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PRESCRIBED FIRE -- EVALUATION OF HAZARD ABATEMENT

by
S. J. Muraro

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ABSTRACT

Four adjacent areas of cedar-hemlock slash (50°45'N, 118°40'W, elevation 3280 ft. a.s.l.) were burned to evaluate prescribed burning as a hazard abatement technique. Sampling intensity was three octagonal plots, perimeter 240 ft., per 2 acres of burn. The efficacy of various parameters are discussed.

Fuel loading qualified by maximum size of fuel components appears to be the best means of differentiating the hazard in fuel complexes. Fire impact integrators, as used, were not an effective means of measuring fire intensity. A formula is presented, indicating that the benefit/cost ratio is optimum in 1-year-old cedar-hemlock slash when the slash hazard index is 11. At a slash hazard index of 9 little abatement is achieved; when the index is higher than 12, with winds in excess of 5 mph., the cost of ensuring confinement may reduce the benefit/cost ratio to less than unity.

EXTRAIT

Quatre aires adjacentes (50°45'N., 118°40'O., altitude absolue de 3280 pieds) couvertes de rémanents de Cèdre et de Pruche furent brûlées dans le but d'évaluer le brûlage dirigé comme moyen de réduire les risques d'incendie. Pour chaque 2 acres brûlées, 3 terrains octogonaux d'un périmètre de 240 pieds furent échantillonnés.

Dans ces expériences, la quantité de combustibles (en tonnes/acres), compte tenu du diamètre maximal des rémanents, s'avère le plus important des divers paramètres étudiés.

Les calorimètres, tels qu'utilisés au cours des études, ne mesurèrent pas efficacement l'intensité du feu.

D'après une certaine formule, le rapport profit/frais est optimal pour les rémanent âgés d'un an lorsque l'indice de brûlage y est de onze. Par contre, si celui-ci baisse à 9, le dit rapport approche l'unité. Et si l'indice monte au-dessus de 12 lorsque le vent souffle à plus de 5 milles à l'heure, les frais peuvent dépasser les avantages de ce traitement.

PREFACE

An abridged version of this paper was one of the special papers prepared for the Congress of the International Union of Forest Research Organizations, Munich, Germany, September 4-9, 1967. This publication presents the subject in greater detail than the former presentation permitted. In this version, more detailed data and discussion of data are given, particularly in the detail concerning the evaluation of prescribed burns with hazard abatement as the sole objective.

ACKNOWLEDGEMENT

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PRESCRIBED FIRE -
EVALUATION OF HAZARD ABATEMENT

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S. J. Muraro[1]

INTRODUCTION

The Society of American Foresters (1958) define prescribed burning as:

> "skillful application of fire to natural fuels under conditions of weather, fuel moisture, soil moisture, etc., that will allow confinement of the fire to a predetermined area and at the same time will produce the intensity of heat and rate of spread required to accomplish certain planned benefits to one or more objectives of silviculture, wildlife management, grazing, hazard reduction, etc. Its objective is to employ fire scientifically to realize maximum net benefits at minimum damage and acceptable costs."

In British Columbia the primary objective of prescribed burning is consumption of the fine fuel components for the purpose of hazard abatement. Of secondary importance in the cedar-hemlock regions is reduction of the organic layer and logging debris to improve site workability to facilitate natural or artificial reforestation.

The application of prescribed fire to accomplish these objectives is justified only if the desired end result is achieved at a cost which is less than that of a comparable end result accomplished by other means. Included in these costs must be the expense of escaped fires and the losses in production resulting from diversion of personnel and equipment to the burning program. However, maximum benefits may be realized only when the land manager can predict the behaviour and effect of fires in various fuel types and burning conditions.

Prescribed burning costs can be minimized if guides to predict behaviour and impact of prescribed fires in various fuel types are provided. The land manager would apply these guides to define weather conditions that allow a sufficient energy release to accomplish the desired predetermined objectives. Guides to predict fire impact would also be useful to determine the chances of using fire to accomplish a particular objective. In some cases objectives are defined that are physically impossible to achieve in the normal burning season. In these cases alternate treatments, more severe

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[1] Research Scientist, Department of Forestry and Rural Development, British Columbia Region, Victoria, B.C.

burning conditions or re-examination of objectives should be considered. However, the land manager must be aware of the maximum fire impact possible in the variety of fuels and weather where prescribed burning is attempted if maximum benefits are to be realized.

This paper discusses methods of evaluating fire impact in terms of initial and residual fuel inventories, based on data from prescribed burns in cedar-hemlock (*Thuja plicata* - *Tsuga heterophylla*) logging slash. An approach to an economic assessment of hazard abatement is advanced and requirements for improving appraisals of this type are outlined.

Study Area

The general study area is located in the King Fisher Creek Drainage, 50°45'N lat. 118°40'W long., in the Enderby Ranger District of the Kamloops Forest District. Specifically, the four areas were located on a moderately sloped, southeast aspect terminating at a benchlike topographic feature at about 3,000 ft. The top area A was about 400 ft. higher than area D which was at the foot of the slope.

Baker[2] described the soils as minimal podzols with abundant stone; drainage, generally unimpeded. Average annual precipitation exceeded 42 inches, the greater proportion occurring as snow.

This area of British Columbia, classified by Rowe (1959) as Cl_2, is a section of the Columbia Forest Region that occurs above the montaine M_2, and below the subalpine SA_2 sections. Mature forests are typified by co-dominant decadent western hemlock (*Tsuga heterophylla*) and western red cedar (*Thuja plicata*) in varying proportions. Other important commercial species are the dominant western white pine (*Pinus monticola*) and Douglas-fir (*Pseudotsuga menziesii*), veterans of a past disturbance.

Gross volumes of the four important species occurring on each study area are shown in Table 1. Similar volumes are considered average for the Interior Wet Belt. Variations in the volume of cedar are especially evident and generally indicative of the wetter sites in the Interior Wet Belt.

DATA PROCUREMENT AND TECHNIQUES

Burn Schedule

To demonstrate differences in fire impact due to weather and slash age, data from three prescribed burns on a southeast aspect were examined. Areas A, B, C and D (Figure 1) were burned under the conditions

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[2] Baker, Dr. Joseph, Research Scientist, Forest Research Laboratory, Canada Department of Forestry and Rural Development, Victoria, B.C.

TABLE 1. CHARACTERISTICS OF TREATED AREAS.

Area	Age of slash (months)	Avg. gradient (%)	Avg. depth of full organic layer (inches)	Gross volume (ccf./acre)			
				Hemlock	Cedar	Douglas-fir	Total
A	10 months	34	4.2	55.8	14.4	1.8	72.0
B	10 months	22	4.2	56.7	7.0	4.7	68.4
C	10 months	27	5.5	53.0	23.7	5.8	82.6
D	24 months	14	6.0	53.2	45.0	6.4	104.6

and on the dates detailed in Table 2. The results from areas A, B and C offer a comparison of the effect of a limited range of weather regimes on fire impact in 1-year-old logging slash. Area C containing slash approximately 1 year old and the adjacent area D containing slash 2 years old were both burned on September 14, 1964. The results from these areas provided data to compare the effect of slash age on fire impact.

Weather

Continuous weather data including relative humidity, temperature, wind speed and direction, and net radiation were recorded throughout the summer at a weather station located in the area (Figure 1). Moisture content of Douglas-fir fuel-moisture indicator sticks were measured at the station and at several locations in the surrounding stands at intervals during the daylight hours. Dry and wet bulb temperatures were measured daily at 0800 and 1600 hrs. PST and prior to each fire.

Initial and Residual Fire Environment

Initial (before burning) and residual (after burning) fuel complexes were assessed on a line transect, starting at an arbitrarily selected point and describing an octagon with sides 30 ft. long. An organic layer reference pin, a fire impact integrator and a wire frame defining the boundaries of a 1-ft.^{2} vertical fine fuel plot were located at the corners of each octagon. A sampling intensity of three octagonal plots for approximately every 2 acres of burn was maintained in the study. There were 9, 11, 13 and 21 octagonal plots on areas A, B, C and D, respectively (Figure 1).

