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Duff Reduction by Prescribed Underburning in Douglas-fir

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Reference Abstract

Sandberg, David V.
1980. Duff reduction by prescribed underburning in Douglas-fir. USDA For. Serv. Res. Pap. PNW-272, 18 p. Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

Predictive equations for duff reduction and mineral soil exposure by prescribed fire are presented. An explanation is suggested for the dependence of duff combustion on surface fuel combustion. Surface fire duration and fuel moisture estimates of the National Fire-Danger Rating 1,000-hour timelag are the best predictors for reduction in moist duff. Duff layers with less than 30-percent moisture burned independently of surface fires.

Keywords: Duff, fire effects, prescribed burning, site preparation.

Research Summary

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Consumption of duff from the forest floor is often the most important effect of prescribed fire. The degree of air pollutant emission, chemical change in the soil, and site preparation are usually dominated by the amount of duff consumed. In this paper, measurements of duff reduction are reported from a series of underburning experiments in partial cut stands of (predominately) Douglas-fir in western Washington and Oregon. The effects of fire on duff were found to be predictable from preburn estimates of duff moisture content, calculated fuel moistures, and/or an inventory of fuel and duff loadings. Certain published predictive schemes are verified. Finally a tentative theory to account for the amount of duff consumed is presented.

There is a critical moisture value, near 30 percent, below which duff burns independently of woody fuels, so nearly all duff is burned. On the other hand, virtually no combustion takes place in any duff layer exceeding about 120-percent moisture content. Between these values, duff burns only under the influence of external heat supplied by the burning of fine surface fuel.

Duff is apparently dried out by a surface fire to a depth dependent more on the duration of fire than on the amount of fuel burned, with that depth equal (in inches) to the square root of diameter reduction (in inches) in the surface fuels.

Thousand-hour timelag fuel moisture estimates from the National Fire-Danger Rating System (NFDR-Th) are the most useful inputs for predicting duff reduction. Approximately 0.06 inches (0.14 centimeters) additional duff is consumed for each 1-percent decrease in NFDR-Th. Assuming a specific gravity of 0.165, this amounts to approximately 1 ton per acre additional duff. An average 2.5-percent additional duff is consumed, and 2.3-percent additional soil is bared by the 1-percent change. The difference between a spring and fall burn, with a typical difference of 15 to 20 percent in NFDR-Th, can result in a difference of 20 tons per acre consumed and 45-percent mineral soil exposure.

Contents

Introduction

Consumption of duff from the forest floor is of interest in planning or evaluating the effects of fire. Duff combustion is often the most important contributor to air pollutant emissions and to chemical changes in the soil. The amount of duff remaining after a wildfire or prescribed burn greatly affects the moisture-holding capacity and erodibility of the soil and its suitability for regeneration by natural or artificial seeding. It is incumbent upon the forest manager to predict and manipulate the factors causing mineral soil exposure, duff retention, and duff reduction by fire.

In this paper, measurements of duff reduction are reported from a series of underburning experiments in partial cut stands of (predominately) Douglas-fir in western Washington and Oregon. Effects of fire on duff are found to be predictable from preburn estimates of duff moisture content, components of the National Fire-Danger Rating System (NFDR), and/or an inventory of fuel and duff loadings. Certain published predictive schemes are verified. Finally a tentative theory to account for the amount of duff consumed is presented.

Several investigators have sought to predict duff consumption, either empirically or from an energy balance approach, from preburn environmental measurements. Those from northern conifer forests are presented here for comparison. None have been verified locally to a degree sufficient for operational use in Douglas-fir. Studies reporting exclusively on experience in ponderosa pine or Southern forests are not mentioned here because of differences in physical properties and moisture relations.

Review

Van Wagner (1972) reported on duff consumption by fire in jack pine and red and white pine stands in eastern Canada. An equation was presented to account for the weight of duff consumed, based on a balance between energy available from a surface fire and that required to preheat the duff to ignition. Duff consumption was also regressed against Duff Moisture Code, a component of the Canadian Forest Fire Weather Index approximating a moisture timelag of 1,000[1] hours (Van Wagner 1975). Mineral soil exposure was also plotted against duff moisture content, but with poor correlation. His duff consumption equation has had the widest application of those reviewed here, having been incorporated in the computer-based fire model package of the USDA Forest Service Northern Forest Fire Laboratory by Albini (1976a, b).

