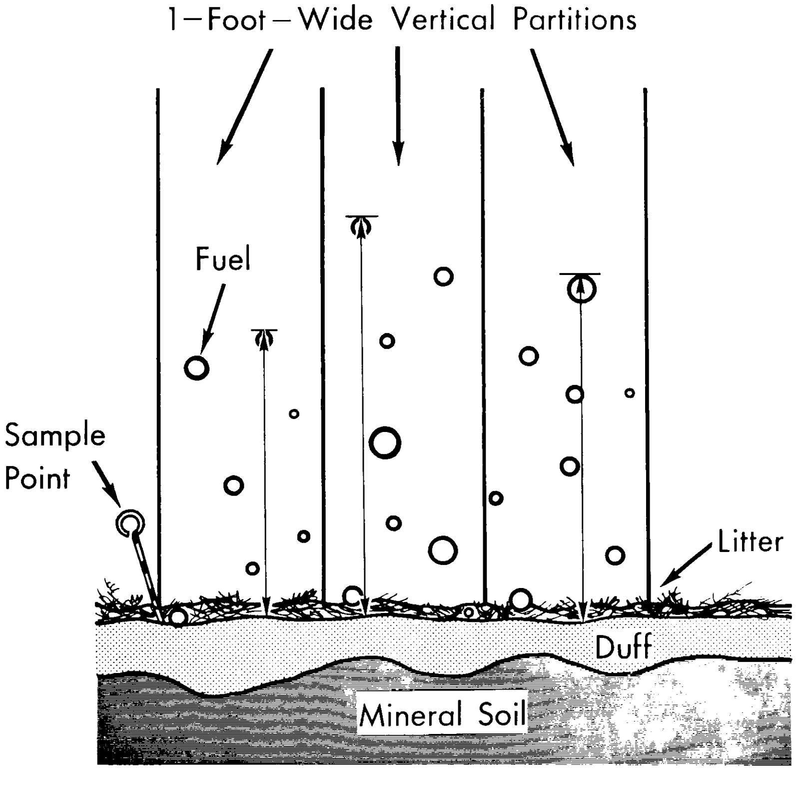


Figure 5.--Cross section of a fuel bed. Depth is measured along the arrows in each 1-foot-wide partition.

Depth should be measured from only those particles included in the inventory for loading. For example, particles acceptable for measurement by the planar intersect technique are also acceptable for determining depth. If other techniques are used to estimate weight per acre of grass and forbs, this vegetation would also qualify for determining depth.

Step 7: *Measure vertical depth of duff* to the nearest 0.1 inch using a ruler along the sampling plane at two points: (1) 1 foot from the plot center; and (2) a fixed distance of 3 to 5 feet from the first measurement.

Duff is the fermentation and humus layers of the forest floor. It does not include the freshly cast material in the litter layer. The top of the duff is where needles, leaves, and other castoff vegetative material have noticeably begun to decompose. Individual particles usually will be bound by fungal mycelium. When moss is present, the top of the duff is just below the green portion of the moss. The bottom of the duff is mineral soil.

Carefully expose a profile of the forest floor for the measurement. A knife or hatchet helps but is not essential. Avoid compacting or loosening the duff where the depth is measured.

When stumps, logs, and trees occur at the point of measurement, offset 1 foot perpendicular to the right side of the sampling plane. Measure through rotten logs whose central axis is in the duff layer (fig. 6).

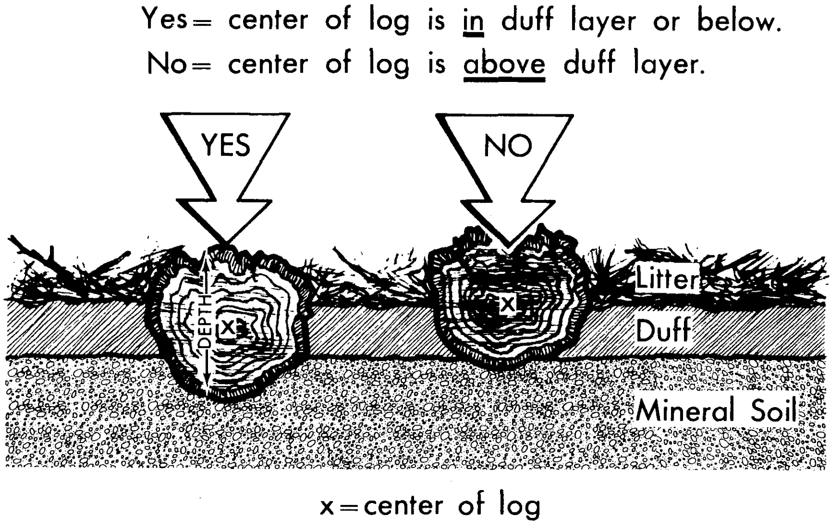


Figure 6.--Duff depth is measured through a rotten log when its central axis lies in or below the duff.

Step 8: *Measure or estimate the diameters* of all pieces 3 inches in diameter and larger that intersect the sampling plane. Measure the diameters at the point of intersection to the nearest whole inch.

Record diameters separately for rotten and nonrotten pieces. Consider pieces rotten when the piece at the intersection is obviously punky or can be easily kicked apart.

A ruler laid perpendicularly across a large piece of fuel works satisfactorily for measuring diameter. Be sure to avoid parallax in reading the ruler. Calipers also work well for measuring diameter. A diameter tape, however, is unsatisfactory for pieces in contact with the ground.

Use as many consecutive lines on the data form (see page 14) as necessary to record diameters.

Step 9: *For the entire sample area, record the predominate species* of the 0- to 1-inch-diameter branchwood. An average diameter for the 0- to 0.25-inch, and 0.25- to 1-inch size classes will be selected from this information. If several species comprise the downed debris, estimate the proportion of the two or three most common species. Base this estimate on a general impression of what exists on the sample area and record as percentages of total 0- to 1-inch branchwood. Or, for a slight reduction in accuracy, omit this step and in the calculations use an average diameter for a composite of species (page 16).

TALLY RULES

The following rules apply to downed woody pieces of all diameters:

1. Particles qualifying for tally include *downed, dead* woody material (twigs, stems, branches, and bolewood) from trees and shrubs. Dead branches attached to boles of standing trees are omitted because they are not downed vegetation. Consider a particle downed when it has fallen to the ground or is severed from its original source of growth. Cones, bark flakes, needles, leaves, grass, and forbs are not counted. *Dead woody stems and branches still attached to standing brush and trees are not counted.*

2. Twigs or branches lying in the litter layer and above are counted. However, they are not counted when the intersection between the central axis of the particle and the sampling plane lies in the duff (forest floor below the litter) (fig. 7).

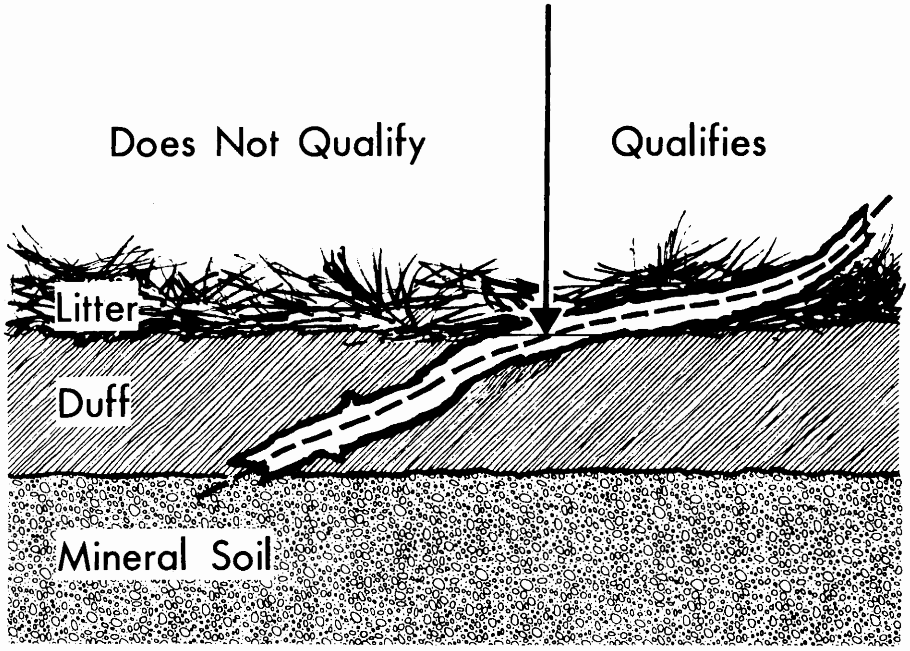


Figure 7.--Regardless of size, pieces are tallied only when intersection lies in and above the litter (right of arrow).

3. If the sampling plane intersects the end of a piece, tally only if the central axis is crossed (fig. 8). If the plane exactly intersects the central axis, tally every other such piece.

