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Abstract. The method requires a tally of intersections between sampling planes and vegetative particles categorized by size and shape classes. These planes may be of any size and positioned at any orientation with respect to the ground. The method applies to both randomly and nonrandomly oriented particles that approximate either circles or rectangles in cross section. Estimates that accounted for all angles of particle intersection were more accurate than estimates that assumed perpendicular angles of intersection in a cheatgrass field test. ***Forest Sci. 17:96–102.***

Additional key words. Forest fuels, sampling methods.

THE WAY a wildland fire behaves depends to a large extent directly on the physical properties of individual and collective fuel particles. Fire research and fire management often require knowledge of the volume of a fuel complex and its surface area. Methods of estimating volume and surface areas also may benefit various other disciplines concerned with plant science. The technique reported on here can be used to estimate volume and surface area of a conglomerate of vegetative particles. Intersections between vegetative particles and sampling planes are counted, using sampling planes positioned within the fuel complex.

The planar intersect technique is a modification of the line intercept technique introduced by Canfield (1941). Some form of the line intercept technique has been used by others to estimate volume of cylindrically shaped vegetative materials. Warren and Olsen (1964) were the first to show the importance of the angle of intersection between a particle and a plane projected by a sampling line to estimates of the volume of large-sized logging slash. Beaufait (1967) estimated the volume of branchwood in logging slash using sampling planes 1 m wide and of variable depth. Brown (1968), working in forest floor and grass fuels, tested the effect of particle orientation on the accuracy of volume and surface area estimates.

The method discussed here is an expansion of the theory and application of a method recently presented by Van Wagner (1968), which incorporates effects of particle orientation in estimation of fuel volume for cylindrical particles. First, it applies to a wider range of fuel conditions. Individual particles may approximate rectangular parallelepipeds (flat leaves, bark flakes) or cylinders (twigs, branches) and they may lie in any position. Errors due to particle tilt can be eliminated by random placement of sampling planes at any possible orientation with respect to the ground. Small sampling planes are suggested for use in sampling fine fuels by particle size classes. Finally, formulas for calculation of surface area are presented.

Procedures

The main task of fieldwork in estimating fuel volume and surface area is to record the number of fuel particles intersecting sampling planes. Sampling planes may be of any size and shape and may have any orientation in space. Usually, long narrow planes are more efficient sampling units

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than squares or circles of the same area, because a wider range of local variation is apt to be included within the long, narrow ones. This has been shown repeatedly in plot sampling (Goodall 1952). The size and shape of the sampling plane should be appropriate for the size of fuel sampled and the abundance of particles. Large fuels require large sampling planes. For example, logging residue may be most efficiently sampled using planes 1 to 30 m long and as wide as the slash depth. Closely packed particles are more efficiently sampled by using as small a plane as practical, depending on the size of the particles. Forest floor litter is probably most efficiently sampled using planes approximately 30 cm long and as wide as the litter depth.

Sampling planes can be systematically or randomly located on the ground. After location of planes, several decisions are required to determine the orientation of planes:

1. Decide on the direction occupied by the predominant axis of fuel particles. Usually fuels are predominantly either horizontal, such as fallen vegetation, or vertical, such as living (some dead, too) upright plants. Particle intersections are counted most easily when sampling planes are oriented perpendicular to the predominant axis of the particles. Vertically positioned planes are best for particles lying mainly on the ground, such as logging slash. But if particles are mainly oriented upright, as is brush, planes positioned at other than vertical are best.

2. Decide whether the orientation of particles within a plane defined by adjacent replications of the predominant axis of particles is random or nonrandom. For example, needles in the forest floor tend to be randomly oriented in a horizontal plane. If the orientation of particles is nonrandom—this is the safest assumption if in doubt—sampling planes should be randomly oriented as in Figure 1. Alternatively, the bias due to nonrandom orientation of particles can be determined experimentally and incorporated in calculations of volume and surface area, as described later.

3. Decide whether particles tilted from the plane defined by adjacent replications of the predominant particle axis will cause considerable error. An error of about 10 percent results at 25 degrees (Van Wagner 1968). Error due to tilt can be eliminated by randomly orienting the sampling planes about two pivot lines that are perpendicular to one another (Fig. 1).