[1]The interpretation of "timelag" is different in American versus Canadian fire-danger rating systems. Duff Moisture Code, according to the Canadian interpretation, has a timelag of 288 hours. According to Van Wagner (correspondence dated October 2, 1979, on file at the Pacific Northwest Forest and Range Experiment Station, Seattle, Washington), that is approximately equivalent to a 1,000-hour timelag fuel in the American system.

Chrosciewicz (1978) also regressed duff reduction and mineral soil exposure on the Duff Moisture Code. Predictive equations are presented for use in jack pine clearcuts.

Shearer (1975) examined the effectiveness of prescribed fire for site preparation in Montana (Miller Creek) larch/spruce/fir forests. Reduction of duff varied with moisture content of the lower one-half of the duff layer. Artley et al. (1978) substantiated that result. Beaufait et al. (1977) also reported on duff consumption in Montana (Miller Creek and Newman Ridge) larch/Douglas-fir harvest units. They found duff moisture content and Buildup Index, which has an approximate 1,200-hour timelag response, to be well correlated with each other and with consumption.

Norum (1975) regressed duff consumption and percent duff reduction on multiple preburn inventory variables in Montana (Lubrecht Experimental Forest) larch/Douglas-fir stands which had been partial cut 50 years before. Early season results were sufficiently different from late season to warrant two sets of regressions. Variables found to be important included preburn loadings of duff, woody fuels, shrubs, and forbs, as well as duff moisture content and windspeed. He found that the same independent variables useful to explain duff consumption are also the best to predict woody fuel consumption, substantiating the hypothesis that duff consumption depends on the burning of woody fuels. Norum (1977) presents aids for predicting percent duff reduction based on moisture content in the lower duff, with optional input of fine (0- to 3-inch diameter) woody fuel consumption (in the range 0-20 tons per acre).

In summary, considerable evidence exists to conclude that duff moisture content, especially that in the lower one-half, is the most important determinant of duff consumption. There is general agreement that there is a critical moisture value, near 30 percent, below which duff burns independently of woody fuels, so nearly all duff is consumed. On the other hand, virtually no burning takes place in duff exceeding about 120-percent moisture content. Between these values, duff burns only under the influence of external heat supplied by the burning of fine surface fuel. Only minor success in predicting mineral soil exposure has been reported.

Much of the research reviewed above appears applicable to underburning in coastal Douglas-fir partial cuts. Such applicability had not been verified in controlled experiments, however.

Methods

This study of duff combustion is part of a larger effort to produce guidelines for prescribed underburning in partial cut stands dominated by Douglas-fir in western Washington and Oregon. Thirteen stands were selected to represent the range of conditions typical of such burns. The study area (fig. 1) includes seven Ranger Districts in four National Forests. The geographic area over which prescribed underburning is operational was spanned, as was the range in elevation (300-1 400 meters or 1,000-4,500 feet), slopes (5-75 percent), fine fuel loadings (1.8-4.4 kilograms per square meter or 8-20 tons per acre), duff thicknesses (unit averages of 4.7-11.2 centimeters, or 1.9-4.4 inches), stand densities (30-1,130 five-inch and larger diameter trees per hectare, or 12-457 per acre), crown covers (10-100+ percent), and time of year (June to October) (table 1, fig. 2).