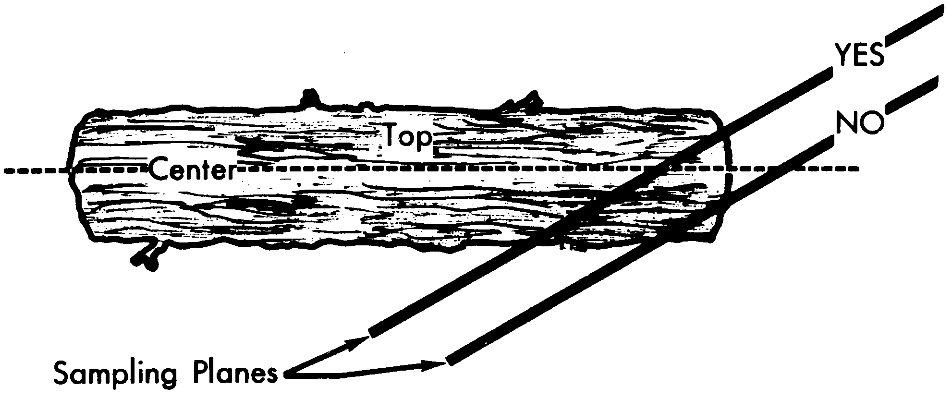


Figure 8.--An intersection at the end of a branch or log must include the central axis to be tallied.

4. Don't tally any particle having a central axis that coincides perfectly with the sampling plane. (This should rarely happen.)

5. If the sampling plane intersects a curved piece more than once, tally each intersection (fig. 9).

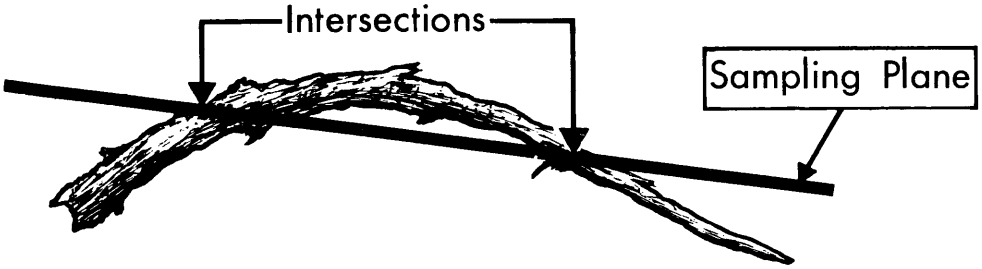


Figure 9.--Count both intersections for a curved piece.

6. Tally wood slivers and chunks left after logging. Visually mold these pieces into cylinders for determining size class or recording diameters.

7. Tally uprooted stumps and roots not encased in dirt. For tallying, consider uprooted stumps as tree boles or individual roots, depending on where the sampling planes intersect the stumps. Do not tally undisturbed stumps.

8. For rotten logs that have fallen apart, visually construct a cylinder containing the rotten material and estimate its diameter. The cylinder will probably be smaller in diameter than the original log.

9. Be sure to look up from the ground when sampling because downed material can be tallied up to any height. A practical upper cutoff is about 6 feet. However, in deep slash it may be necessary to tally above 6 feet.

When standing trees are inventoried along with downed material, it is necessary to fix a limit above the ground for sampling downed material. An upper limit helps define a downed tree so that inventory of standing and downed materials will not overlap.[1]

HEAVY SLASH OPTIONS

1. A yardstick attached to a Jacob's staff is useful for marking the sampling plane and speeds the counting of small particles (fig. 10). Erect the Jacob's staff at the sample point. Aline the yardstick with the direction of the sample plane and level it using an attached bubble level.

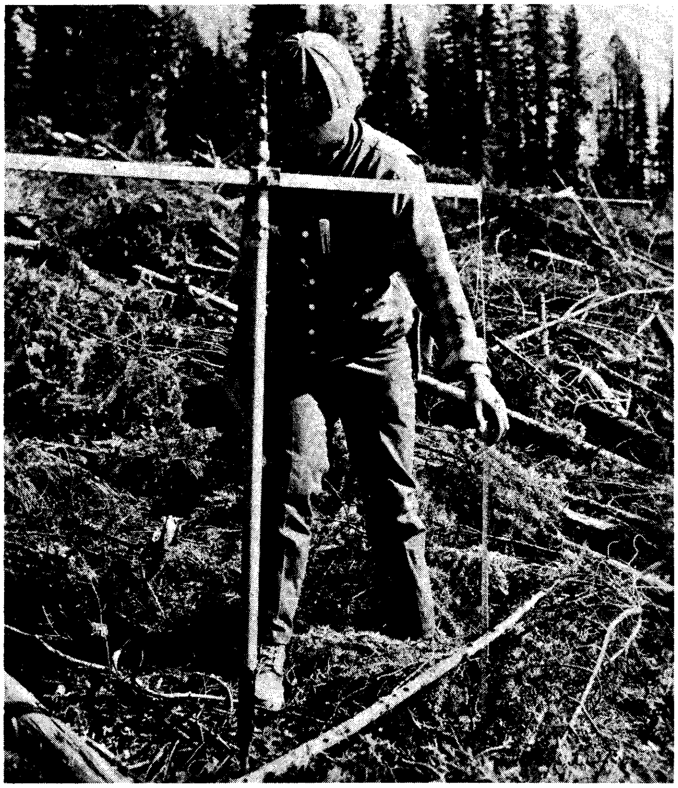


Figure 10.--A yardstick or meter stick attached to a Jacob's staff defines the sampling plane in heavy slash.

2. In areas with considerable slash, sampling efficiency is improved by ocularly estimating the number of 0- to 0.25-inch intersections and actually counting the number of intersections at a subsample of points. The ocular estimates are adjusted using the ratio of ocular estimates-to-actual counts. This method, incorporating 3P sampling, is described in detail by Beaufait and others (1974).

---

[1] In the USDA Forest Service Northern Region, a rule has been established that a stem is "downed" and thus qualifies for tallying when the intersection of the sampling plane and central axis is 6 feet or less from the ground. If the midpoint of the bole is more than 6 feet above ground for trees encountered in fixed and variable radius plots, they are inventoried as "standing."

3. For each sampling plane, estimate the proportion of 0- to 1-inch-diameter branchwood to the nearest 10 percent for the three most common species.

UTILIZATION OPTIONS

For pieces over 3 inches in diameter, the following additional measurements can be useful for describing utilization potential:

1. Species
2. Length of piece
3. Diameter at large end
4. Degree of checking, rot, and other defects that apply to the entire piece.

Field Equipment

Item	*Use*
1. Hand compass	Transect and plot layout.
2. Gaming die	Random orientation of sampling planes.
3. 50-foot tape or string and one chaining pin	Delineate the sampling planes.
4. Plot rod	Delineate sampling planes and if calibrated, measure fuel depth.
5. Go-No-Go gage (fig. 11)	Determine size class of borderline particles.
6. 1-foot ruler or steel pocket tape	Measure duff depth and diameters of pieces over 3 inches. Fuel depth could be measured with steel pocket tape.
7. Hypsometer with percent scale	Slope measurement.
8. Sample forms	Record data.
9. For slash: Jacob's staff with attached yard or meter stick and level	Delineate sampling plane for counting small particles.

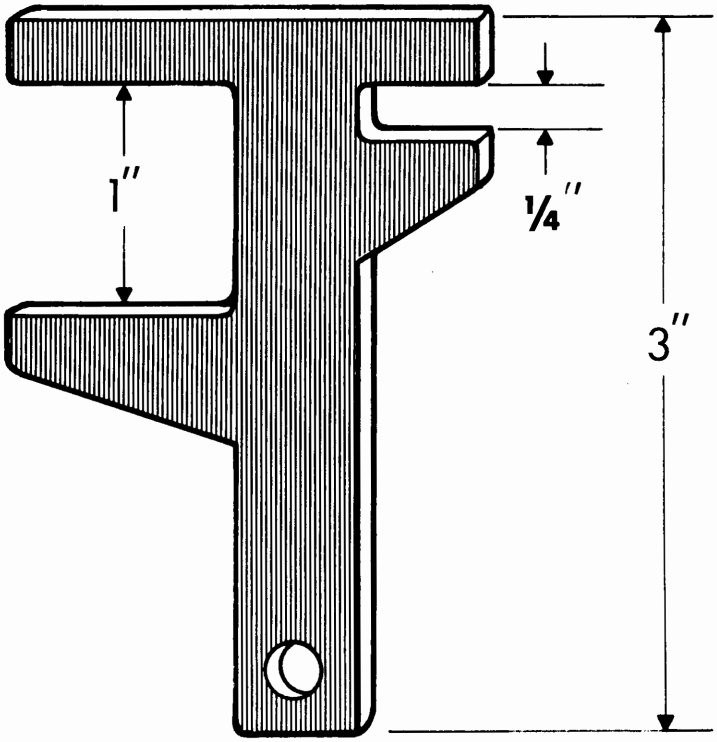


Figure 11.--A Go-No-Go gage can be cut from 1/16 or 1/8-inch sheet aluminum. Cut the notches slightly tight and file smooth to final dimensions.