Organic Layer

The upper end of an organic layer reference pin (9 inches of #8 steel wire) defined the top of the initial organic layer. The depletion of the organic layer as a result of burning was determined by measuring from the

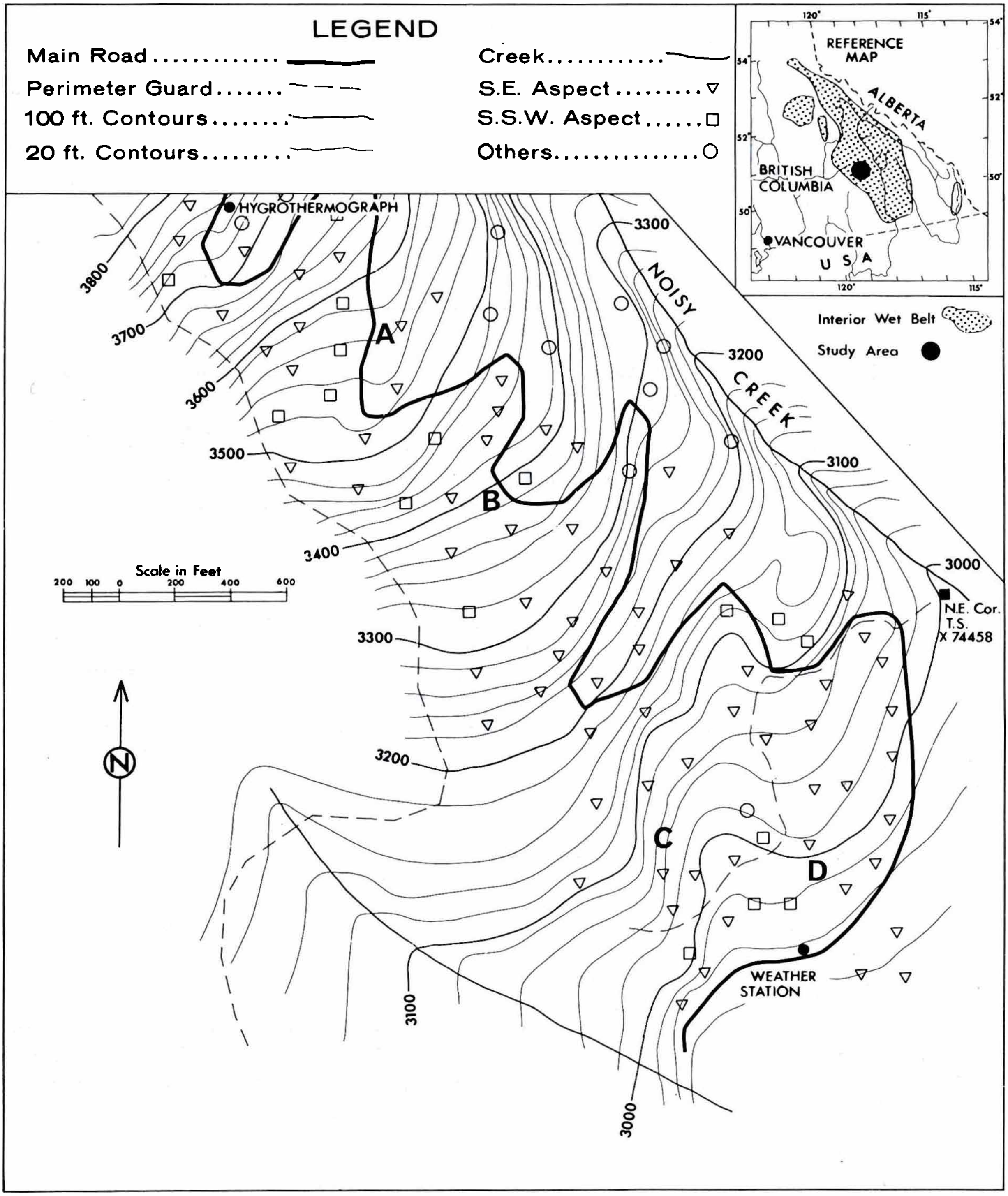

Figure 1. Map of study area.

top of the pin to the residual organic layer. The total depth of organic layer was determined during the residual assessment by digging alongside the reference pin and measuring the distance from the top of the pin to mineral soil.

Fine Fuels (.10 to 1.0 inches)

A fine fuel reference frame defined the boundaries of an arbitrarily selected 1-ft.^{2} profile of the lower portion of a vertical plane through the fuel complex. All fuel components penetrating the defined boundaries were tallied in two diameter classes, 0.10 to 0.50 inches and 0.51 to 1.0 inches, measured at the point of plane penetration. The difference between the initial and residual number of fuel components was used to compute fuel depletion in each size class. On the initial assessment, the proportions of foliage remaining on the slash and density of minor vegetation at each corner of the octagons were estimated.

Fire Impact

A fire impact integrator, similar to those described by Beaufait (1966), was located at each corner of the octagon. The integrators were sealed No. 2½ cans measuring 4.6 inches high by 3.9 inches in diameter and containing 500 cc. of water. In conjunction with the initial assessment, each integrator was placed in an upright position on the undisturbed organic layer, and wired to an aluminum stake, a hole punched in the top of each can. Two layers of "Saran Wrap" were secured by a rubber band to prevent loss of water in the interval between placement and the onset of the fire. During the residual assessment the volume of water remaining in the integrator was measured. The difference between the initial (500 cc.) and residual amount of water was assumed to be an integrated measure of the total radiant, convective and conductive heat energy sustained by the immediate locality during the life of the fire.

Large Fuels (greater than 1.1 inches)

Fuels greater than 1.1 inches in diameter were sampled on a 240-foot transect circumscribing the perimeter of the octagonal plot. Plots were delimited by a surveyor's tape, at the upper limit of a vertical cross section of the fuel complex. The position of the tape, overlying all fuels greater than 1.1 inches in diameter, also defined the depth of the fuel complex which was measured at the midpoint each side. The diameter of all fuels larger than 1.1 inches penetrating the defined vertical plane were tallied by species and 2-inch diameter classes measured at the point of plane intersection. During the residual tally of the large fuels the intersect distance on which complete exposure of mineral soil resulted was measured and recorded.

DATA ANALYSIS

Four measurements required to fully describe the physical characteristics of a fuel complex are:

a) V_1 Volume of the fuel complex ($ft.^3$)

b) V_2 Volume of fuel components constituting the fuel complex ($ft.^3$)

c) S Surface area of fuel components within the fuel complex ($ft.^2$)

d) D Density of fuel species ($lb./ft.^3$)

The line intersect method discussed by Van Wagner (1965) is well adapted to provide the first three, while standard references (Anon., 1951) provide the fourth.

When the intersect method of fuel assessment is used, the volume of the fuel complex V_1 is the product of transect length L, in feet, and the depth of fuel h, also in feet. For calculation purposes the thickness of the transect is unity. When L is the length of transect in feet and d is the diameter in inches at the point of intersection, fuel volume V_2 is obtained by:

$$V_2 = \frac{.00857\Sigma d^2}{L} = ft.^3/ft.^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

The surface area of fuel per $ft.^2$ of fuel complex, S, when L and d are the same as above is determined by:

$$S = \frac{0.4112\Sigma d}{L} = ft.^2 \text{ of fuel surface}/ft.^2 \text{ of fuel complex} \ldots\ldots\ldots\ldots (2)$$

FUEL CHARACTERISTICS

The measurements discussed in the preceding section are used to determine the characteristics of loading, fineness, porosity and compactness of the fuel complex.

Fuel Loading

Fuel loading is an important parameter of the fuel complex. Anderson *et al.* (1966) and Fahnestock (1960) report a direct relationship between rate of spread and fuel loading. From formula (1) fuel loading, W, in $lb./ft.^2$

of a number of fuel components of density D and diameter d inches intersecting a transect L ft. long is determined by:

$$\frac{.00857\ D\Sigma d^2}{L}\ \text{lb./ft.}^2 \quad\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

When species were differentiated densities of 21 and 27 lb./ft.^{3} were used for cedar and hemlock, respectively; when there was no differentiation as to species a density of 24 lb./ft.^{3} was used. The weight of organic material was determined by measuring the density of several samples of the full organic layer. The average weight of the full organic layer was 0.78 lb./ft.^{2} per inch of depth while the upper layers weighed 0.6 lb./ft.^{2} per inch of depth. The weight of the initial organic layer was determined using a density of 0.78 lb./ft.^{2}, whereas 0.6 lb./ft.^{2} was applied to calculate the depletion of organic material.

Foliage weights were determined from crown-weight and fuel-proportion tables by Fahnestock (1960), using stump cruise data and standard height tables for the study area. The product of the mean estimated percent of foliage remaining at each of the eight corners and the data from Fahnestock's tables provided the initial weight of foliage. The weight of foliage consumed was the product of initial foliage weight and the percent depletion of fuel components in the .11 to .50 inch diameter class.