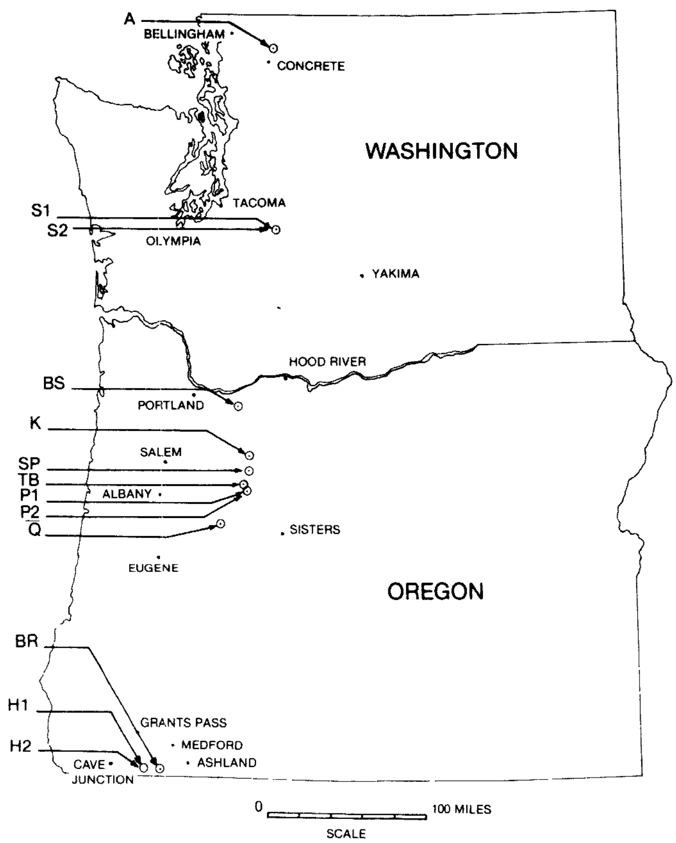

Figure 1.--Map of western Washington and Oregon showing location of prescribed underburning study units.

Table 1--Characteristics of prescribed underburning study units

Unit	Elev.	Slope	Aspect	Fuel load <7.6 cm	Fuel load >7.6 cm	Crown cover	Average tree diameter	Date burned
	Meters	Percent		kg/m^2	kg/m^2	Percent	Centimeters	
A	300	45	W	2.9	9.4	71	57	6/28/78
S1	700	60	NW	4.0	7.9	13	72	6/20/78
S2	700	60	NW	3.1	6.7	12	65	7/12/78
BS	700	35	S	2.5	15.0	56	43	6/08/78
K	1 000	5	W	2.9	9.0	13	62	6/16/77
SP	1 200	45	N	2.5	7.9	17	69	10/20/77
TB	1 400	45	SW	1.6	12.1	31	49	6/28/78
P1	700	40	NE	2.5	5.8	82	43	7/31/78
P2	800	25	N	2.5	4.5	69	34	7/30/78
Q	1 000	50	S	1.6	10.3	32	57	6/08/78
BR	1 400	45	NW	2.9	7.6	100+	25	10/14/77
H1	1 100	55	N	2.2	13.0	15	38	8/31/77
H2	1 000	75	N	2.5	11.0	10	52	9/17/77

Figure 2.--Photographs of underburning study units BS (top), and H1 before and after treatment.

No effort was made to reduce variability included in the sampling by limiting the environmental conditions encountered. Rather, by selecting burn sites as different as possible from one another, we intended to develop predictive equations useful in the broadest practical applications. No doubt the varied and unmeasured soil conditions and the differing techniques for applying fire were limiting factors in the goodness-of-fit of our regression equations. On the other hand, we meant to stretch each theoretical relationship to its limit and provided equations with the least potential for misuse.

Duff thickness and consumption were measured at 192 grid points over a 1-hectare (2-1/2-acre) plot area within each unit burned. Spikes were driven flush with the top of the duff (F and H layers), and the exposed length and distance to mineral soil measured after burning according to the method described by Beaufait et al. (1977). The percent of mineral soil exposed by fire was estimated by subtracting the percentage of spikes found in mineral soil after burning from the percent found in soil before burning. Preburn mineral soil exposure averaged 3.3 percent on skyline-yarded units. Moisture content in both the upper and lower one-half of the duff layer was sampled at 5-12 locations within the plot just prior to burning. Moisture contents are expressed as a percentage of ovendried fuel weight.

Fine fuel loading was measured at crossed pairs of 1-1/2-meter (4.9-foot) transect planes (Brown 1974). Fuel consumption was calculated by remeasuring fuels along each transect plane. The average reduction in fuel particle diameters for fine and coarse fuels was calculated and used to estimate flame residence time (Anderson 1969, Harmathy 1976), T_R (minutes), where

$$T_R = 3.15\Delta d,$$

and Δd is the fuel diameter reduction in centimeters. This relationship was originally derived for cases where T_R represented the burnout time for pieces completely consumed by fire. The relationship between residence time and partial diameter reduction is even more likely to be linear, but the coefficient shown may be in error. It is the best estimate available.