CALCULATIONS

The calculations can be readily processed by computer[2] and are also easy using a desk calculator. Sample calculations are shown in figures 12 and 13. For a given stand or sample area, fill in the computation summary sheet as follows:

1. Calculate the average slope correction factor (c) using slope correction factors for each sampling plane. Look up the correction factors in table 1 or compute them by:

$$c = \sqrt{1 + \left(\frac{\text{Percent slope}}{100}\right)^2}$$

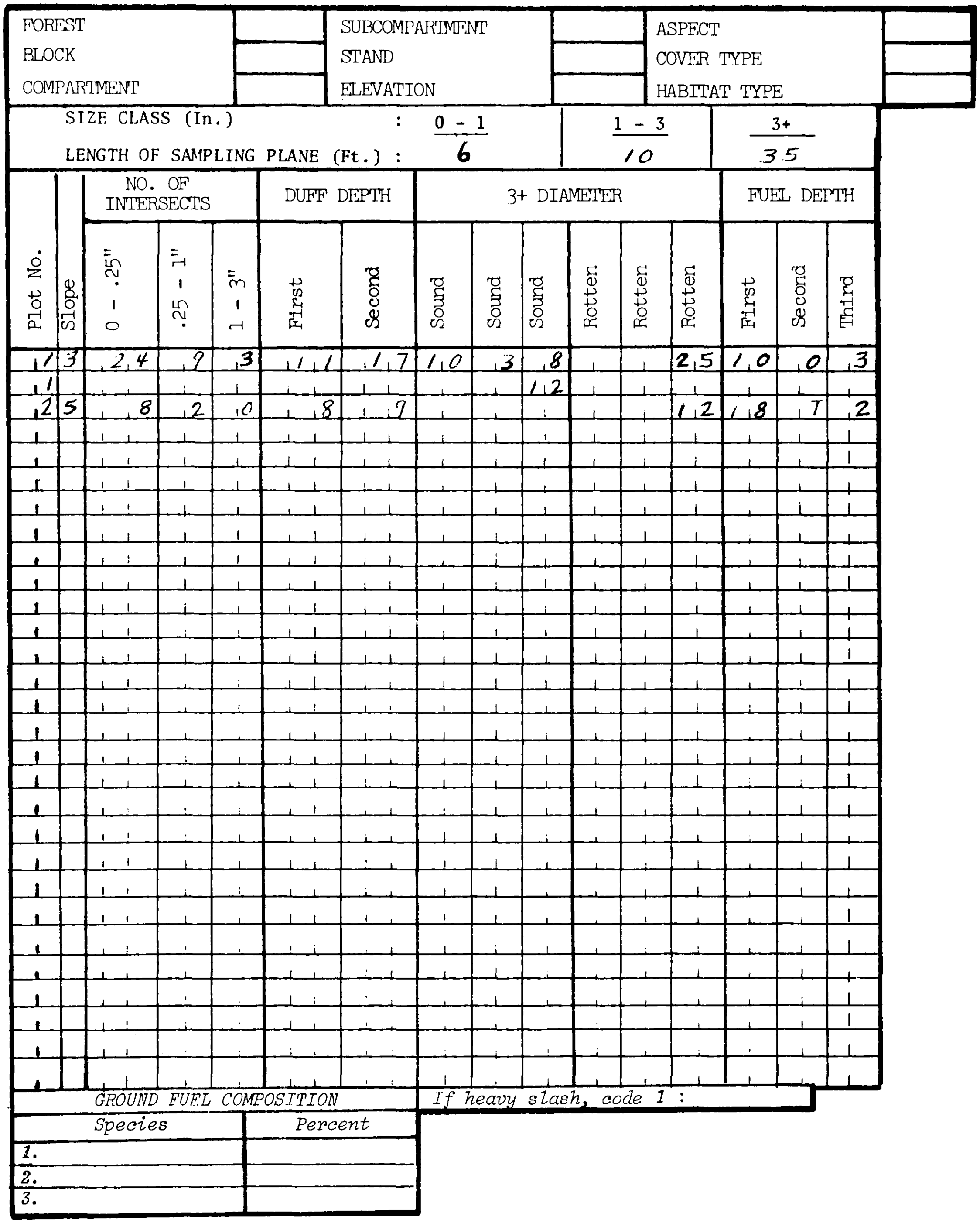
No slope correction is needed for samples taken using the Jacob's staff.

Table 1.--*Slope correction factors for converting weight/acre on a slope basis to a horizontal basis*

Slope	Correction factor	Slope	Correction factor
Percent	*c*	*Percent*	*c*
0	1.00	60	1.17
10	1.00	70	1.22
20	1.02	80	1.28
30	1.04	90	1.35
40	1.08	100	1.41
50	1.12	110	1.49

---

[2] Card punching instructions and a FORTRAN program for computing the inventory results are available upon request from the Northern Forest Fire Laboratory, Drawer G, Missoula, Montana 59801.



DOWNED FUEL INVENTORY

FOREST		SUBCOMPARTMENT		ASPECT	
BLOCK		STAND		COVER TYPE	
COMPARTMENT		ELEVATION		HABITAT TYPE	

SIZE CLASS (In.) :	0 - 1	1 - 3	3+
LENGTH OF SAMPLING PLANE (Ft.) :	6	10	35

		NO. OF INTERSECTS			DUFF DEPTH		3+ DIAMETER						FUEL DEPTH		
Plot No.	Slope	0 - .25"	.25 - 1"	1 - 3"	First	Second	Sound	Sound	Sound	Rotten	Rotten	Rotten	First	Second	Third
1	3	24	9	3	11	17	10	3	8			25	10	0	3
1									12						
2	5	8	2	0	8	9						12	18	7	2

If heavy slash, code 1 :

GROUND FUEL COMPOSITION	
Species	*Percent*
1.	
2.	
3.	

Figure 12.--Sample data form.

DOWNED WOODY MATERIAL COMPUTATION SUMMARY

FOREST:__________ COMPARTMENT:__________ STAND:__________

Formulas to compute tons/acre:

(A) 0- to 3-inch material: $= \frac{11.64 \times n \times d^2 \times s \times a \times c}{N\ell}$

(B) 3+-inch material : $= \frac{11.64 \times \Sigma d^2 \times s \times a \times c}{N\ell}$

Size class	Constant	n	d^2	s	a	c	$N\ell$	Tons/ acre	
0 - .25	11.64	32	.0151	.48	1.13	1.08	12	.275	I
.25 - 1	11.64	11	.289	.48	1.13	1.08	12	1.81	II
1 - 3	11.64	3	2.76	.40	1.13	1.08	20	2.35	III
		Σd^2 for 3+							
3+ Sound	11.64	317		.40	1.0	1.08	70	22.8	IV
3+ Rotten	11.64	769		.30	1.0	1.08	70	41.4	V
				3+ Sound & Rotten = IV + V =				64.2	VI
				Total = I + II + III + VI =				68.6	VII

	Sum of 3+-inch diameters	Number of pieces	Average diameter
Sound :	33	4	8.25 in.
Rotten :	37	2	18.5 in.

Sum of duff depths: : 4.5 in.

Number observations : 4

Average duff depths : 1.1 in.

Sum of fuel depths : 40 in.

Number observations : 6

Average fuel depths : 6.7 in.

Figure 13.--Computation summary sheet. The input values are from figure 12.

2. Total the number of intersections (n) over all sample points for each of the 0- to 0.25-inch, 0.25- to 1-inch, and 1- to 3-inch size classes.[3]

3. From table 2, enter the appropriate squared average diameters (d^2) for each size class on the computation sheet. If species composition has been determined, calculate an average d^2 as:

$$d^2 = \frac{P_1 d^2{}_1 + P_2 d^2{}_2 + P_3 d^2{}_3}{P_1 + P_2 + P_3}$$

Where P_1, P_2, and P_3 are percentages for composition of the species recorded in Step 9 (page 9).

If several species are present and their composition unknown, the composite d^2 values can be used as approximate averages.

Table 2.--*Squared average-quadratic-mean diameters for nonslash and slash ground fuels*

Size class (inches)	Nonslash		Slash	
	Cover type[1]	Average d^2	Species[1]	Average d^2
		Inches^2		*Inches*^{2}
0 - 0.25	PP	0.0342	PP, LP	0.0248
	LP	.0201	L	.0149
	S, DF, AF, C	.0122	DF, GF, C, S	.0122
	L	.0149	Composite[2]	.0151
	Composite	.0151		
0.25 - 1	LP	.344	PP, C	.317
	S, DF, AF, C	.304	DF, GF, LP, L, S	.278
	L, PP	.238	Composite	.289
	Composite	.289		
1 - 3	PP, AF	3.12	LP	3.50
	S, DF, C, LP	2.87	DF, PP, GF	2.83
	L	2.17	L, C, S	2.30
	Composite	2.76	Composite	2.76

[1] PP=ponderosa pine (*Pinus ponderosa)*; LP=lodgepole pine (*Pinus contorta)*; S=Engelmann spruce (*Picea engelmannii)*; DF=Douglas-fir *(Pseudotsuga menziesii)*; L=western larch *(Larix occidentalis)*; GF=grand fir *(Abies grandis)*; C=western redcedar (*Thuja plicata)*; AF=subalpine fir *(Abies lasiocarpa)*.