Fineness

The size of individual fuel components plays an extremely important role in the combustion process, not only influencing the spread and intensity of an established fire, but also the rate of drying and the ease of ignition. Sigma (σ) or fuel fineness is defined as the ratio of the surface area of a fuel component to the volume occupied by that component. For fuel components of equal length, sigma varies proportionately and inversely with the diameter of the components. For a fuel component having a volume V_2 and a surface area S,

$$\sigma = \frac{S}{V_2} = \text{ft.}^2/\text{ft.}^3 \quad\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

For fuel components larger than 1.1 inches, the surface area S and volume V_2 of the fuel components per ft.^{2} of fuel bed were determined from equations 1 and 2. For fuel components in the 0.1 to 0.5 and 0.51 to 1.0-inch classes, surface areas of 8.1 and 2.9 ft.^{2}/lb., respectively, were used (Muraro, 1964). Calculations, utilizing results from Barker (1967), determined that there is approximately 78.3 ft.^{2} of surface area per pound of hemlock foliage. To determine volumes of the smaller fuel components, densities of 34.3 and 29 lb./ft.^{3}, respectively, for foliage and fuels smaller than 1.0-inch diameter were applied (Fons, 1946).

Porosity

Rothermel and Anderson (1966) define porosity as the void volume of the fuel complex divided by the surface area of the fuel components. This parameter, lambda (λ), of the fuel complex is rarely used; however, the above-mentioned authors suggest the product of lambda and sigma may be closely related to burning characteristics of a fuel complex. Curry and Fons (1939) showed rate of spread to be proportionate to the square root of lambda.

Compactness

Compactness is the reciprocal of porosity. This parameter expresses the relation between the void volume of a fuel complex and the surface area of fuel components within the fuel complex. For a heterogeneous fuel complex the compactness ratio is determined by:

$$\frac{1}{\lambda} = \frac{S_F + S_{(0.1 - 0.5)} + S_{(0.5 - 1.0)} + S_{(1.1+)}}{V_1 - V_{2(F)} + V_{2(0.1 - 0.5)} + V_{2(0.5 - 1.0)} + V_{2(1.1+)}}$$

$$= \text{ft.}^2/\text{ft.}^3 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

where V_1 is the volume of the fuel complex

V_2 is the volume occupied by fuels of the specified size class

S is the surface area of fuels within the specified size class.

Fire Danger Rating

Table 2 shows the Fire Danger Index and Slash Hazard Index for each area adjusted for time of day. The Coast Forest Fire Danger Tables (Mactavish, 1965) has a scale from zero to 16 units. The slash hazard tables for "brown slash", slash which still retained foliage, was applied to all of the areas except D where the hazard index for leafless slash was applied. In Table 2, except for the change in drying code, the difference between the Hazard Index on areas C and D are entirely due to slash age.

RESULTS AND DISCUSSION

Fuel Size

The percent of total initial fuel weight by species and size class and the actual fuel loading, including the organic layer, were plotted on a logarithmic scale (Figure 2). The range of total fuel loading on the four

TABLE 2. FIRE DANGER AND SLASH HAZARD RATINGS ADJUSTED FOR PERIOD OF BURN.

Area	Date	R.H. at start	20 ft. wind mph.	Days since .06 inches of rain	Drying code at start	Drought index	Fire danger index	Slash hazard index
A	July 25	35	5	3	90	3	6	13
B	Aug. 7	40	1	3	84	3	4	11
C	Sept.14	80	2	5	80	4	2	9
D	Sept.14	80	2	5	81	4	2	6

areas was small (222.7 to 235.4 tons/acre). About 40% of total weight of fuel were components of greater than 11.1 inches diameter; the organic layer accounted for about 40%, while the remaining slash fuel components and natural litter constituted approximately 21% of the total fuel by weight. The preponderance of large fuel components was strongly indicative of the decadent, over-mature condition of the stand. On the four areas, the weight of the full organic layer averaged about 39% of total fuel loading (88 tons/acre). The proportion of this fuel component varied from about 30% of total fuel weight on the highest area A to about 41% on the lowest area D.

The percent of total fuel weight within each size class, and the percent of weight by species in each size class depleted by burning as well as the percent loss of water from the integrators, are shown in Figure 3. Figure 3, in conjunction with Figure 2, allows determination of total fuel depletion and depletion by size class and species on each area. The percent depletion of a fuel component is determined from Figure 3, while the proportion of the total fuel complex occupied by that fuel component is derived from Figure 2. The product of the percentages from Figures 2 and 3 and the total weight of fuel shown in Figure 2 approximate fuel consumption in tons/acre.

In Figure 3, a migration of initial fuel diameters toward smaller residual diameters is evident. Percent depletion in the 4-, 6- and 8-10-inch classes is apparently less than in the larger size classes. This is a result of partial consumption of large fuel components, thereby reducing their diameter; subsequently, they are assigned to a smaller size class in the residual inventory than on the initial inventory. On area A, the residual assessment of the 4-inch class yielded a larger quantity of cedar than the initial assessment, although total fuel depletion did occur. On area D, the total number of fuel components and the number of hemlock components was greater on the residual assessment. The migration of fuel sizes is greater for cedar than for hemlock. In the 2-, 4- and 6-inch classes, depletion of cedar is apparently less than hemlock; however, in

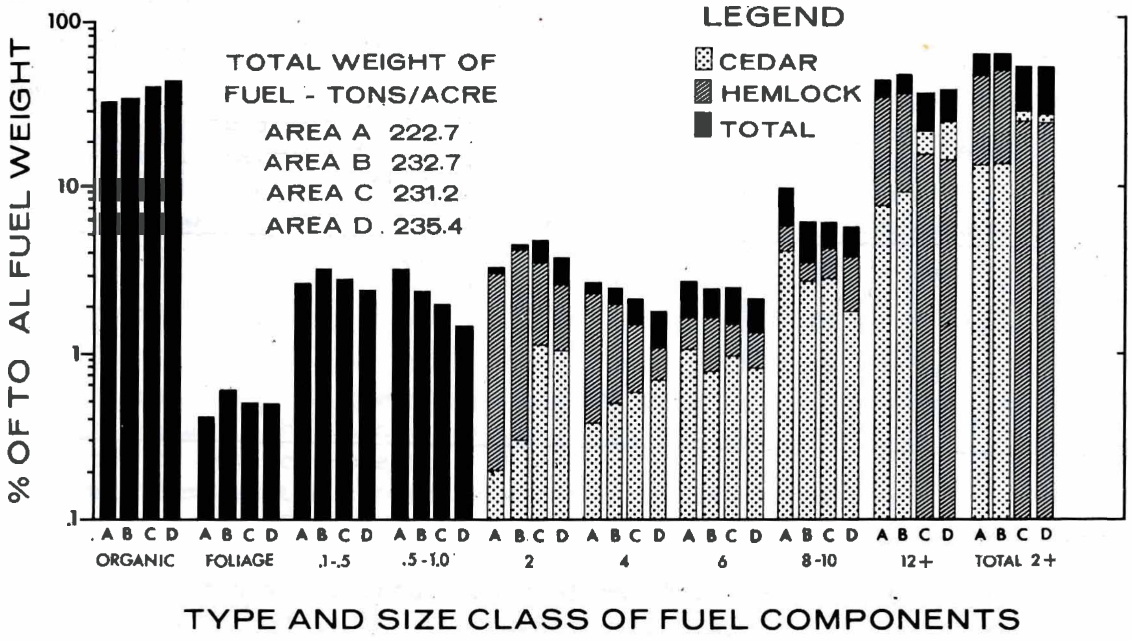

Figure 2. Distribution of initial fuel weight on each area by size class and species shown as a percentage of initial fuel weight.