Standard errors were calculated for each mean fuel loading estimate on each unit. Standard errors in duff loading and reduction in duff thickness averaged less than 0.4 centimeters (0.16 inch). Estimates of percent duff reduction have a standard error of 3.7 percent. Estimates of down woody fuel loading have standard errors of less than 15 percent of their mean value. Duff moisture contents, which have typical coefficients-of-variation of about 40 percent of their mean value, have standard errors near 20 percent.

Standard fire-weather observation stations were set up on each unit, usually several weeks in advance of burning. All components of the National Fire-Danger Rating System (NFDR) were calculated (Deeming et al. 1977). NFDR components were also calculated from observations at the nearest permanent fire-weather station for comparison.

Results and Discussion

The units burned under a variety of conditions. Some barely carried fire, while others were on the verge of creating control difficulty. Strip headfires generally were used, with strip widths averaging about 7 meters (20 feet) and ranging from 2 to 20 meters (6 to 66 feet). Backing fires were occasionally used in slash concentrations (e.g., Unit A),[2] and often used where fuel moistures were especially low (H1, P2). Flame lengths ranged from 0.15 to 3.7 meters (0.5 to 12 feet) and were usually held to between 0.9 and 1.5 meters (3 and 5 feet).

Multiple linear regressions were calculated for duff depth reduction, duff thickness remaining after fire, percent duff reduction, and percent mineral soil exposure. NFDR fuel moisture estimates, measured fuel and duff moisture contents, preburn duff thickness, and woody fuel diameter reduction were used as independent variables. Each regression presented includes only those independent variables theorized to have a direct causal relationship, are readily available to the user, and are significant at the 95-percent level.

[2]Specific units will hereinafter be referred to by using the one- or two-character code shown in figure 1.

Data from all units were used in at least one regression, but several events occurred which required exclusion of one or more units from others. For example, two units (TB, A) had duff layers in excess of 10.5 centimeters (4.1 inches). While this created no difficulty in explaining the amount (depth) of duff reduction, neither the percentage of duff removed nor the percentage of mineral soil exposed nor the amount of duff remaining after fire was predictable from weather or fuel moisture data without their exclusion. Duff on two units (P1, H2) continued to smolder for several hours after surface fuels ceased burning. Naturally, the amount of duff consumed on those units showed no relationship to the amount of surface fuels consumed. Finally, sufficient rainfall occurred during ignition on two units (TB, H2) to invalidate any regression attempting to predict percentage consumption on those units. These anomalies helped to define the endpoints of applicability in the predictive equations that follow and resulted in a variable sample size of from 9 to 13 units for regression analysis. Exclusions are noted below when regressions are presented.

In the remainder of this section, results will be presented and discussed separately for each objective. Our understanding of the thermophysical process involved will be presented, followed by an evaluation of the degree to which the current literature explains our findings. Regression equations will then be presented and discussed. Regressions on one variable are plotted along with the 95-percent confidence interval for the regression line.

Duff Depth Reduction

Duff combustion usually occurs under the influence of an external heat load supplied by burning woody surface fuels. It is known, however, that duff will burn independently under some conditions. Several burns in this experiment were observed to contain plots that smoldered for several hours after surface fuels ceased burning. Insufficient data were collected to model the event; but in all cases, the moisture content of the upper duff was less than 30 percent; in the lower duff, less than 90 percent; and the National Fire-Danger Rating System 1,000-hour timelag fuel moisture (NFDR-Th) was 17 percent or less. Windspeed also has an important but unmeasured influence.

Duff depth reduction for the 24 plots within each unit was regressed against fine fuel consumption on each plot in an effort to further describe the conditions under which duff combustion depends on surface fuel combustion. A low correlation coefficient would be consistent with the hypothesis that a duff layer was sufficiently dry to burn independently of surface fuels, once ignited. The variation in fuel or duff moisture content within each unit is unknown other than by coefficients of variation between moisture samples. Linear correlation coefficients (r) for the five units where NFDR-Th moisture content was greater than or equal to 23 percent, and for the two units where rain fell, range from 0.52 to 0.72, while those for units where the NFDR-Th estimate was 22 percent or less range from 0.00 to 0.25.