[2] All composite values are averages of nonslash and slash fuels with each cover type and species weighted equally.

---

[3] For calculating standard errors of the estimate, the number of intersections (Step 2) and the sum of squared diameters (Step 7) must be recorded for each plot.

4. Determine specific gravity(s) of materials from known sources or from laboratory studies. Approximate specific gravities for conifers are:

Diameter class (*inches*):	0-0.25	0.25-1	1-3	3+Sound	3+Rotten
Specific gravity :	0.48	0.48	0.40	0.40	0.30

Decay and variability in density make this variable difficult to handle with accuracy. More accurate estimates for large sound material can be obtained by using specific gravities from the USDA Forest Service (1955) *Wood Handbook*. Special studies, as shown in Appendix II, are needed to improve accuracy for the other particle categories.

5. For slash, determine the nonhorizontal angle correction factors (a) from table 3. For nonslash fuels, use the following correction factors based on a composite of western species:

0 to 3 inches: 1.13

3+ inches: 1.00

The correction factor adjusts weight estimates for the fact that all particles do not lie horizontally as assumed in the planar intersect theory.

Table 3.--*Average secant of nonhorizontal particle angles for correcting orientation bias for slash*

Size class (*inches*)	Species[1]	Average (a)	
		Fresh slash	1-year and older slash
0 to 0.25	PP	1.25	1.25
	Others	1.40	1.15
0.25 to 1	PP	1.25	1.25
	Others	1.13	1.13
1 to 3	PP	1.22	1.22
	Others	1.10	1.10
3+	All (an assumption)	1.00	1.00

[1] PP=ponderosa pine; Others=based on data for Douglas-fir, lodgepole pine, Engelmann spruce, western redcedar, western larch, and grand fir.

6. Calculate the total length of sampling line ($N\ell$) for each size class: $N\ell$ = number of sample points multiplied by length of sampling plane (feet).

7. For material 3 inches and larger, square the diameter of each intersected piece and sum the squared values (Σd^2) for all pieces in the sampled area.[4] Compute

---

[4] *Ibid.*

Σd^2 separately for sound and rotten categories. To obtain weights or volumes for certain diameter ranges (3 to 9 inches, for example), compute Σd^2 for the specified range.

8. Calculate the sum of diameters for all intersected pieces 3 inches and larger (calculate sound and rotten materials separately).

9. Calculate the sum of all measurements for duff depth.

10. Calculate tons/acre, using formulas on the computation sheet (fig. 13).[5] If desired, calculate volumes:

$$\text{Cubic feet per acre} = \frac{32.05 \times \text{tons per acre}}{\text{Specific gravity}}$$

11. Calculate average diameters of intersected pieces 3 inches and larger.

12. Calculate average fuel depth and duff depth as the sum of the depths divided by the number of measurements.

13. Appendix III shows how to calculate needle quantities in slash.

When inventorying large areas that hold many species it is practical to use composite values and approximations for diameters, specific gravities, and nonhorizontal corrections. For example, a timber management and downed-debris inventory in the Northern Region of the USDA Forest Service utilizes composite average diameters, composite average nonhorizontal correction factors, and best approximations for specific gravities.

For the Northern Region inventory, the formulas in figure 13 simplify to:

1. 0- to 0.25-inch size class: $w = 0.09533\ nc/N\ell$
2. 0.25- to 1-inch size class: $w = 1.825\ nc/N\ell$
3. 1- to 3-inch size class : $w = 14.52\ nc/N\ell$
4. 3+-inch sound : $w = 4.656\ \Sigma d^2 c/N\ell$
5. 3+-inch rotten : $w = 3.492\ \Sigma d^2 c/N\ell$

where:

w = weight, tons/acre.

---

[5] The formulas incorporate an insignificant bias because n, Σd^2, and c are totaled separately. Summing $n \times c$ or $\Sigma d^2 \times c$ over all plots would eliminate the biases; however, this is unnecessarily troublesome.

FURTHER APPLICATIONS

If only debris larger than 3 or 4 inches in diameter is to be inventoried, the line intersect technique described by Howard and Ward (1972) and Bailey (1969) might be more appropriate than the planar intersect method, especially in logging slash. The line intersect method employs a few long sampling planes; the planar intersect method employs many small sampling planes. If debris both greater than and less than 3 or 4 inches in diameter must be inventoried, the planar intersect technique is more efficient. The planar intersect technique can also be coordinated with other measurements of vegetation taken on plots (for example, an inventory of timber volume).

The procedures in this Handbook can be applied to downed debris in areas other than the western United States by assuming or measuring average diameters for the three size classes of particles. Average diameters have been determined for red pine (*Pinus resinosa*), jack pine (*Pinus banksiana*), and oak (*Quercus* spp.) (Brown and Roussopoulos 1974). A convenient method for estimating slash weights of several Lake States tree species has been reported by Roussopoulos and Johnson (1973).

If fire behavior is to be mathematically modeled using models such as Rothermel's (1972), weights of other fine fuels such as needle litter, dead grass, and dead forbs also should be determined by sampling or by extrapolating from existing information. Sampling for quantities of grass, forbs, and litter requires methods other than the planar intersect technique (USDA Forest Service 1959; Brown 1966; Hutchings and Schmautz 1969).

Because practical methods of inventory have been lacking in the past, accumulations of downed fuel and debris have been described in vague terms such as "light," "medium," and "heavy." Using the simple field procedures in this Handbook, weight and volume of downed woody material can be inventoried to provide an objective basis for managing debris.

LITERATURE CITED

Bailey, G. R.
1969. An evaluation of the line-intersect method of assessing logging residue. Can. Dep. Fish. & For., For. Prod. Lab. Inf. Rep. VP-X-23, 41 p.

Beaufait, William R., Michael A. Marsden, and Rodney A. Norum
1974. Inventory of slash fuels using 3P subsampling. USDA For. Serv. Gen. Tech. Rep. INT-13, 17 p., illus.

Brown, J. K.
1966. Forest floor fuels in red and jack pine stands. USDA For. Serv. Res. Note NC-9, 3 p.

Brown, James K.
1971. A planar intersect method for sampling fuel volume and surface area. For. Sci. 17(1):96-102, illus.

Brown, James K.
1972. Field test of a rate-of-fire-spread model in slash fuels. USDA For. Serv. Res. Pap. INT-116, 24 p., illus.

Brown, James K., and Peter J. Roussopoulos
Eliminating biases in the planar intersect method for sampling small fuel volumes. For. Sci. (In press.)

Deeming, John E., James W. Lancaster, Michael A. Fosberg, R. William Furman, and Mark J. Schroeder
1972. National fire-danger rating system. USDA For. Serv. Res. Pap. RM-84, 165 p.

Fahnestock, G. R.
1960. Logging slash flammability. USDA For. Serv. Res. Pap. INT-58, 67 p., illus.

Fosberg, Michael A.
1970. Drying rates of heartwood below fiber saturation. For. Sci. 16(1): 57-63, illus.

Howard, James O., and Franklin R. Ward
1972. Measurement of logging residue--alternative applications of the line intersect method. USDA For. Serv. Res. Note PNW-183, 8 p.

Hutchings, S. S., and J. E. Schmautz
1969. A field test of the relative-weight-estimate method for determining herbage production. J. Range Manage. 22:408-411.

Roussopoulos, P. J., and V. J. Johnson
1973. Estimating slash fuel loading for several Lake States tree species. USDA For. Serv. Res. Pap. NC-88, 8 p.

Rothermel, R. C.
1972. A mathematical model for predicting fire spread in wildland fuels. USDA For. Serv. Res. Pap. INT-115, 40 p., illus.

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

USDA Forest Service
1955. Wood Handbook No. 72, 528 p. For. Prod. Lab., Madison, Wis.

USDA Forest Service
1959. Techniques and methods of measuring understory vegetation. Southern and Southeast For. Exp. Stn. Symp. Proc., 174 p.

APPENDIX I

Sampling Intensities

NUMBER AND SIZE OF SAMPLING PLANES

Sampling precision can be controlled by altering the number of plots and length of sampling planes. As a general rule, the more downed material on an area, the fewer the number and shorter the length of sampling planes required to achieve a given level of precision. Figure 14, based on average sampling variation for number of intersections of 0- to 1-inch and 1- to 3-inch particles, can help in choosing number of plots and length of sampling planes. The data for figure 14 are from many stands of varying composition and downed debris accumulations in northern Idaho and western Montana. Curves for all material under 3 inches in diameter would fall between those for the 0- to 1-inch and 1- to 3-inch classes.