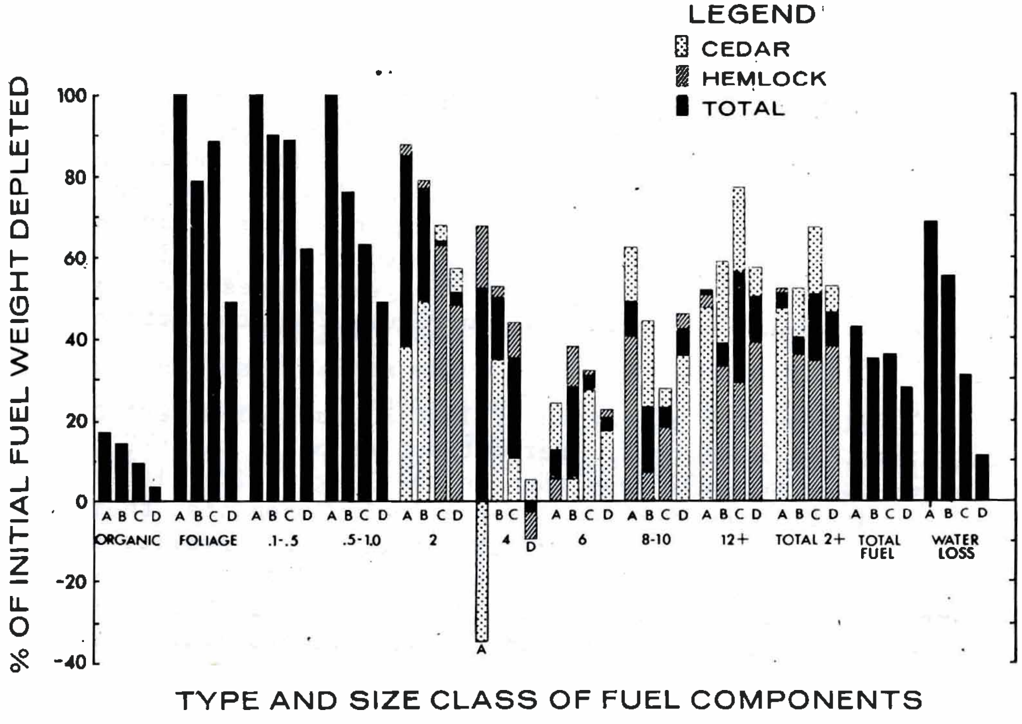

Figure 3. Depletion of fuels on each area by size class and species shown as a percentage of initial fuel weight of each species within the size class.

the 8-10 and 12+ inch classes, the depletion of cedar is greater. The larger quantity of residual cedar fuel components in the smaller size classes indicate an apparently low rate of depletion; actually this is the result of larger diameter cedar components burning in such a manner that one or more smaller components remain. The higher depletion rate of the larger sized cedar components substantiate this anomaly. Due to this migration, the actual amount of fuel consumed in each size class is usually greater than indicated by the differences between initial and residual fuel assessments. Underestimates of fuel depletion due to component migration are greatest in the 2- and 4-inch classes and are inversely related to the size class. Only the largest size class and total fuel depletion are unaffected by component migration.

Fire Impact Integrators

Figure 3 also shows the gross relation between depletion of the organic matter and other fuels, and the amount of water lost from the integrators. The mean values of water loss are directly related to depletion of some fuel components, namely the 0.1 to 0.5 and 0.51 to 1.0-inch classes and the organic layer; but the mean depletion of fuels by the remaining size classes and the mean depletion of total fuel are only loosely related to water loss from the integrators. That water loss is not better correlated with fuel consumption is not surprising, since in all cases the available fuel is many times the amount required to evaporate 500 cc. of water. Rough calculations show that only about 0.146 lb. of wood having a heat of combustion of 8600 Btu./lb. would be required to evaporate 500 cc. of water if efficiency was 100%. The utilization of heat energy to dissipate water from the integrators was calculated for areas A, B, C and D, where the water loss was 3.9, 3.0, 2.3 and .9 cc. per ton of fuel consumed and the actual slash fuel consumption was 89, 71, 74 and 63 tons/acre, respectively (4.1, 3.3, 3.4 and 2.9 lb./ft.^{2}). The respective efficiencies were 2.5, 1.9, 1.5 and .6% for the four areas considering fuel utilization from 1 ft.^{2}, whereas in reality radiational and convectional heating from a larger area would contribute to water loss, thereby further reducing these efficiencies. It was postulated that the differences in efficiencies could be explained by the variation of moisture contents of the various sized fuel components at the time of burn. Estimates of water content by size class of depleted fuel from each burn were added to the water loss from the calorimeter and a second set of efficiencies calculated. These were essentially unchanged relative to each other although the efficiencies of all burns were increased.

As a gross assessment of fire impact, the integrators appear to be of some value in estimating organic layer depletion, but the organic layer reference pins are less complicated and more meaningful unless the possibility of complete removal of the organic layer exists (Figure 4). The use of calorimeters should be investigated, with emphasis on their parametric interpretation. No doubt a time scale showing the period of boiling would be valuable; however, the location of the calorimeters in relation to the organic layer and to slash fuels greatly influences their value as a

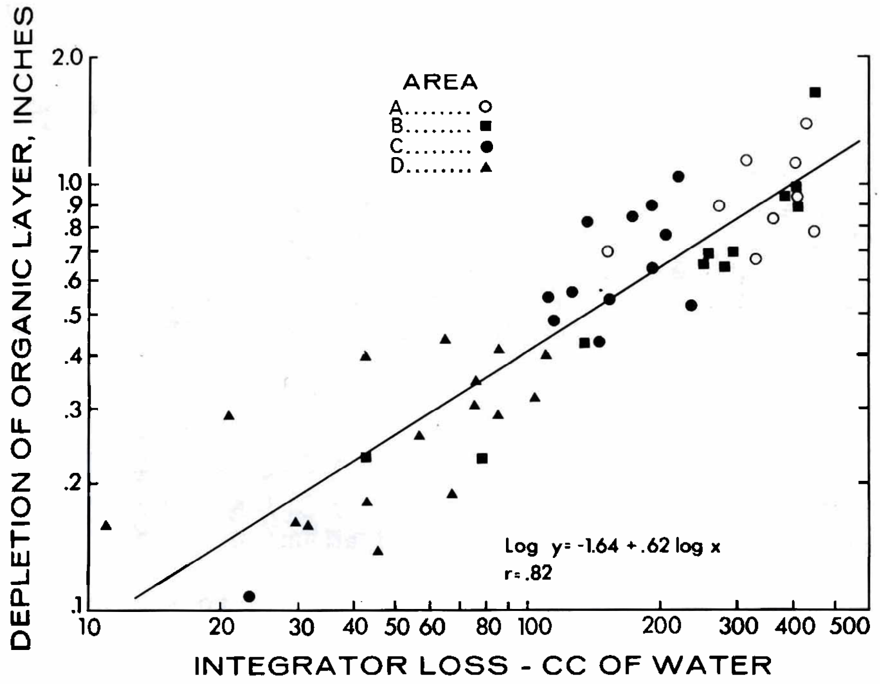

Figure 4. Relation of water loss from integrators with depletion of organic layer.

standard reference device when used in a variety of fuel arrangements. The regression of integrator water loss and organic layer depletion as determined by the organic layer depletion pins is shown in Figure 4. The regression equation was calculated to be: log of organic depletion (inches) = -1.64 + .62 log of water loss (cc.) with a correlation coefficient of .82. In a study conducted by Wade (1965), duff reduction explained 49% of water loss whereas a six variable regression explained 81% of the variation in water loss.

Rate of Spread

If potential rate of spread can be related to the fuel complex, the hazard abatement benefit from any prescribed burn can then be ascertained from an iventory of initial and residual fuel complexes. If an assessment of hazard is needed to decide if hazard abatement is necessary, only an initial inventory is required, however, if it is necessary to determine the effect of treatment then an inventory of the initial and residual fuel complex is required. Correlations of fire spread with fuel characteristics of fineness and compactness (Fons, 1946), a dimensionless parameter (Rothermel and Anderson, 1966), and fuel loading (Fahnestock, 1960), and their application to slash fuel complexes common to the cedar-hemlock type are discussed in this section. These characteristics of the initial and residual fuel complexes on each area are shown in Table 3.

TABLE 3. INITIAL AND RESIDUAL FUEL CHARACTERISTICS

Area	Fuel loading by type and size class						Depth of fuel (ft.)	Fineness σ ($ft.^2/ft.^3$)	Compactness $\frac{1}{\lambda}$ ($ft.^2/ft.^3$)	σ λ Dimensionless
	Foliage (lb./$ft.^2$)	0.1-0.5 (lb./$ft.^2$)	0.51-1.0 (lb./$ft.^2$)	1.1+ (lb./$ft.^2$)	Total* (lb./$ft.^2$)	Total* (tons/acre)				
A Initial	.0459	.2708	.3305	6.271	6.918	150.7	3.38	30.03	2.56	11.82
Residual	.000	.000	.000	2.824	2.824	61.5	2.35	4.57	.24	19.30
B Initial	.0688	.3397	.2617	6.743	7.413	161.5	3.61	35.00	3.03	11.51
Residual	.0137	.0367	.0596	4.036	4.146	90.3	2.46	13.15	.94	14.09
C Initial	0.550	.2938	.2112	5.790	6.350	138.3	3.09	35.35	3.23	11.02
Residual	.0091	.0321	.0780	2.819	2.938	64.0	2.04	13.71	.92	14.91
D Initial	.0550	.2708	.1744	5.629	6.129	133.5	2.93	36.85	2.97	12.47
Residual	.0275	.1010	.0918	3.026	3.246	70.7	2.23	30.39	1.89	16.10

*Weight of organic layer omitted.