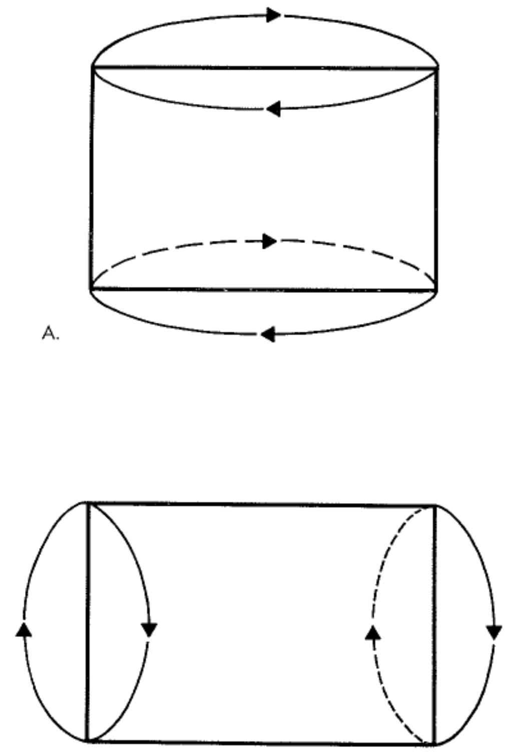

FIGURE 1. *Rotate sampling planes as in A to randomly chosen positions when particles are nonrandomly oriented and lying predominantly within a plane that is perpendicular to the sampling plane in A. Do similarly for B. For elimination of error due to particle tilt, rotate sampling planes in two directions to randomly chosen positions (both cases A and B).*

The edges of planes can be delineated by means of a metal frame, a string, or similar material. The ground and the top of a fuel complex can serve as two of the edges for vertically positioned planes. Sampling planes can be randomly oriented by picking one of eight or more compass directions, or equidistant points on a circle, and positioning the planes accordingly. A rotating arm that supports two parallel sliding metal rods (to delineate the plane) will facilitate placement and orientation of sampling planes that contain edges not more than 1 or 2 m in length.

Particles intersecting each plane are counted and recorded according to their characteristic size and shape classes. Each particle is categorized as a cylinder or rectangular parallelepiped by size class. Limits for size classes should be picked to include a size range of particles that are present in noticeably different quantities than particles of other sizes. Average particle diameters, widths, and thicknesses must be known or determined for each size class. Existing sources of this information furnish good reason to select certain size classes. Enough size classes to maintain accurate volume estimates that are based on average particle dimensions should be used.

Particles that appear to be borderline between two size classes should be measured with a go-no-go gage or similar device. Living and dead fuel can be tallied separately if desired. Tallying rules suitable for particles that have marginal intersections are listed by Van Wagner (1968). In fuels where the number of intersections is large and considerable time would be required to count them, the 3P sampling system (Grosenbaugh 1967) provides an efficient means to obtain unbiased estimates of the number of intersections.[1] Precision for estimates of mean volume and surface area is determined by locating and collecting data from a number of sampling planes.

In a fuel complex that occupies a volume equal to the product of the area of sampling plane (A) and any length (L) that is perpendicular to the sampling plane, fuel volume and surface area are calculated, using Eq. 1 and 2:

$$V = L\left(\sum_{i=1}^{k}\frac{\pi^2 n_i d_i^2}{8} + \sum_{j=1}^{z}\frac{m_j t_j w_j \pi}{2}\right) \quad (1)$$

$$S = \sum_{i=1}^{k}\sigma_i V_i + \sum_{j=1}^{z}\sigma_j V_j \quad (2)$$

where

V = fuel volume, m^3.
n_i = number of particle intersections for i^{th} cylinder size class.
d_i = average diameter of i^{th} size class, m.
k = number of classes for cylinders.
S = fuel surface area, m^2.
m_j = number of particle intersections for j^{th} parallelepiped size class.
t_j = average thickness of j^{th} size class, m.
w_j = average width of j^{th} size class, m.
z = number of classes for parallelepipeds.
σ = particle surface area-to-volume ratio, m^{-1}.

The ratio σ is determined as $4/d$ for cylinders and $2/t$ for thin parallelepipeds such as hardwood leaves (Brown 1970).