Percent errors of 20 percent or less are probably adequate levels of precision for assessing most fuel problems. Percent error is the standard error of the estimate divided by the mean estimate and expressed as a percentage. More precision, such as percent errors of 10 to 15 percent, may be desirable for evaluating utilization potential of downed woody material.

Precision is maximized using a different length of sampling plane for each size class. However, considering both field effort and precision, it is more efficient to use the same plane length for sampling the 0- to 0.25- and 0.25- to 1-inch classes. The following suggestions will help determine the most efficient number and length of sampling planes for a given area:

1. Record data from about 20 sampling planes in an area and calculate the variation for guiding further sampling.

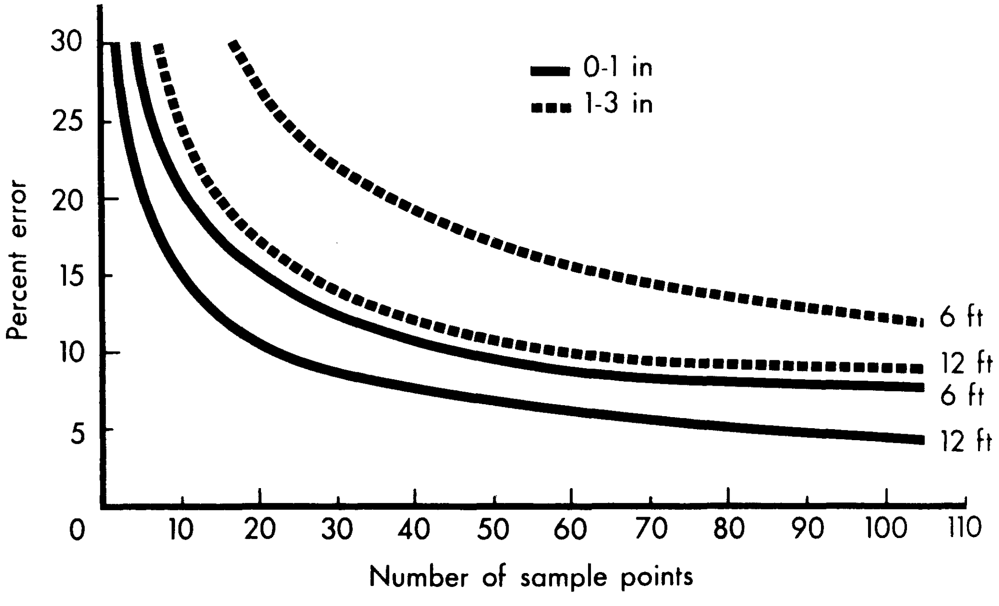


Figure 14.--Percent errors for number of particle intersections along 6- and 12-foot-length sampling planes related to number of sample points for quantities of light slash and nonslash. Percent error is 100X (standard error of the estimate divided by the mean estimate).

2. For material larger than 3 inches in diameter, the sampling plane should be long enough so that on the average at least one intersection occurs with three-fourths or more of the planes. A large sampling variance results when many zeros are recorded for intersections. In areas where very little downed material exists, sampling planes should actually be one to several hundred feet long to provide respectable precision. Where many sampling planes have zero entries, other methods such as measurement of length and diameter of all downed pieces may be the most efficient method of inventory.

3. The number and length of sampling planes should be chosen so that for a piece size of interest, such as material over 3 inches in diameter, at least 35 to 50 intersections occur over an entire sampled area.

SAMPLING PRECISION FOR DEPTH MEASUREMENTS

To achieve percent errors of 15 and 20 percent using two-stage sampling, the most efficient number of secondary sampling units appears to be three for fuel depth and two for duff depth (fig. 15).

The data for figure 15 represent average variation from sampling a wide variety of forest and downed fuel conditions in northern Idaho and western Montana. Several thousand measurements were taken using two secondary sample points for duff depth and three secondary sample points for fuel depth. Vegetation qualifying for fuel depth measurements included all dead downed woody material and dead brush, grass, and forbs. The data were subjected to analysis of variance for two-stage sampling.

The number of sample plots required to attain a given level of precision varies considerably among different areas. For choosing sampling intensities for specific areas the number of primary sample points in figure 15 could be adjusted up or down considerably, depending on homogeneity of the dead vegetation strata.

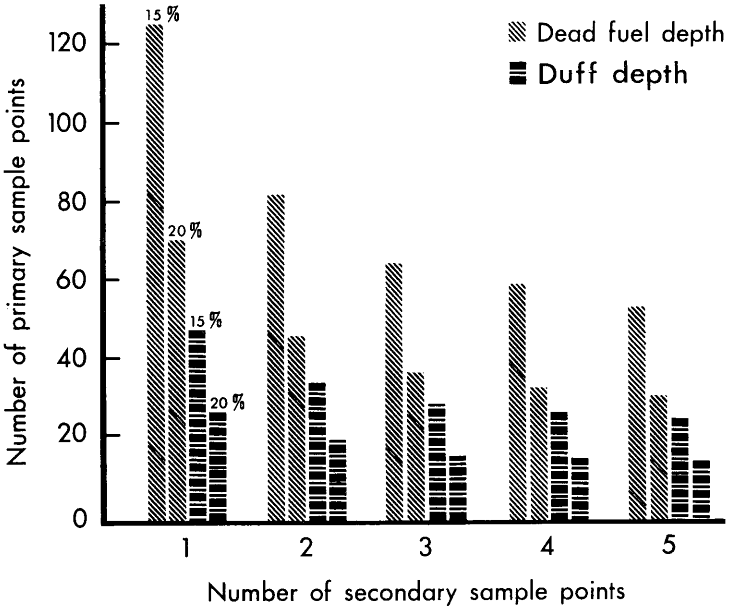


Figure 15.--Number of primary and secondary points needed to achieve percent errors of 15 and 20 percent for fuel depth and duff depth.

APPENDIX II

Specific Gravities of Sound Material

The specific gravities in table 4 are based on ovendry weight and airdry volume and can be used for calculation of loadings.

Table 4.--*Specific gravity of woody twigs and branches with bark attached*

Species	Diameter size class (cm)				
	[1] 0 - 1	[1] 1 - 10	[2] 0 - 1	[2] 1 - 3	[2] 3 - 5
Ponderosa pine	0.41	0.51	0.57	0.53	0.49
Douglas-fir	.55	.43	.56	.56	.52
Western larch	.46	.55			
Lodgepole pine	.49	.41			
Engelmann spruce	.34	.34			
Subalpine fir	.41	.40			
Western redcedar	.48	.33			

[1] William R. Beaufait and Charles E. Hardy. Fire quantification for silvicultural use. USDA For. Serv., Intermt. For. & Range Exp. Stn. (In preparation.)

[2] Brown (1972).

APPENDIX III

Calculating Needle Quantities

Weight of needles can be determined by multiplying ratios of needle-to-branchwood weights (table 5) times estimated branchwood weight. The estimates in table 5 are for branches having all needles attached. The data are based on estimates of needles and branchwood from total living crowns for trees between 2 and 30 inches d.b.h.

Table 5.--*Foliage-to-branchwood ratios based on ovendry weight*

Species	Diameter of branches		No. trees sampled
	0- to 0.25-inch	0- to 1-inch	
Western larch	0.70	0.43	13
Ponderosa pine	14.10	.98	14
Western white pine	3.30	1.02	5
Douglas-fir	2.19	.82	9
Western hemlock	1.90	.80	17
Engelmann spruce	2.38	1.34	4
Western redcedar	5.00	1.45	13
Lodgepole pine[1]	1.34	.31	3
Grand fir[1]	2.52	1.00	3

[1] Data by Fahnestock (1960).

☆GPO 1979—680-128/475

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

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

FUEL MOISTURE AND FIRE DANGER -- SOME ELEMENTARY CONCEPTS

by

Clive M. Countryman

INTRODUCTION

There are many characteristics of wildland fuel beds and of the fuel pieces making up the fuel bed that affect the ease with which the fuel will burn and the behavior of the resultant fire. Most of these characteristics change rather slowly with time, however, and for a given fuel complex have little effect on the day to day variations and seasonal trends in fire danger. An exception to this is the moisture content of the wildland fuels. The amount of moisture in the fuel can change rapidly -- for some fuels within a few minutes -- and seasonal trends in moisture are also apparent in most fuel types. Consequently, fuel moisture is a major determinant of variations of fire behavior and potential fire hazard.