It appears from these data that two moisture regimes were encountered. Under moist conditions, i.e., in all cases where NFDR-Th timelag moisture was greater than 22 percent and lower duff moisture exceeded 135 percent, or where rain fell, duff reduction is strongly dependent on fine fuel consumption. Where those indexes were dry, i.e., less than 18 and 90 percent, respectively, woody fuel consumption is not important. A transition regime exists where parts of a unit are dry and others moist, so that duff reduction is only weakly dependent on fuel consumption.

Burnout Theory.--Van Wagner (1972) provides the only algorithm available for which we collected the necessary input data. He theorized that the efficiency of heat transfer from a surface fire to the duff surface, which he called "emissivity," is variable. The approach was rendered empirical by obtaining the dependence of emissivity, e, on duff moisture content, M_D (percent), through linear regression:

$$e = 0.77-0.00543\ M_D. \qquad (1)$$

Combined with this expression is the duff weight consumed, W_D, obtained from an energy balance equation:

$$W_D = \frac{T_R \times 1074e}{110 + 6.2M_D}\ \text{kg/m}^2, \qquad (2)$$

where T_R (minutes) is the fire duration. Substituting equation 1 for e into equation 2 and allowing T_R = 1, yields the expression in common use:

$$W_D = \frac{0.941\ (141.8-M_D)}{17.74 + M_D}\ \text{kg/m}^2.$$

His equation, however, is unsuitable for our use in its present form because the empirical coefficients are limited to light surface fuels (less than 0.25 kg/m^2 or 1.1 T/A).

Whereas Van Wagner's (1972) observations of duff reduction have a maximum value of 2.9 kg/m^2, our measured duff reduction ranged from 3.0 to 11.1 kg/m^2 (assuming an average specific gravity of 0.165)[3]. Van Wagner's fuels were composed of longer needles than Douglas-fir and would result in a lower bulk density. Similarly, his predictive equation is based on an assumed fire duration of 1 minute, while we estimate flame durations of 6-12 minutes. Finally, his empirical derivation of emissivity becomes unrealistically low, in fact negative, for some of our measured duff moistures.

In retrospect, it appears that had Van Wagner ignored all samples where $M_D \leq 35$ percent, an average value of e = 0.34 could have been used for the remainder of his examples. A better fit of those data would result from substituting that value of e in equation 2, such that:

$$W = \frac{58.9\ T_R}{17.74 + M_D}\ kg/m^2 \qquad (3)$$

avoiding the conceptual difficulty a variable emissivity presents.

A comparison of our results with predicted values from the modified form of Van Wagner's equation 3 comprises figure 3. Our calculated values of residence time were used, arbitrarily limited to a maximum of 12 minutes, i.e., considering consumption of 3.8-centimeter (1.5-inch)-diameter and smaller fuels. Duff moistures, M_D, are the average of upper and lower duff moisture contents.

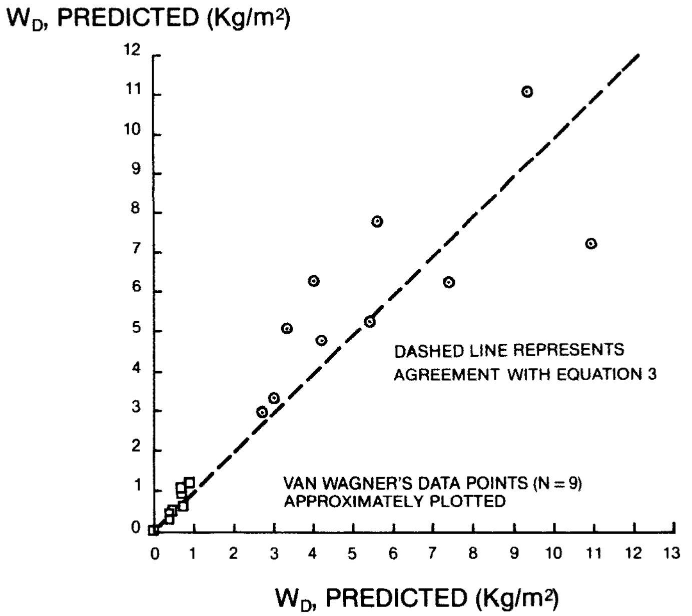

Figure 3.--Comparison of duff weight consumption with a prediction equation (eq. 3) adapted from Van Wagner (1972). Duff moisture content exceeds 35 percent.