Any length L corresponds to the height or the length of the fuel complex. For convenience, express L as a unit length in whatever units are used to express fuel volume. Eq. 1 and 2 are simplified when all particles approximate either cylinders or parallelepipeds.

Fuel weight can be calculated from

$$W = Vp \quad (3)$$

where

W = ovendry weight, g.
p = density, g/cm^3.
V = volume, cm^3.

For best accuracy calculate fuel volume and density for each kind of fuel. A measure of fuel complex porosity (λ)—the amount of void volume per unit of fuel surface area—can be calculated from:

$$\lambda = (AL - V)/S. \quad (4)$$

Theory

Fundamentally, sampling planes serve as plots, and—if the assumptions in the theory are met—the expected values of repeated samples will equal the true cross-sectional area parameter. The estimated volume of a particle equals the product of its cross-

[1] Beaufait, W. R., and M. A. Marsden. Inventory of slash fuels with 3P subsampling. Manuscript in preparation, USDA Forest Serv., Intermountain Forest & Range Exp. Sta., Ogden, Utah.

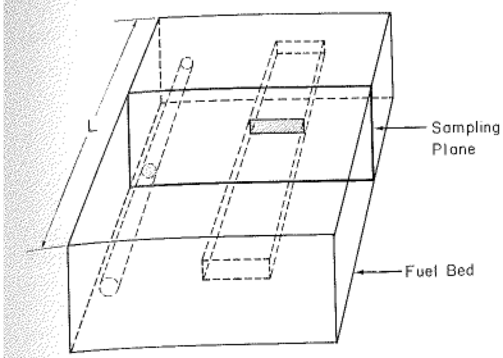

FIGURE 2. *A sampling plane intersects a cylindrical and a rectangular parallelepiped fuel particle in this idealized fuel bed. Volume of fuel equals L times area of cross sections.*

sectional area, which is formed by intersection with a sampling plane and the length of the fuel complex perpendicular to the sampling plane (Fig. 2). The sum of all cross-sectional areas times the length of fuel complex yields total volume.

When particles intersect the sampling plane perpendicularly, cylinders in cross section are represented by circles and rectangular parallelepipeds by rectangles. Normally, particles will intersect a sampling plane at all angles. However, when angles of intersection are not perpendicular, cylinders in cross section are represented by ellipses and rectangular parallelepipeds by rectangles and rhomboids depending on the orientation of particles with respect to the sampling plane.

Suppose that a uniform distribution of all possible particle orientations exists for a sampled fuel complex and that the number of intersections is large. Then, regardless of its actual crossing angle, each intersection can be shown to have an expected cross-sectional area that is the sum of all possible cross-sectional areas weighted by their fractional probability. Van Wagner (1968) demonstrates this for cylindrical particles.

The following equations for expected cross-sectional areas of rectangular parallelepiped particles were developed in a manner similar to Van Wagner's. Area A_x of a cross section through a given rectangular parallelepiped depends on angle θ—the angle that the particle axis makes with the plane (Fig. 3). A_x is a minimum value when $\theta = \pi/2$. It approaches infinity as θ approaches zero, provided the sampling plane is infinitely large. The probability of an intersection depends on the projected length of this particle perpendicular to the sampling plane. The ratio of projected length to actual length is sin θ. It follows that the probability of θ equaling a given value after an intersection has occurred is also proportional to sin θ and can be shown to equal sin θ when probability density is used for probability (Van Wagner 1968, Kendall and Moran 1963).

Area A_x of the rectangular intersection is a function of angle θ and, as shown in Figure 3, is expressed by

$$A_x = tx = tw/\sin\theta. \qquad (5)$$

Since A_x is a function of angle θ and the probability of θ acquiring a given value equals sin θ, the expected area E_A is given by

$$E_A = \int_0^{\pi/2} A_x \cdot p \, d\theta \qquad (6)$$

$$= \int_0^{\pi/2} \frac{tw}{\sin\theta} \cdot \sin\theta \, d\theta \qquad (7)$$

$$= tw \int_0^{\pi/2} d\theta = \frac{tw\pi}{2} \qquad (8)$$

where

t = particle thickness, m.
w = particle width, m.