FUEL MOISTURE VARIATION

Dead Fuels

Dead wildland fuels can absorb moisture from the air and also lose moisture to it. It is this capability that controls dead-fuel moisture in the absence of precipitation. The amount of moisture that fuels can absorb and hold from the air depends primarily on the relative humidity of the air immediately surrounding the fuel. If a piece of very dry fuel is exposed to air with moderate humidity, the fuel moisture will increase. The increase is rapid at first, then slows, and finally stops. Exposing the fuel for a longer time does not further increase the moisture content. The moisture in the fuel is then at equilibrium with the relative humidity, and the moisture content of the fuel is its equilibrium moisture content. The equilibrium moisture decreases as the fuel temperature increases but this temperature effect is relatively small. For every combination of relative humidity and fuel temperature, then, there is a corresponding equilibrium moisture content.

Moisture gained or lost must pass through the surface of the fuel. Therefore, the amount of surface area a piece of fuel has compared to its volume has a major effect on the rate of moisture change in the fuel. Small diameter and thin fuels have a large surface area compared to their volume, and can change in moisture content rapidly. But the ratio of surface area to volume of large fuel is small, and the rate of change in moisture is slow. The interior of a large log with a high moisture content, for example, may require months of dry weather to become dry enough to burn.

The rate at which the moisture in a piece of fuel increases or decreases when the relative humidity changes is called the time lag of the fuel. Short time-lag fuels change in moisture quickly with changes in relative humidity, but the moisture change in long time-lag fuels is relatively slow. For fire danger rating, the dead fuels are grouped into four classes according to their time lag. These classes have approximate time lags of 1 hour, 10 hours, 100 hours, and 1000 hours.

Dead grass and foliage, twigs less than one-fourth inch in diameter, and the thin surface layer of the litter are classified as 1-hour time-lag fuels. Because of their short time lag, these fuels are usually near the equilibrium moisture, and their moisture content follows fluctuations in humidity and temperature closely.

Fuels from one-fourth inch to one inch in diameter, and the litter layer from just below the surface to a depth of about three-fourths of an inch are in the 10-hour time-lag class. Fuel-moisture indicator sticks are used to estimate the moisture content of these fuels. The moisture in

10-hour time-lag fuels tend to follow the daily trends in humidity and temperatue rather than short term fluctuations. Their moisture also tends to be higher than the equilibrium value when the humidity is decreasing, and lower than equilibrium with increasing humidity. Under a normal weather pattern, for example, the minimum humidity usually occurs shortly after noon. But the minimum moisture in the 10-hour time-lag fuels is more likely to be reached about 1600 to 1700 hours. Thus, the moisture in these fuels may still be decreasing while the humidity is increasing.

The 100-hour time-lag class includes fuels from one to three inches in diameter and the litter layer from three-fourths to four inches deep. Daily changes in the moisture of these fuels is small -- their moisture is more closely associated with average humidity conditions extending over several days. Limbs larger than three inches in diameter and logs averaging six inches in diameter make up the 1000-hour time-lag class. The trend in moisture content of these fuels is seasonal -- daily variations are scarcely noticeable. Normally, 1000-hour time-lag fuels have high moisture contents at the beginning of the fire season, and decrease in moisture as the season progresses. The rate of moisture decline and the minimum moisture reached depend on the season's weather pattern. Because moisture changes first at the fuel surface, the moisture content of the surface layer of the 100-hour and 1000-hour time-lag fuels is frequently close to that of the shorter time-lag fuels, and may be quite different from the average moisture content of the fuel as a whole.

Rain can increase the moisture content of dry fuels quickly. If the duration of the rain is short, much of the moisture increase will be in the surface layer of the long time-lag fuels. Because of the rapid loss of moisture from fuel surfaces, a short period of drying weather will restore the moisture content of the long time-lag fuels to their pre-rain condition -- often nearly as quickly as the short time-lag fuels.

Chaparral Fuels

California chaparral fuels are made up of a mixture of both dead and living materials. Typically, 55 to 75 percent of the total standing fuel in chaparral is living material. The moisture content of the dead fuel is controlled chiefly by relative humidity and fuel temperature (as discussed in the previous section). But the moisture in the living material is influenced mainly by the physiological activity of the shrubs, and follows a distinctive pattern during the year. When growth starts in the spring, the moisture content of the new plant material rises rapidly to a peak -- often to more than 200 percent of its dry weight. The moisture in the older foliage and twigs also increases during this period, but to a lesser degree than for the new growth. In the larger stems and trunks of the shrub, the increase in moisture is relatively small. Consequently, most of the change in moisture is in the foliage and small material. As the season progresses and the long, nearly rainless season sets in, the moisture content of the shrubs decreases, reaching a minimum when the shrubs become dormant in the fall. Some increase in moisture may occur when fall rains begin, but the moisture generally remains at a relatively low level until growth resumes in the spring. Although the living-fuel moisture in chaparral follows the same general pattern each year, there are wide variations from season to season and from place to place in the amount of new growth, the rate of decline in moisture, and the minimum moisture reached.

Under normal weather conditions, the moisture content of the living material is not influenced greatly by daily fluctuations in relative humidity and temperature. During very hot and dry periods, however, the moisture may decrease somewhat during the daytime, paricularly when soil moisture is low. Warm, dry Santa Ana and Mono winds can cause a rapid drop in the moisture, and several days may pass before the moisture recovers to more normal levels. Rain during the fire season may slow the decline in moisture briefly, or occasionally even raise it slightly.

FUEL MOISTURE AND COMBUSTION

How Fuels Burn

Solid organic materials do not burn in flaming conbustion directly, but must first be decomposed or <u>pyrolyzed</u> by heat and chemical reactions into various gases -- some combustible and some not. The combustible gases do not contain enough oxygen to burn when emitted from the fuel, and must first mix with the surrounding air to produce a flammable mixture. If the pyrolysis is slow, not much gas is generated and the flames are short and intermittent. But when large amounts of fuel are burning rapidly, the volume of gas is large and some must move a considerable distance from the fuel before the mixture becomes flammable. Long and massive flames are then produced. Fire intensity thus depends greatly on the rate of pyrolysis.

When a piece of fuel is first ignited, the pyrolysis takes place in a thin layer at the surface. As the combustion continues, the pyrolysis penetrates into the fuel, leaving behind a layer of char and ash. The chemical reactions in the char are different than in solid wood, and char can burn directly -- mostly by glowing combustion -- without first being pyrolyzed into gases. Thus, if we examine a cross section of a partially burned piece of wood, we see, from the surface inward, first a thin layer of ash, next a layer of char, then a layer, usually shading from dark to light brown, where the pyrolysis has been taking place, and finally unburned wood. The speed with which the pyrolysis layer moves through the fuel determines its burning rate.

Moisture Effects on Pyrolysis

When water is heated, its temperature rises to the boiling point (212°F at sea level). The water will then boil and vaporize, but its temperature remains constant. This trait of water temperature to remain constant while turning to steam is also characteristic of moisture in wildland fuels. When heated, the temperature of the layer of the fuel will rise rapidly to 212°F. The temperature will then remain constant until all of the moisture in the layer is vaporized. The temperature of the fuel layer will then continue to rise.

The delay in temperature rise and the amount of heat needed to vaporize all the moisture both become greater as the amount of moisture in the fuel increases. Combustible gases are not produced from heated fuel until its temperature reaches 400°F or greater. Consequently, as the fuel moisture increases, more heat is required for ignition and pyrolysis and the pyrolysis rate is slowed.

The moisture in the fuel also serves to reduce the amount of heat available for pyrolysis, thus further slowing the pyrolysis rate. The released water vapor must pass through the hot char where it absorbs part of the heat that otherwise would be available to pyrolysis. Outside the fuel, the water vapor dilutes the combustible gases and delays the production of a flammable mixture, sometimes preventing it entirely. When flaming is estalished, the water vapor reduces flame temperature by absorbing the heat, and by reducing the flammability of the air and gas mixture. Often not all of the fuel in a fire is consumed. But the unburned fuel also releases water vapor and absorbs heat, thus hindering the combustion process while not adding heat.

FUEL MOISTURE AND FIRE BEHAVIOR

Once started, if a wildland fire is to continue to burn and spread, heat from the ignited fuel must be transferred to the unburned fuel ahead of the fire. As we have seen, fuel moisture affects wildland fires by increasing the amount of heat needed for the ignition and continued pyrolysis of the fuel, and, at the same time, by reducing both the amount and the rate of heat production from the burning fuel. Theoretically, enough heat can be produced from burning fuels to vaporize all of the moisture they are likely to contain and to cause them to burn. But in the wildland situation, heat losses by convection and radiation from the combustion zone are very large, and only a small part of the total heat produced is transferred to the fuel ahead of the fire. As a result, fuel moisture content has a significant effect on fire behavior and may prevent the fuels from burning at all.

If the behavior of wildland fires depended solely on fuel moisture, the prediction of fire characteristics with moisture changes would be relatively simple. But fire behavior is strongly affected by other fuel and fuel bed characteristics and by environmental conditions. Wind, for example, increases the combustion rate and the amount of heat transferred to the fuel ahead of a fire. Also, more heat is transferred to fuel above a fire when the fire is burning on a slope, and the amount transferred increases with the steepness of the slope. Thus, fires will burn more intensel and spread more rapidly under windy conditions and on slopes than under calm conditions and on level ground.