Three units (K, Hl, SP) were excluded from the comparison because the average duff moisture content was less than 35 percent. Agreement is good, considering that no empirical coefficients remain. Admittedly, both residence time and duff bulk density were estimated from other measurements, so that the comparison does not have the complete credibility it might otherwise have. The close agreement supports, but in no way proves, the theory proposed by Van Wagner, as amended. However, the plotted results appear nonlinear, suggesting yet a more complex relationship of W_D with T_R.

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[3]Ryan, K. C. Unpublished literature review dated November 18, 1977, on file with the Forest Residues Program, Pacific Northwest Forest and Range Experiment Station, Seattle, Washington.

Van Wagner's (1972) theory also includes an assumption that all duff consumed is ignited during passage of the flaming front in surface fuels. He points out that some duff is probably partially dried by the flaming front but ignites later. To the extent that the latter is true, the amount of heat absorbed by the duff layer may be limited by the rate of heat diffusion through the layer which will be related, but not linearly, to the duration of heat supplied.

Temperature rise ($t_i - t_x$) at depth x (centimeters) within a simple conducting solid when the surface temperature is suddenly raised to t_s (°C) is described by the equation:

$$\frac{t_x - t_s}{t_i - t_s} = \mathrm{erf}\left(\frac{x}{2\sqrt{\alpha T}}\right), \qquad (4)$$

where t_i is initial temperature, α is the thermal diffusivity of the substance (cm^2/s), and $\mathrm{erf}\left(\frac{x}{2\sqrt{\alpha T}}\right)$ is Gauss' error integral (Jakob and Hawkins 1957). If we assume that t_x, t_i, and t_s are equal to 100°, 20°, and 800°C, respectively, an equation can be written to estimate the depth of heat penetration:

$$X \cong 2.2\sqrt{\alpha T} \quad . \qquad (5)$$

Equations 4 and 5 are not sensitive to t_s, which must vary by about 200°C to produce a 10-percent change in x.

Thermal properties of most organic materials are similar to the properties of water, which has a thermal diffusivity of about 14×10^{-4} cm^2/s. For example, Martin (1963) showed that the diffusivity of bark is near 13×10^{-4} cm^2/s over a wide range of bark densities and moisture contents. Diffusivity in forest duff layers has been reported in the approximate range of 10 to 14×10^{-4} cm^2/s (e.g., Feddes 1973, VanWijk 1963, Baver et al. 1972). We will assume $\alpha = 14 \times 10^{-4}$ cm^2/s for the duff layers consumed, due to their high moisture content.

Finally, it is necessary to estimate the duration, T, of the external heat load supplied. Since woody fuels on the surface burn in residual flaming, then smoldering, stages long after the flaming front has passed, the heat load must exceed flame duration, i.e., $T > T_R$. Harmathy (1972, 1976) describes the residual phase, dominated by the oxidation of char, and suggests that a reasonable estimate of total fire duration is twice the flaming duration, i.e.,

$$T = 2\,T_R \cong 6.3\Delta d \text{ (minutes)},$$

where xd (centimeters) is the diameter reduction of woody fuels. When an equation is substituted in equation 5 for duff drying depth, x, duff consumption, cm_D (centimeters), results, such that:

$$X = cm_D \cong 1.6\sqrt{\Delta d} \text{ (centimeters)}; \qquad (6a)$$

or with X and Δd in English units, simply:

$$X = in_D \cong \sqrt{\Delta d} \text{ (inches)}. \qquad (6b)$$

Equation 6 is plotted as a solid line in figure 4. Also plotted, for comparison, are the data from this study and a dashed line representing a linear regression of cm_D on the square root of αd, such that:

$$cm_D = -0.16 + 1.59\sqrt{\Delta d} \text{ (centimeters)}, \quad (7)$$

$(N = 11;\ r^2 = 0.71;\ s_{\hat{y}.x} = 0.48 \text{ cm})$,

where N is the number of observations, r^2 is the coefficient of determination, and $s_{\hat{y}.x}$ is the standard error. Excluded from this analysis were two units (H2, P1) where duff burned independently for several hours after surface burning ceased.