For any given θ, the area of A_x in Figure 3 remains the same when the particle is rotated about its central axis, as can be shown from the principles of Euclidean geometry.

Proper application of the planar intersect method requires that the angles of intersection be determined as random events. Either sampling planes, particles, or both must be randomly oriented. Error is minimized by taking a numerically large sample.

Error due to tilt can be eliminated by randomly orienting planes about two axes that are perpendicular to each other (Fig. 2). The angle θ is still measured between the particle axis and its projection upon

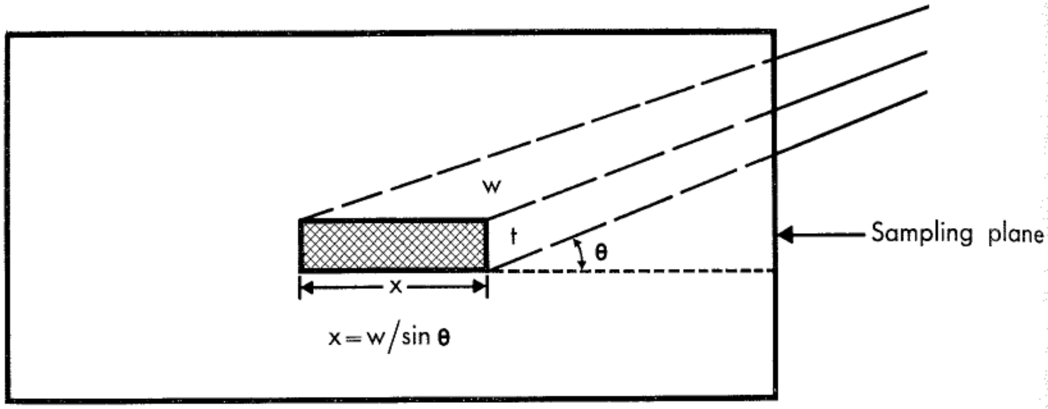

FIGURE 3. *The sampling plane cuts this rectangular parallelepiped particle at an acute angle across its width* (w = *width,* t = *thickness,* x = *variable length side of rectangle in cross section,* θ = *angle of intersection between particle and sampling plane).*

the sampling plane. This three-dimensional randomization permits valid calculation of volume for particles oriented in any direction.

Surface area could be estimated using expected perimeters derived in the same manner as expected cross-sectional areas. However, estimating surface area using the product of volume and the surface area-to-volume ratio, as shown, is simpler and just as accurate.

Possible Sources of Error

One source of error is failure of particles to be circular or rectangular in cross section. Accurate determination of average diameters, widths, and thicknesses of the particle size classes should minimize this error.

Using an average diameter in a squared term for calculation of the volume (Eq. 1) in a size class can introduce error. Up to a certain point the accuracy of the estimates should improve as more size classes are recognized because the possible deviation between dimensions of the sampled particles and those used in the calculations becomes less. However, too many size classes will increase the likelihood of misclassifying particles and add to the time and costs required for measurement of borderline cases.

Errors could result if assumptions regarding random angles of intersection are not met. In vegetation having a variety of particle sizes, shapes, and orientations, there may be doubt as to whether assumptions underlying the planar intersect method are met. If so, double sampling using regression estimates of fuel volume and surface area will furnish a check on estimates based on the planar intersect method. Double sampling will require complete volume and surface area measurements on a number of plots that are sampled by the planar intersect technique.

Testing Effect of Particle Orientation

Estimates of volume and surface area were compared with completely measured values to demonstrate the effect of the angle of intersection on accuracy of the estimates. In a stand of cheatgrass (*Bromus tectorum* L.), each of 38 plots was subsampled, using 15 horizontal planes, 2.5 by 10 cm in size. The number of particle intersections was recorded by the angle of intersection for each of six different cheatgrass particles: stalks, awns, peduncles, and spikelets (all assumed to have circular cross sections) and leaves and glumes (all assumed to have rectangular cross sections).