All of the heat absorbed by the fuel must go through the fuel surface. Consequently, small and thin fuels with their large surface to volume ratio, and fuel mixtures containing a high proportion of such fuels, ignite more easily and release heat more rapidly than do large fuels. The amount of fuel in the fuel bed and the compactness of its arrangement also affect the amount and rate of heat production. Accurate prediction of fire behavior thus requires the evaluation of many factors, and often requires the use of complex mathematical equations.

Although precise prediction of fire behavior cannot be made from fuel-moisture conditions alone, some generalizations concerning fuel moisture and fire can be made that are useful in assessing the potential fire hazard and the probable general characteristics of a fire. Fires do not burn well and will spread slowly, if at all, when the moisture content of the 1- and 10-hour time-lag fuels is above 11 or 12 percent. Large dead-fuels add little heat to the combustion zone if their moisture is above 30 percent and may actually absorb more heat than they produce. As the large fuels dry, however, more and more of the fuel burns, thus adding increasing amounts of heat to the combustion zone. By the time the large fuel mositure declines to 10 or 11 percent, the large fuels have become a significant factor in fire behavior. At moistures below this level, fires in fuel beds containing large fuels become increasingly difficult to control because of the very high fire intensity, the rapid rate of speed, and the persistent burning of the large fuel.

Chaparral fuels are made up mostly of small or thin fuels with a large surface area to volume ratio. These fuels are loosely arranged in deep fuel beds. This combination is nearly ideal for high-intensity and fast-spreading fires when most of the fuels can burn. But during the peak of the growing season, the high moisture content of the living fuel prevent much of it from burning, and the living fuel absorbs a large part of the heat produced by burning dead fuel. As a result, early season chaparral fires seldom spread rapidly or burn intensely. As the moisture in the living fuel declines, however, more of the living fuel can become involved in a fire, and the probability of ho fast fire runs increases. Experience has indicated that, in general, sustained fast-spreading and high-intensity fires in chaparral are infrequent until the living-fuel moisture has declined to about 60 percent in chamise chaparral and 80 percent in manzanita. These moisture levels are ofen designated as the "critical" fuel moisture for these fuels.

Because of the high moisture content of living chaparral, the net heat production from this fuel is much less than from the dead fuel in the stand, and much of the heat from the dead fuel is used to dry the living material. Consequently, the relative proportion of dead and live material in the stand greatly affects the way chaparral burns. Chaparral does not burn well, and may not burn at all, except on steep slopes or with strong winds, if the amount of dead fuel is less than 20 percent of the standing fuel loading. As the proportion of dead fuel increases, so does the fire intensity and rate of spread at any given level of moisture. The strong dependence of chaparral fires on the amount and the moisture content of dead fuels may often result in rapid changes in the behavior of an existing fire. An increase in relative humidity, such as may occur with an influx of marine air to the fire area, can increase the dead fuel moisture sufficiently to cause a dramatic and sudden decrease in the fire activity.

The amount of lesser vegetation, such as grass, forbs, and other annuals, can also have a major effect on the behavior of chaparral fire. During the spring growing season, this material adds to the amount of living material in the stand, and decreases the chaparral stand flammability. However, these plants usually cure and dry early in the season, increasing the proportion of dead material in the stand. Fuel beds made up principally of grass, buckwheat, and California sage are often highly flammable early in the fire season.

9/1/1986

FUEL MOISTURE AND FIRE BEHAVIOR: AN UPDATE

by Carol L. Rice and Robert E. Martin

Fuel Moisture

Live Fuel Moistures

Fuel moisture in living foliage is controlled by the genetic make-up of plants as well as environmental conditions. Chief environmental factors regulating activity in shrub foliage are temperature, light, rain, and relative humidity, although most research has focused on drought indices and the effects of soil moisture.

While most species follow the same trend, a great variation in levels of moisture, rates of drying, and responses to weather exists between species. The root structure, leaf physiology, and ability to drop leaves during stress control the relative ability of plants to respond to atmospheric and soil moisture conditions. Hard chaparral generally has deep roots, and leaves which minimize water loss, whereas soft chaparral generally has fine leaves, shallow roots, and in some cases, drought-deciduous leaves. Most monitoring has focused on hard chaparral, (specifically manzanita and chamise) but the moisture of foliage of all fuels in the complex, including coniferous foliage is beginning to be monitored to determine crowning potential and to refine fire behavior estimates.

Moisture levels - It was thought the foliage of evergreen species tends to be more combustible than deciduous species because all foliage in deciduous species is the current year's growth. However, extensive monitoring showed the moisture contents of deciduous species are often lower than evergreen shrubs and trees, therefore more combustible than thought. Sage (Salvia sp.) and sagebrush (Artemisia sp.) are examples of very flammable deciduous shrubs. The moisture content of ceanothus is similar to chamise whereas Laurel sumac does not normally drop below 200% moisture content and follows an entirely different pattern of drying. Thus the percent of each species in the stand can be used either to dampen or provide heat and increased fire vigor. Likewise, species composition will affect the number of ignitions, given the same risk.

Rate of drying - Soft chaparral species such as sage and sagebrush are most sensitive to atmospheric conditions, whereas the moisture content of hard chaparral species can be more easily predicted. Fine-leafed soft chaparral have steeper rates of desiccation and recovery but drop to the same minimum at the same time as hard chaparral species. Because some species in both hard and soft chaparral lack a period of fall dormancy, differences in moisture content can be used to aid timing of burning. The moisture content of hard chaparral can be more easily predicted because these species respond more to soil moisture and period of drought rather than atmospheric conditions.

In all species, stomata are the main path of water loss. The regular closure of stomata at night and opening at day causes diurnal fluctuation in fuel moisture and thus fire behavior. As soil moisture decreases, the size of opening and length of time stomata remain open decreases and the magnitude of diurnal fluctuation of moisture diminishes as summer drought progresses. A mid-morning minimum in moisture is a function of high transpiration rates that cause incipient wilting and start stomatal closure during the day. After the leaf moisture builds up around noon, the stomata reopen. The moisture content then drops to an afternoon minimum. The moisture content of foliage rises to a maximum after the stomata close and relative humidity rises at night. However, this exact pattern is not present for all species or climates. When nighttime moisture recovery is absent, moisture loss is a continual process, possibly reducing the size and changing the timing of stomatal openings and thus reducing foliar moisture.

Response to rain - If rain of two hours duration or over one half inch in amount occurs after about 90 days of drought, the live fuel moistures of chamise increase an average of 12 percentage points, but the gain takes three to five days to occur, possibly because the roots require that time to absorb moisture. The majority of the rise in moisture occurs in a short period of time (on the third, fourth or fifth day after rain). While the amount of increase in moisture content of other species varies greatly, the delay is similar, regardless of the type of chaparral. For example, sage may rise from 100% to 350% in moisture content after rain in June and the foliar moisture in poison oak may elevate 72 percentage points in one day. Because the number of days since last rain is often used as a parameter in prescriptions, the delay of response and sharp increase in live fuel moistures takes on added importance.

New and old foliage respond differently to rain. New growth reacts one day quicker than old for many shrubs -- especially deciduous species. As the summer drought progresses, the difference between new and old foliage diminishes, and all species are slower to respond to rain.

The season of the rain affects chaparral's response but this phenomennon is not well understood. If the plant has not entered dormancy, a complete growth cycle (including shoot elongation and flowering) may occur. However, if rain occurs later in the fire season, plants will not respond to the added moisture. Whether the regulator is length of day, temperature or another factor needs to be determined.

Volatiles - Each species also fluctuates in its total combustibility because of the amounts of ether extractives, oils, ash or mineral content in the plant. Ether extractives as a percent of dry weight can rise from 8.3% to 15% during fire season, making the plants much more easily ignited. The energy content of ether extractives is 23,000 BTU/lb (vs. 8,230 - 8,900 BTU/lb in needles). Because volatiles have a high vapor pressure, they are more available to combust. Oils dramatically affect fire behavior in chaparral, possibly enhancing flame propagation within conifer crowns and thus the extent of crowning. Moisture in both living and dead fuels acts to dilute volatiles and exclude oxygen from the combustion zone.

Live fuel moisture predictors - Although some of the processes regulating live fuel moistures are becoming better understood, the ability to predict foliar moisture has eluded fire managers. Of eight indices of drought or live fuel moistures studied (including the NFDRS moisture content estimates for live woody and herbaceous fuels as well for 100 and 1000 hour time lag fuels) only the Keetch-Byram Drought Index had a consistent correlation with foliar moisture of any (one) of four plant species, and that index accounted for only 37% of variation in moisture. Additionally, indiscriminate use of calculations of live fuel moistures from NFDRS fuel models can result in overly conservative decisions. Techniques exist to "force" woody living fuel moistures in NFDRS which allow the system to better "track" these moisture levels.