Agreement with equation 7 is insufficient to prove the theory embodied in equation 6 because of the limited number of observations and the assumed relationship of fire duration to the reduction in fuel diameters. There is no doubt, however, that our results are better explained by the duration of fires than by the heat load supplied (i.e., fuel consumed) by the fires. That explanation also rectifies the knowledge that duff consumption depends on woody fuel consumption with observations that the relationship is neither linear nor direct, nor is the consumption of the two strata entirely simultaneous.

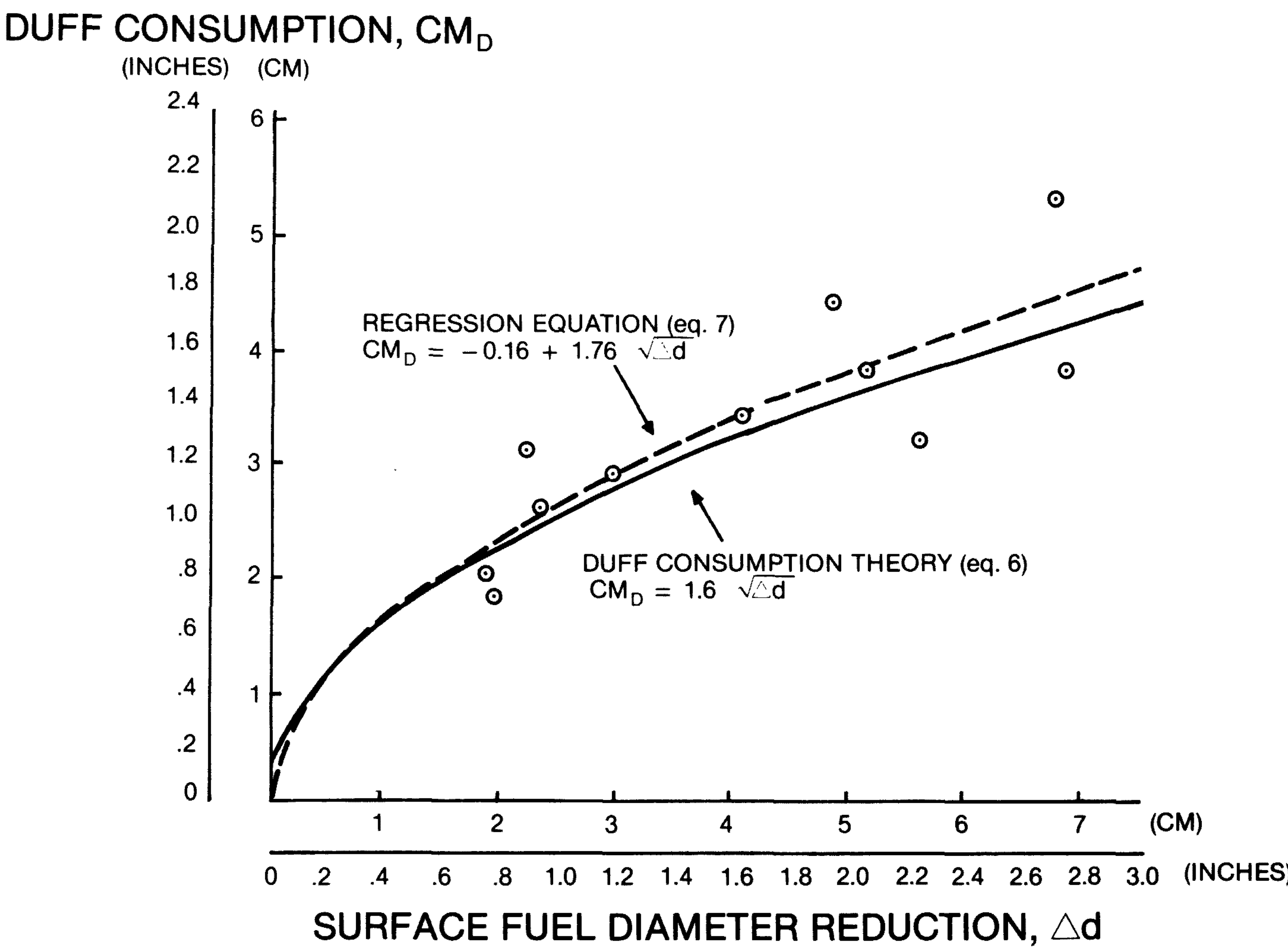

Figure 4.--Comparison of duff consumption with theory and with regression dependent on surface fuel diameter reduction. Analysis limited to fuel-dependent duff consumption.