Fineness refers to the size of a fuel component without regard to the total number of components. The fineness ratio in Table 3 is the average fineness ratio for the fuel complex determined by dividing the total surface area of fuel components by their total volume. Fons (1946) showed rate of fire spread to be directly related to fineness; however, the limited range of values (36.85 to 4.57 ft.^{2}/ft.^{3}) encountered in this study for the entire fuel complex are difficult to interpret from Fons (1946), which ranges from 0 to 120 inch^2/inch^3 (1440 ft.^{2}/ft.^{3}). Within this range, rate of spread varies from about 20 to 180 ft./hr. If the average fineness is calculated for fuels up to 7 inches in diameter, the fineness ratios vary from 139 to 180 ft.^{2}/ft.^{3} for the initial fuels to from 5.8 to 12 ft.^{2}/ft.^{3} for the residual fuels. Fineness values of 250 and 25 were determined, respectively, for initial and residual fuels when only material up to 3 inches was considered. From these calculations the change in rate of spread due to burning, according to Fons (1946), would be in the order of 50 ft./hr. to 25 ft./hr. From field observations this reduction in spread rates is much less than that attained in practice.

Anderson *et al.* (1966) plotted the logarithm of compactness and rate of spread to obtain an inverse linear relation. For the same range of compactness, rate of spread varied considerably for wood cribs, needles and slash fuel complexes. Fons (1946) showed rate of spread as varying in an asymptotic fashion and inversely with compactness. Obviously for any given fuel size there exists a compactness ratio that is optimum for fire spread. This optimum compactness lies between infinity which would be a solid, and a value barely larger than zero for a fuel complex containing only the necessary fuel components to obtain a multiple component, three dimensional fuel complex. The compactness-spread relation is best illustrated by a gas-air fuel complex which explodes at certain proportions but will not ignite if the proportion of gas is either too low or too high.

The fuel concentrations sampled in this study were considered extremely hazardous; initial compactness ratios varied from 2.56 to 3.23 ft.^{2}/ft.^{3}. Residual values of compactness were even smaller, varying from 0.24 on area A, the best burn, to 1.89 on area D, the poorest burn. According to the literature, fire spread should be more rapid in the residual fuel complex than in the initial fuel complex of all burns, and greater in the residual complex of the more complete burn than in that of the less complete burn. Obviously the residual values of compactness, and very likely the initial compactness values, are below the optimum for fire spread in these fuels. The decrease in compactness of the residual fuel complex is explained by examining the equation $\frac{1}{\lambda} = \frac{S}{V_1 - V_2}$. In the residual fuel bed, V_1 was reduced by approximately one-third and V_2 by approximately two-thirds. The result of these changes is a larger divisor in the residual compactness equation than in the initial compactness equation. Because the greatest proportion of the depleted volume V_2 occurred in the smaller size classes; that is, those classes with a large surface to volume ratio, the dividend S was reduced. The net effect of these changes, reducing the dividend and increasing the divisor in the residual compactness calculations, can only have the effect of reducing compactness. Rates of spread were also calculated according to equations 32 and 39 from Fons (1946), which apply the factors of loading, compactness and fineness. The spread values determined by these equations were comparable only amongst the abated or unabated fuel complexes, but could not be applied to compare an abated fuel complex with an unabated fuel complex without the use of a proportionality constant that would have involved test fires in abated fuel complexes.

Calculation of compactness in other natural fuel complexes, including dense stands of grass, surface fuels under stands of lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) and lodgepole pine aerial fuels, resulted in values of the same magnitude as the cedar-hemlock logging slash. However, these low compactness ratios seem to have been ignored by other researchers; although in natural fuel complexes, excepting the organic layer, they are the rule rather than the exception.

Rothermel and Anderson (1966) suggest the use of a dimensionless parameter of the fuel complex which is the product of sigma (ft.^{2}/ft.^{3}) and lambda (ft.^{3}/ft.^{2}). This dimensionless parameter was calculated for the initial and residual fuel complex on each area and appears in Table 3. The residual dimensionless parameter is larger than the initial parameter, indicating more rapid rates of spread in the residual fuel complex than in the initial fuel complex. This parameter is obviously unsuitable for differentiating between rates of fire spread in the treated and untreated slash fuel complexes encountered in this study.

Fuel Loading

The simplest parameter, fuel loading, is related to fire spread in fuel complexes having a similar range of size classes, but equal loadings of differing size class distributions will not necessarily result in the same rate of spread. The size class distribution of fuel components in a residual fuel complex may be quite different from the distribution in the initial fuel complex depending on the effectiveness of the treatment, but, in any case, the distribution of the smaller fuel components is most affected. It is also the smaller, less than 1.0-inch diameter fuel components, which most influence rate of spread and contribute least to total loading of slash fuel complexes (an average of about 10% in the fuels on these areas). For this reason a comparison of fire spread in initial and residual fuel complexes via the characteristic of fuel loading tends to underestimate the effect of treatment. The validity of using this characteristic to compare potential rates of spread in slash fuel complexes of different ages is also doubtful for the same reason. Fahnestock (1960) showed the rate of spread in logging slash which retained foliage to be significantly greater than similar loadings of slash of the same species that had dropped foliage. Insofar as fire spread is concerned, loading is a valid parameter only if the distribution of size classes are similar.

Because Fahnestock's (1960) spread data are for fires backing from the central ignited fuel complexes, rate of spread is independent of wind and therefore is a good basis for comparing fuel dependent fire characteristics. The fuel complexes tested by Fahnestock (1960) had a maximum loading of 32.5 tons/acre, the majority of components being less than 2 inches diameter. The fuel complexes in this study had a total loading of slash fuel components of from 161.5 to 133.5 tons/acre, but only a small proportion (20%) was less than 7 inches diameter. Initial and residual cumulative fuel loadings for fuel components less than 7 inches diameter (6-inch diameter class) and for the total slash fuel complex are shown in Table 4. Initial and residual rates of spread were determined on the basis of loadings from Fahnestock's (1960, p. 44) curves for fresh cedar and hemlock slash and are also shown in Table 4. (Fahnestock's tests were conducted under the following conditions: no rain preceding 2 days, less than .02 inches in preceding 5 days, minimum indicator stick reading of 8.0% minimum R.H. 40%, mean wind less than 2 mph. and minimum mid-afternoon temperature 70°F). The reduction in spread rates due to burning are probably conservative because the fuel loading within each size class will consist of a different distribution of sizes within the class. In the initial fuel complex, the number of fuel components tends to be skewed toward the lower class limit but the larger components at the upper class limit contribute to loading disproportionately with the number of components. In the residual fuel complex, the number of components tends to be skewed to the upper class limit because of greater depreciation of the smaller components.

In Figure 5, the residual fuel loading of slash fuel components up to 7 inches diameter and for all slash fuel components is shown as a percentage of the initial fuel loading in the same categories. The lesser residual percentage of total fuel on area D is a species effect resulting from the predominance of decadent cedar on this area; in fact the shape of this entire curve is affected by the pronounced migration of fuel diameters mentioned earlier. The predominance of hemlock accounted for the larger than expected total residual fuel on area B (Table 1). If only the 1- to 7-inch diameter classes are considered, the change in residual fuel due to increasing diameter class is about 20% for all burns except the most intense burn on area A, which is about 30%. However, there is little change in the residual percentage when fuels up to 7 inches are compared with fuels up to 27 inches in diameter. Figure 5 emphasizes the difference in residual fuel as a function of weather conditions at the time of burn by comparing residual fuel on area A, B and C, and the difference due to slash age by comparing area C and D.

Figure 6 shows the effect of residual fuel loadings on potential fire acreage one hour after ignition in weather conditions equivalent to those previously described. The values in Figure 6 assume a backing fire on level ground, and are computed from the lineal rate of spread shown in Table 4. Heading fires would, of course, reflect a faster rate of spread, dependent on wind velocity and the frequency of unburned fuel concentrations. The weather conditions in which these spread rates apply occur frequently in the interior wet belt. In 1964, which was a wet year, the weather limitations under which Fahnestock's 1960 tests were conducted were satisfied on 16 days out of the 79-day period extending from June 22 to September 9.