Two estimates of volume and surface area were made: The first was based on the assumption that all particles intersect the sampling plane at a perpendicular angle, and the second on actual observation of

TABLE 1. Differences between complete and sample estimates of volume and surface area per plot.[a]

Comparison	Volume: Average actual difference	Volume: Percent	Surface area: Average actual difference	Surface area: Percent
	*Cm*³		*Cm*²	
Complete vs. all-angle estimate	0.43*	11.5	13.4	2.9
Complete vs. perp. angle estimate	1.13*	30.2	94.7**	20.4

[a] Significance of differences determined using a paired comparison test (* significant at the .05 level; and ** significant at the 0.01 level).

angles of intersection. Volume of cheatgrass per plot was determined by multiplying calculated cross-sectional areas (Eq. 5 and 9), number of particle intersections, and cheatgrass height. Surface area was determined similarly using calculated perimeters (Eq. 10 and 11).

$$A_e = \frac{\pi r^2}{\sin\theta} \tag{9}$$

$$P_e = \pi k\left(r + \frac{r}{\sin\theta}\right) \tag{10}$$

$$P_r = 2\left(\frac{w}{\sin\theta} + t\right) \tag{11}$$

where

A_e = area of an ellipse, cm².
P_e = approximation for perimeter of an ellipse, cm (Baumeister 1958).
P_r = perimeter of a rectangle, cm.
r = semiminor axis of ellipse, cm.
$k = f(r, \frac{r}{sin\theta})$.

Complete measurements were made, using several techniques (Brown 1968). For the all-angle estimates, particle intersections were ocularly observed by 30°-wide sectors. A weighted average sin θ was used in calculations of cross-sectional areas and perimeters for each sector. For the 30°-wide sector from 0° to 30°

$$\overline{\sin\theta} = \sum_{i=0°}^{30°} \sin^2\theta \Big/ \sum_{i=0°}^{30°} \sin\theta$$

Weighting $\overline{\sin\theta}$ by sin θ seemed appropriate since the probability of a particle being intersected by a randomly located plane is proportional to the sin of the angle between particle and plane. Thus, in effect, $\overline{\sin\theta}$ is weighted by expected number of particle intersections occurring at each whole degree angle. Weighted $\overline{\sin\theta}$ for 30° to 60° to 90° is determined in the same manner as for 0° to 30°.

The all-angle estimates were close to the complete measurement values; only the estimate of volume differed significantly from the complete value (Table 1). Expressed as a percent of the complete value, the all-angle estimate of volume was closer than the perpendicular angle estimate by 19 percent. In a similar comparison for surface area, the all-angle estimate was closer by 18 percent. All estimates were less than the complete measurements.

The planar intersect technique furnishes estimates of fuel volume and surface area which are basic to quantitative prediction of fire behavior. The technique is best suited for fuels or vegetation within man's reach of the ground. It has been used successfully in estimating quantities of slash[2] (Brown 1970) and forest floor litter.[3]

Compared to destructive sampling, the technique is probably more efficiently used for estimating volume of large-sized fuel, but it can be effectively used for small fuels such as needles and twigs. It is particularly useful for estimating surface area and vol-

[2] Beaufait and Marsden; see footnote 1.

[3] Reid, J. R. Project Firescan ground fuel study. USDA Forest Serv., Northern Forest Fire Laboratory, memo for the record (unpublished).

ume for a series of size classes and where nondestructive sampling is desirable such as for quantifying undisturbed fuels for experimental fires. The details of field application need further study before the method can be used efficiently for many types of fuels.

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Announcing FORTRAN IV Program for Computing and Graphing Tree Growth Parameters From Stem Analysis

This FORTRAN IV program computes individual tree growth parameters and through CalComp subroutines graphs the derived tree growth parameters of periodic annual increment (p.a.i.) and mean annual increment (m.a.i.) in basal area, height, and total volume. Control variables in the program are length interval between cutting points, time period for measurement of growth increments, age adjustment for extrapolations to total age, model for volume calculations, and axes and lettering dimensions for the graphs. Standard data arrays in the printed output consist of: (1) age at each cutting point, (2) average diameter, basal area, and section volume, all by heights of cutting point and age intervals, (3) total volume increments by age intervals, (4) heights by cumulative age, (5) cumulative age by cutting points, and (6) cumulative height and total volume by one-year intervals. Program prepared by D. J. Pluth and D. R. Cameron.

A source deck, detailed program description, and sample output may be obtained from D. J. Pluth, Dep. of Soil Science, University of Alberta, Edmonton, Alberta, Canada.