Dead Fuel Moisture

Low moisture in live fuels makes more of the foliage available to burn. Drought-induced mortality further increases the amount of fuel available, and changes the percent dead in the complex until the next fire.

While there is a widely held assumption that the moisture of increasing duff depths is related to that of increasing diameter fuels, there is little correlation between the moisture content of duff and larger woody material. This poor relationship may be explained by two reasons. Moisture exchange in duff may be influenced less by ambient conditions than by recent precipitation and soil moisture. Additionally, the moisture content of logs is influenced most by the duration of rain, whereas the moisture content of duff is dependent on the amount of rain. Measurement of moisture in duff as well as 100 and 1000 hour fuels is therefore critical. Because the moisture content of large fuels varies with the distance to the center, it is important the sampling integrates both the center and the surface. One can cut a one inch thick cross-section then cut it into small pieces to dry and weigh. Another technique is to auger a one to two inch diameter hole through the center of the log then dry and weigh the chips.

As with live fuel moistures, the response to atmospheric conditions of dead fuels varies with species. Response times of fine fuels vary from less than an hour for grasses to more than 24 hours for some conifer needles. Drying of woody material usually takes a shorter time than wetting, and weathered material responds quicker than fresh.

Applications

Fuel Consumption

Models are now available to estimate fuel consumption and heat release. These guides also identify the effects on fuel consumption and heat release by manipulating combustion through varying ignition techniques, dousing or removing smoldering fuels. Estimates of woody material and duff consumption under both flaming and smoldering phases of combustion are developed for a variety of fuel conditions: loadings, moisture contents, and size class distributions. Refinements to estimates for situations with thin duff layers, impervious layers, or soil/duff mixes are now ongoing.

Models are currently available for short needle conifer and hardwood stands. Models for fuel consumption in both duff and woody material in long-needle pine stands are being developed. The models for short needle conifer and hardwoods are the same except where a thin duff layer exists in hardwoods. In long-needle pines, the same short needle conifer and hardwood equation can be used for woody fuel consumption, but different duff consumption predictors are needed. The percent consumed in duff is related to moisture content of larger diameter fuels. In contrast, the percent combustion of woody material is a function of the loading, not moisture content of smaller diameter fuels. With varying snow pack in long needle pine stands, the model for duff consumption may be different because the duff is layered year by year with mycelia which may be affecting moisture transport.

These biomass consumption equations are accepted by the Environmental Protection Agency in Washington and Oregon as the method to measure emissions from woody material and 30% lower than 1980 EPA accepted emsission levels.

Dispatching

The Sequoia National Forest has instituted a matrix which incorporates the Ignition Component, wind speed, humidity, and fuel moistures as factors. The ranges of values in each factor provide ratings which determine the level of dispatch.

Three matrices cover the fire season. As soon as grass or needle cast carries the fire the forest uses the matrix reflecting conditions in NFDRS fuel models, A, C, L and T. Then as light, intermediate brush and one hour fuels in timber (fuel models F and B) carry fire, these are considered major fuels sustaining fire spread. When live fuel moistures drop under 130%, brush is considered a major contributor to fire behavior as are 100 and 1000 hour fuels. An estimated $70,000 was saved in 1983 and 1984 in more efficient dispatching using to the pre-planned response.

Available Fuel

A more specific breakdown of adjective classifications based on the Burning Index is being developed for each fuel model. The concept of available fuel is a key since the same BI could warrant an "extreme" classification in a more flammable fuel complex than a less flammable one. These classifications should apply throughout California, however the boundaries of the different adjective classifications are localized by running FIREFAMILY, and comparing historical fire activity with weather and resultant Burning Indices.

Estimates of fuel amount available to burn in logging slash are tending to recognize more standing material as part of the fuel complex. During times of severe drought and low foliar moisture, much more living fuel and standing dead fuel will be correctly considered available to burn using the new criteria.

Fire Season Severity Predictors

When used as an indicator secondary to short term fire danger ratings, fire season severity predictors can forewarn more or larger fires and more complete burnout when in-depth dryness is present. Persistant smoldering and danger of holdover lightning fires also relate to long-term drought indicators.

The Los Padres National Forest (LPF) uses a system to predict large fire potential that weights amount of rainfall according to the timing of its occurence. All rain from 7/1 to next 1/31 is weighted one half its actual value. Rain from 2/1 to 2/28 is weighted as its measured value. Rain from 3/1 to 6/30 is weighted twice its real value. When the weighted average rainfall for the last 118 years is compared to acreages burned since 1950, the correlation was significant and positive. If weighted rainfall is above the historic average, the staff predicts a fire over 5,000 acres will not occur on the LPF that year. This localized program can be modified to apply in areas without significant amounts of snow since the amount of snowpack and timing of melt will influence when fuels start to dry, thus the length and possible severity of the fire season.

The LPF also looks closely at the timing of decrease and rate of decline in live fuel moistures because both factors will influence the length of time the foliar moisture is at or below the critical point. Concern can be generated over a live fuel moisture of 90% if it is two months earlier than normal, or if it dropped 30 points in 10 days, because both indicate the possibility of a longer period of high fire danger.

Other indicators of fire season severity include a variety of calculated drought indices: Keetch-Byram Drought Index, Palmer Drought Severity Index, Canadian Drought Code, and 1000`hour time lag fuel indicator. The amount of consumption of large fuels in early burning is a more general and immediate indicator of moisture content of large fuels, and should be compared to the 1000 hour time lag calculations or actual measurements made as described earlier.

Fire Behavior Modeling

New thinking regarding the minimum requirements for flame propagation incorporates factors additional to moisture which determine fire's ability to spread. Slope, flaming zone depth, fuel continuity, fuel arrangement, and wind speed also affect flame propagation. Thus if any of these other factors increase, the moisture content required to allow ignition in live or dead fuels can be higher and still result in the same flame characteristics.

In marginal burning conditions, a higher amount of heat must be generated in order for flame propagation to occur. Longer flame lengths are needed to dry fuels to a point of combustion and for spread to continue. This threshold can be produced by manipulating ignition techniques or increasing the amount of fuels which are drier. As fuel bed moisture decreases, a smaller flaming zone is required for spread, so a greater variety of manipulations are possible in ignition, even though the fire behavior in the steady state may be extreme. In contrast, mass fires produce tremendous intensities by synergism of radiative and convective transfer of heat from the multiple flame zones.

Additionally, fires have demonstrated an ability to carry well in chaparral stands without dead material, contrary to common belief that chaparral fires require 25% dead material to burn well. Young chaparral stands contain a larger proportion of its live biomass in finer fuels than older stands. These fine fuels are thus more available to burn at a higher moisture content, with less dead fuels than in older stands. Fuel arrangement and continuity appear to be much more important than once thought.

The production of dead material in chaparral apparently is dependent both crown closure and age. Thus on more productive sites, the percent of dead fuels will rise earlier because of insufficient light and/or moisture. Ten years after crown closure, the percent of dead material appears to stablize rather than continue to increase.

Monitoring

Evaluation of fire effects necessitates a definition of the treatment itself - in this case fire. Documentation should include flame length (which is proportional to intensity), angle, height, and depth as well as rate of spread, and residence time. Flame depth can be divided by rate of spread to calcualate residence time if not measured directly. Use of an object of known size is helpful for comparison. Fuel consumption, as well as soil and duff moisture are necessary items to document. Photographs of burns, especially at locations of previous fuels and vegetation samples are useful, but can be expensive and deceptive. The more complete and comparable the documentation is, the more rapidly fire managers can discern generalities, and develop and test critical hypotheses.

Safety

Four common denominators of near-miss or fatal fires are: (1) small flare-ups occur in a quiet sector, (2) presence of light fuels, (3) unexpected shift in wind direction or speed, and (4) response of fire to topographic conditions and uphill runs.

Light fuels (light chaparral plus dead and downed fuels) are more dangerous than heavy fuels because as mentioned earlier, these fuels respond quicker to atmospheric conditions. Winds profoundly affect the direction of exceedingly rapid fire spread. Few visual clues warn of changes in fire behavior, because fine fuels burn with little or no smoke.

Box canyons, narrow canyons, and gulches tend to act like the chimney of a stove. The concentrated hot air preheats the fuels much more rapidly. Radiant and convective heat as well as spot fires are funneled uphill and speed up, as if a damper were opened in a chimney.

Human behavior is the most vital and uncertain factor because fire behavior is the same in near losses as in fatal situations. Recognizing this heightens the need to prepare and train crew to behave correctly. Human behavior is influenced by many things, but carbon monoxide levels found on fires can impair alertness, judgment, vision and psychomotor functions. This odorless, colorless gas is cumulative in its effect. Carbon monoxide is heavy, thus firefighters should be aware that higher concentrations are found in depressions, saddles, and deep canyons.