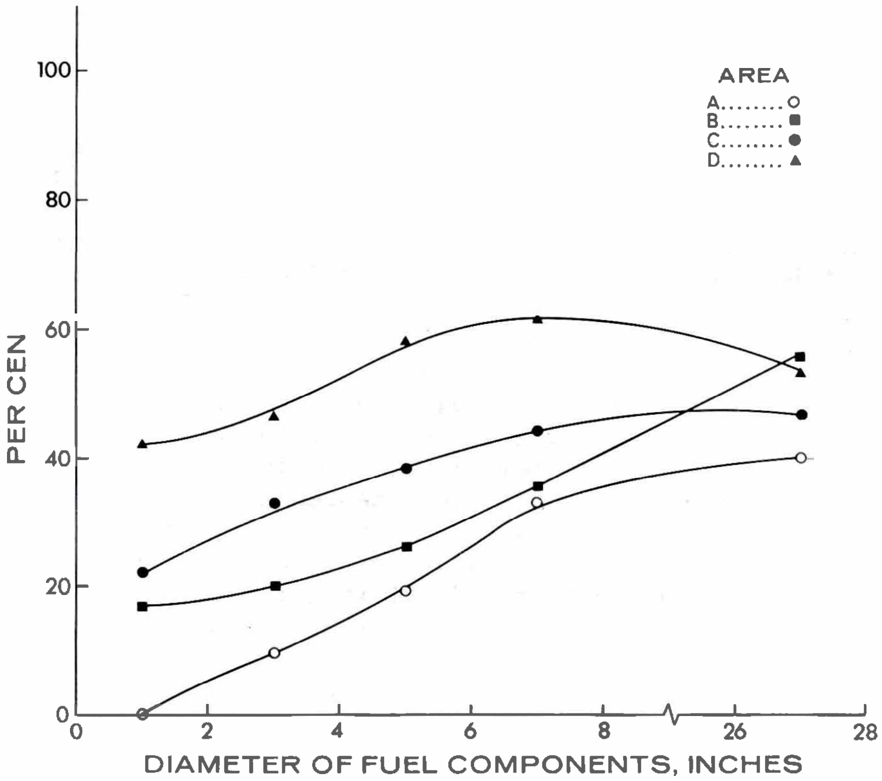

Figure 5. Residual fuel loading cumulated by size class and shown as a percent of initial fuel loading for the same diameter limits.

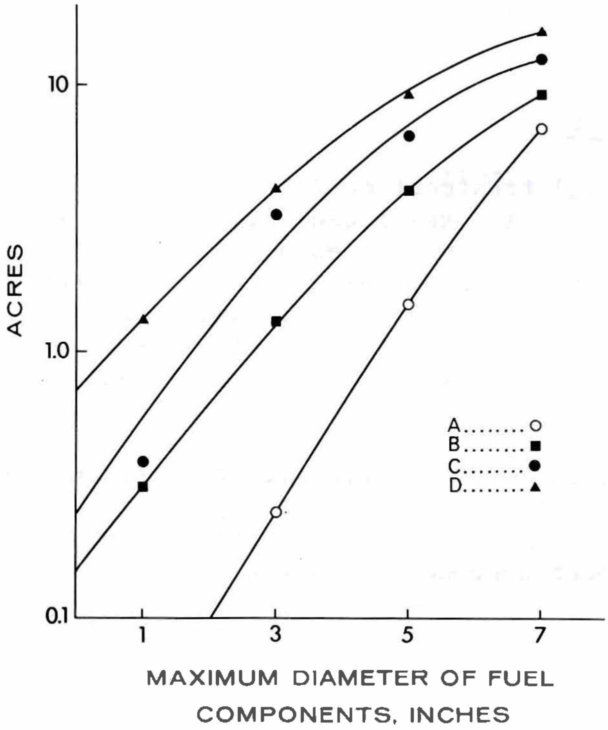

Figure 6. Fire size after 1 hour in residual fuels of each area according to cumulated fuel loading by maximum diameter.

From the preceding discussion there is little doubt that fuel loading, although not entirely satisfactory, is the most realistic and practical parameter of fire characteristics in the fuel complexes considered. Until a better fuel parameter is developed, fuel loading qualified by the maximum size of fuel considered is probably the most appropriate means of assessing hazard abatement. The questions are what fuel diameter should be used as a criterion for fuel loading and what level of abatement should be considered adequate. If fuel loading is used as a parameter of fire characteristic, it must be qualified by cumulated loading to a certain diameter. The data on fire spread from Fahnestock (1960), applied in this report, qualified the fuel loading by an upper diameter limit of 2 inches. From the cumulated fuel loading shown in Table 4, a diameter qualification of 3 inches more appropriately qualified fuel loading of 20 to 32 tons/acre in non-artificial slash fuel complexes. Use of a 3-inch diameter; that is, the upper limit of the 2-inch diameter class, is within the range of fuel loading tested by Fahnestock and is recommended as the qualifying diameter limit for fuel loading. If the 3-inch diameter class is used as the maximum fuel size (Figure 6), the variation of potential fire size ranges from .25 to 4.1 acres/hour on the 4 areas. Of this range, .25 to 2.5 acres/hour is due to weather regimes prior to and at the time of the burn, while the remaining variation from 2.6 to 4.1 acres/hour was due to the difference between 1-year-old and 2-year-old slash. One hour after ignition fires in the initial fuel complexes of areas A, B, C and D would have been 17, 22, 17 and 12 acres, respectively. The differences between the initial and residual spread values may be applied to assess the direct benefit derived from the treatment. Noteworthy is the fact that although area D represented the least hazardous initial fuel complex, the residual fuel complex was the most hazardous. This illustrates one guideline for maximization of benefit, that of devoting available resources to treatment of the most recently logged areas.

Assessing Economics of Hazard Abatement

The objectives of any remedial treatment must be the criterion of evaluating the results of the treatment. In prescribed burning, this rule applies and is one reason why specific objectives of each prescribed burn should be stated. If the purpose of prescribed burning is hazard abatement, then the criterion of assessment must be the reduction of hazard obtained, even though other benefits may be incidental. The adage, "The operation was a success, but the patient died," is especially appropriate to hazard abatement treatments.

The question raised earlier in the text, what constitutes adequate hazard abatement, must be qualified according to one of two philosophies regarding hazard abatement: that of maximization of benefit/cost ratio, and that of reducing the hazard to an extent dependent upon the suppression capability of the agency.

The first philosophy requires the greatest hazard reduction for the least cost and involves a minimum standard geared to the suppression capability of the agency; in this philosophy these standards are not considered as a goal, but are regarded as the tolerable limit. The second involves minimum treatment cost to accomplish a residual hazard which is commensurate with the fire control capability of the responsible agency. This involves a range of standards between agencies of varying control capabilities and individual areas within each agency's jurisdiction due to area accessibility and travel time. In the author's opinion, maximization of benefits is most valid from the viewpoint of long-range fire control planning. This concept is also the least complicated and best suited to illustrate a technique of applying fuel inventories to determine a benefit/cost ratio of the treatment.

The primary objective of a hazard abatement treatment is to reduce the quantity of fuel readily available for combustion, to achieve a minimal benefit of limiting a potential fire control task to the capabilities of the controlling agency. The advantage of treating a fuel complex is therefore a function of the difference in control difficulty in an untreated fuel complex and in the treated fuel complex.

A formula for determining the benefit/cost ratio of prescribed fire for hazard abatement must include a number of variables dependent on both the fire environment and the control agency. The factors which are determined by the fire environment are:

a) potential fire size in initial fuel complex,

b) potential fire size in residual fuel complex,

c) annual expectancy of wildfire ignition per unit area.

d) difficulty of treatment.

Factors which are dependent on the control agency are:

a) cost of wildfire suppression, dollars per acre,

b) mobilization time required to muster an effective control effort,

c) travel time to the area concerned.

Other benefits occurring from the treatment may be included in either category, dependent on the specific nature of the benefits and the policies of the administrative agency; however, if the primary purpose is hazard abatement, the assessment should be oriented toward this purpose. The inclusion of other benefits is justified only if the agency actually utilizes these benefits. The cost of site deterioration, if it results, should also be considered a cost factor.

Fire size in the initial or residual fuel complexes is a function of the rate of spread values from Table 4, the sum of the usually fixed mobilization time required by the control agency and the variable travel time to the area involved.

TABLE 4. CUMULATED FUEL LOADING (TONS/ACRE) BY SIZE CLASS AND PREDICTED LINEAL RATE OF SPREAD (CH./HR.) OF BACKING FIRES IN FRESH CEDAR-HEMLOCK LOGGING SLASH -- FAHNESTOCK (1960).

Area	Max. fuel diameter (inches)									
	1.0		3.0		5.0		7.0		27.0	
	Loading (tons/ acre)	Rate of spread (ch.5/ hr.)	Loading (tons/ acre)	Rate of spread (ch.5/ hr.)	Loading (tons/ acre)	Rate of spread (ch.5/ hr.)	Loading (tons/ acre)	Rate of spread (ch.5/ hr.)	Loading (tons/ acre)	Rate of spread (ch.5/ hr.)
A_I	14.1	5.8	21.8	8.9	28.6	11.5	35.4	14.3	150.7	60
A_R	0	0	2.2	.9	5.4	2.2	11.5	4.7	61.5	25
B_I	14.5	6.0	24.9	10.2	31.7	13.0	38.2	15.5	161.5	64
B_R	2.4	1.0	4.9	2.0	8.4	3.5	13.2	5.4	90.3	37
C_I	11.9	4.8	23.6	9.7	28.6	11.5	35.2	14.2	138.3	55
C_R	2.6	1.1	7.7	3.3	10.9	4.5	15.6	6.4	64.6	26
D_I	10.6	4.3	19.1	7.9	23.3	9.5	28.5	11.4	133.5	52
D_R	4.4	2.0	8.8	3.6	13.3	5.5	17.5	7.2	70.7	28

$$A = .314\ (T\ RS)^2 \tag{6}$$

where A is fire size in acres

T is mobilization and travel time to effective attack

RS is rate of lineal fire spread in chains/hour.

The cost of sustaining a wildfire is

$$C_w = C_S + C_D \tag{7}$$

where C_W is total cost per acre and C_S and C_D are average suppression and damage costs, respectively, in dollars per acre.

In a prescribed burn, which has hazard abatement as the primary objective, it is reasonable to evaluate the benefit of the treatment in terms of the difference in damage and suppression costs of a fire occurring in treated slash and in untreated slash. If the occurrence of a fire is certain, then the benefit portion of the benefit/cost formula may be expressed as:

$$A_I\ (C_S + C_D) - A_R\ (C_S + C_D) \tag{8}$$

where A is the area in acres, I is the subscript denoting initial or untreated fuel and R is the subscript denoting residual or treated fuels.

Applying the rate of spread values for fresh slash in Table 4, (Fahnestock, 1960), assuming utilization of benefit for each season following treatment, the benefit portion of the ratio is:

$$.314\ (C_{WI}\ (TRS_I)^2 - C_{WR}\ (TRS_R)^2) \tag{9}$$

where T is total travel time in hours, RS_I and RS_R are initial and residual lineal rates of spread in chains/hour adjusted for the particular year of treatment and C_{WI} and C_{WR} are wildfire cost + damage in initial and residual fuels, respectively.

The cost term of the ratio includes the per acre cost of preparation and burning C_P, and the per acre cost of damages C_D, sustained during the course of treatment. Thus cost per acre C_T, which is considered only for the first year because money appreciation is not included, will be:

$$C_T = C_P + C_D \tag{10}$$

while total cost will be the product of C_T and A_T when A_T is the acreage treated. Other benefits such as increased planting efficiency, which is utilized and which can be expressed as a dollar benefit, should be considered as a negative cost and deleted from the sum of C_p and C_D. This particular benefit is subtracted from the cost only if it will be utilized as a matter of policy because, like the cost of treatment, it is not dependent on fire occurrence for utilization of benefit. Assuming certain utilization of benefit, that a wildfire will occur, and assuming that planting benefits are not utilized, the benefit/cost ratio of a hazard abatement treatment for any single season following treatment is:

$$\frac{.314(C_{WI}(TRS_I)^2 - C_{WR}(TRS_R)^2)}{A_T C_T} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

where C_{WI} is cost of wildfire suppression + damage in initial (untreated) fuel, dollars/acre

C_{WR} is cost of wildfire suppression + damage in residual (treated) fuel, dollars/acre

RS_I is rate of lineal fire spread in initial fuels, chains/hour

RS_R is rate of lineal fire spread in residual fuels, chains/hour

T is effective attack time, hours

A_T is area treated, acres

C_T is cost of treatment + damage, dollars/acre.

Application of this benefit/cost formula to the initial and residual fuel complexes of the four areas serves to illustrate the effects of slash age and fuel depletion on the benefit/cost ratio. The benefit/cost ratios in Table 5 are computed on the assumed treatment acreage of 100 acres, a treatment cost of $6.00 per acre, a wildfire cost of $100.00 per acre in both fuel complexes and assumed weather conditions similar to those outlined immediately prior to Table 4. Rates of spread were those given in Table 4 for a 3-inch maximum fuel diameter. Rates of spread in the initial fuel complex are reduced to 75, 60, 50 and 40% of the spread rate in fresh slash for 1, 2, 3 and 4-year-old slash, respectively, thereafter remaining constant. (Fahnestock (1960) suggests the more drastic reduction of spread due to age of 25% per year for the first 3 years, thenceforth remaining essentially unchanged.)

An effective attack time of 2 hours is assumed in all cases. No advantage of other benefits and no site deterioration is assumed. The cumulated benefit/cost ratio for the 5-year period is shown in the last column of Table 5, assuming that the slash was treated the same year as logged and that the hazard of residual fuel complexes increases at a rate of 5% per year because of a gradual replacement of flash fuel resulting from ingrowth of herbaceous material. To calculate the 6-year benefit/cost ratio, a maximum spread rate for the residual fuel complex was considered not to exceed that year's spread rate for the initial fuel complex. Cost of treatment is considered only on the year of treatment and is not appreciated over the remaining 6 years. The benefit/cost ratio over the 6-year period following treatment is not necessarily equal to the sums of the individual annual ratios and is a rather meaningless figure because the benefit ratio is highly dependent on the year that the potential wildfire occurs. The annual benefit ratios show that maximization of benefits is achieved by treatment of fresh slash and benefits diminish rapidly with time. For the entire 6-year period there is a favourable ratio for the

TABLE 5. BENEFIT/COST RATIO OF HAZARD ABATEMENT AS INFLUENCED BY YEAR OF TREATMENT AFTER LOGGING AND RATE OF FUEL DEPLETION.

Area	Year of treatment - since logging						Benefit/cost for 6-year period treated during year 0
	0	1	2	3	4	5	
A	16.4	9.1	5.5	3.8	2.5	2.5	40
B	20.9	11.4	7.0	4.4	2.7	2.7	48
C	17.4	8.8	4.8	2.7	.9	.9	33
D	10.3	4.6	2.0	.5	0	0	16

hazard abatement treatment resulting from the fuel depletion achieved on areas A and B; however, on areas C and D a favourable ratio lasts for only 4 and 3 years, respectively.

Actual cost of treatment on the four areas was unrealistic because of the research activity associated with the treatment; however, if the $6.00 per acre B.C. coastal approximate cost of treatment is accepted as a base, relative estimates of treatment costs may be deduced. On area A ignition was easy but an escape into adjacent slash required enlistment of a suppression team, which raised the relative cost to about $18.00 per acre. Area B was burned under optimum burning conditions when ignition was easy and a well-developed convection column reduced the spotting potential, resulting in the short duration, high intensity burn typical with centrally induced circulations. Relative to coastal costs, an estimated $4.00 per acre would be expected on area B. On area C, although control difficulties were not encountered, ignition was relatively slow due to the high density of sets required and the low flammability of the fuels. Burning costs on this area would be about $6.00 per acre, equivalent to the coastal average. On area D, ignition was more difficult than on area C. In addition, because of the spotty nature of the treatment, a relatively large quantity of unburned fuel remained, requiring extra patrol and raising the cost of treatment to an estimated $12.00 per acre.

If these estimated costs are substituted for standard costs of treatment assumed in Table 5, quite different benefit ratios are achieved which are largely dependent on the difficulty of control and ignition at the time of treatment.

The cost benefits in Table 6 are not in strict proportion to the difference in treatment costs in Table 5 because appreciation of the residual fuel complex was commenced following the actual year of treatment rather than after year 0, as in Table 5. The slash on areas A, B and C was 1 year old when treated while that on area D was 2 years old. The results

TABLE 6. BENEFIT/COST RATIO OF HAZARD ABATEMENT CONDUCTED ACCORDING TO THE NUMBER OF YEARS SINCE LOGGING USING A VARIABLE TREATMENT COST INFLUENCED BY THE SLASH HAZARD INDEX.

Area	Treatment cost (dollars/acre)	Year of treatment - since logging						Slash hazard index
		0	1	2	3	4	5	
A	18.00	5.4	3.0	1.8	1.3	.8	.8	13
B	4.00	31.4	17.0	10.4	6.3	3.7	3.5	11
C	6.00	17.4	8.8	4.5	2.2	.9	.9	9
D	12.00	5.2	2.3	1.0	.2	-	-	6

achieved from the treatment of area D show that the break-even point was achieved for only the first season after treatment, whereas the more recent slash on area C, burned during the same conditions, maintained a benefit for 2 years subsequent to treatment.

Although rather nebulous, the ratios in Table 6 for the year following treatment may be related to the fire danger rating system so that the potential benefit/cost ratio as well as the physical characteristics of the treatment can be estimated in advance. The benefit/cost ratios are shown as a dependent of the slash hazard index at the time of treatment in Figure 7. Noteworthy is the skewed parabolic relation of benefit/cost with hazard index. During periods of low index value, costs are high due to the extra effort required to achieve ignition and benefits are reduced because of reduced fuel consumption. During periods of high index, especially if there is wind, burning costs tend to be high because of either potential or actual control difficulties which offset the effect of the additional benefit of increased fuel depletion. However, if control can be maintained, treatments at the high index values would result in the most favourable benefit/cost ratio, unless extra preparatory costs are sustained to avoid later suppression costs.

The greatest benefit/cost ratio is achieved within a limited range of index values when ignition and spread are rapid and control difficulties are not encountered.

None of the benefit/cost ratios shown in Tables 5 and 6 and Figure 7 include a fire expectancy rate. In fact, if the assumed costs and burned acreages are in the proper perspective, an extremely high fire expectancy must be anticipated to maintain even the highest benefit/cost ratio at a value greater than one. Application of fire expectancy rates to any benefit/cost analysis has a pronounced effect on the analysis and should be considered when initiating a policy of prescribed fire for the single

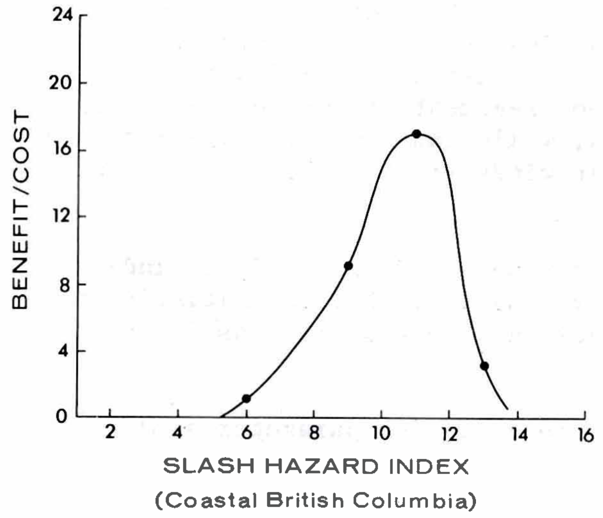

Figure 7. Relation of benefit/cost to the slash hazard index for the year following treatment.

purpose of hazard abatement. Burning with additional objectives other than hazard abatement, providing these objectives are satisfied and utilized, is one method of achieving abatement at a favourable benefit/cost ratio. In areas where other benefits are not evident or will not be utilized, hazard abatement should be selectively applied to establish or maintain a fire break system of well-treated areas rather than a broadcast application of mediocre treatments.

CONCLUSIONS

The conventional fuel complex parameters of fineness and compactness for predicting rate of fire spread are not applicable to prediction of fire spread in heterogenous fuel complexes that consist of different distributions of size classes encountered in initial and residual fuel complexes. Fuel loading qualified by the maximum size of fuel component appears to offer the most valid means of differentiating hazard in fuel complexes.

Cedar and hemlock slash fuel components exhibit differences in depletion rates that have the apparent effect of reducing fuel depletion in the smaller (4- and 6-inch) size classes. This results from large cedar components being reduced to a number of smaller sized components. This migration of fuel components is much more pronounced in cedar than hemlock and is associated with the proportional to decadence.

The fire impact integrators exposed in this study are of little value as a measure of fire intensity because water loss is affected by a number of variables which are independent of fuel consumption, the most important being fuel arrangement. Incorporation of a time scale will undoubtedly increase this value as an intensity integrator, but it is doubtful whether they can be used as a corporative measure of intensity in different fuel types.

Potential rate of wildfire spread in 1-year-old Cat-logged interior cedar-hemlock slash can be economically reduced by prescribed burns conducted during periods when the Federal slash hazard index is between 9 and 12. Fuel reductions resulting from treatment at indexes less than 9 result in only slight hazard decreases, while index values higher than 12 involve a high probability of escape if winds greater than 3 or 4 mph. are experienced during treatment.

The assumed values used in this benefit/cost analysis indicate that fire expectancy should be strongly considered before initiating a prescribed burning policy which considers hazard abatement as its primary objective.

There is a need to develop a fuel complex parameter similar to those discussed, which is representative of natural fuel complexes and can be applied to predict fire characteristics as a fuel variable.

Realistic application of economic principles to prescribed fire activities requires a greater knowledge of the short- and long-term effects of fire on all parts of the ecosystem and the result of these effects on a variety of land uses.

REFERENCES

Anderson, H.E., A.P. Brackebusch, R.W. Mutch, and R.C. Rothermel. 1966. Mechanisms of fire spread - Research Progress Report No. 2. U.S. Forest Serv., Res. Paper INT-28.

Anon. 1951. Canadian woods, their properties and uses. Dept. Resources Develop., Forest. Br., Forest Prod. Res. Div., Queen's Printers, Ottawa.

Barker, H. 1968. Methods of measuring leaf surface area of some conifers. Dept. Forestry and Rural Development, For. Br. Publ. No. 1219. 5 pp.

Beaufait, W.R. 1966. Prescribed fire planning in the intermountain west. U.S. Forest Serv., Paper INT - 26.

Curry, J.R. and W.L. Fons. 1939. Forest fire behaviour studies. Mech. Eng. 62:219-225.

Fahnestock, G.R. 1960. Logging slash flammability. Intermountain Forest Range Exp. Sta., Ogden, Utah. Paper No. 58.

Fons, W.L. 1946. Analysis of fire spread in light forest fuels. J. Agri. Res. 72(13).

Mactavish, J.S. 1965. Forest fire danger tables. British Columbia Coast. Canada Dept. Forestry Publ. No. 1099.

Muraro, S.J. 1964. Surface area of fine fuel components as a function of weight. Canada Dept. Forestry Publ. No. 1080.

Rothermel, R.C. and H.E. Anderson. 1966. Fire spread characteristics determined in the laboratory. U.S. Forest Serv. Res. Paper INT - 30.

Rowe, J.S. 1959. Forest regions of Canada. Canada Dept. Northern Affairs and National Resources, For. Br. Bull. 123.

Society of American Foresters. 1958. Forestry terminology. Society of American Foresters, Mills Building, Washington 6, D.C. Library of Congress Catalog Card Number: 58-9365.

Van Wagner, C.E. 1965. The line intersect method of fuel sampling. Petawawa Forest Experiment Station, Internal Report PS-1. Canada Dept. Forestry.

Wade, D.D. 1965. Response of fire analogs to duff conditions during prescribed fires, thesis presented in partial fulfilment of the requirements for the degree of Master Science in Forestry, University of Montana, Missoula, Montana.

APPENDIX

Standard factors for converting English measure to Metric:

Inches	X	2.54	Centimeters
Foot	X	0.3048	Meters
Foot^2	X	0.0920	Meters^2
Foot^2	X	9.2903×10^{-6}	Hectares
Foot^3	X	0.02831	Meters^3
Acres	X	0.404068	Hectares
Pounds	X	0.45359	Kilograms
Pounds/Ft.^{2}	X	4.882	Kilograms/Meter^2
Pounds/Ft.^{3}	X	16.018	Kilograms/Meter^3
Ft.^{3}/Ft.^{2}	X	0.303 approx.	Meter^3/Meter^2
Ft.^{2}/Ft.^{3}	X	3.27 approx.	Meter^2/Meter^3
Tons/Acre	X	0.3621	Tons (Metric)/Hectare
Btus./Lb.	X	0.5556	Gram Calories/Gram

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