Regression Analysis.--NFDR estimates of moisture content appear to be more useful in both a statistical and practical sense than collected samples of duff moisture content. Most previous work, and common sense, concludes that measured duff moisture content is the most important determinant of duff consumption. Yet, in the statistical analyses that follow, NFDR estimates of fuel moisture are more significant when used as independent variables. Duff moisture contents varied widely from point to point within a sampled unit. Our sampling procedures did not allow stratification of the area into separate moisture regimes, which would have been necessary for duff moisture to appear as a useful independent variable. The difficulty of collecting samples will usually preclude use of the variable in operational use; and it is certainly unreasonable to expect field units to stratify their collected data. NFDR estimates, on the other hand, are routinely available.

NFDR fuel moisture estimates were compared to measured fuel moistures. Since the NFDR system is not designed to represent conditions below tree canopies, the comparisons are illustrative rather than a test of the efficacy of NFDR values. The comparison is part of an ongoing study[4] and will not be reported here in full. We did establish in our partial cut stands, however, that bivariate correlation coefficients were highest with lower duff moisture content, M_{L_D} (percent), for NFDR-Th fuel moistures than with any alternate timelag classes. Figure 5 compares NFDR-Th with M_{L_D}. No doubt the errors in prediction are due, at least in part, to NFDR-Th responding primarily to precipitation duration, while duff moisture is affected more by precipitation amount.

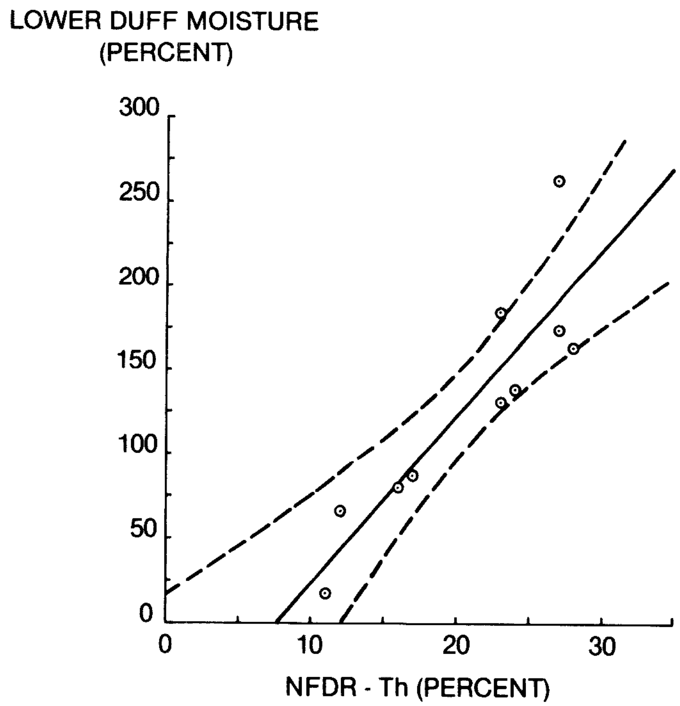

Figure 5.--Comparison of NFDR-Th fuel moisture with average duff moisture content.

NFDR-Th moisture content requires several weeks to stabilize to measured weather conditions, so fire weather stations in operation less than that period are of no value in predicting moisture contents in coarse fuels or duff. Other stations are closed in early fall, when much prescribed burning is done. Three units (K, BR, SP) are not shown in figure 5 because of such problems.

[4]Ottmar, R. D. 1979. Use of NFDR indices for prescribed fire planning. Study plan on file with Forest Residues Program, USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Seattle, Washington.

Duff consumption was well fit by regressions on NFDR-Th alone (equation 8 and fig. 6). Units where duff burned independently of surface fuels (H2, P1) or where rainfall interrupted burning (TB) are excluded.

$$cm_D = 6.67-0.13 \text{ NFDR-Th (centimeters)} \quad (8)$$

$$N = 10;\ r^2 = 0.78;\ s_{\hat{y}.x} = 0.47 \text{ cm}).$$

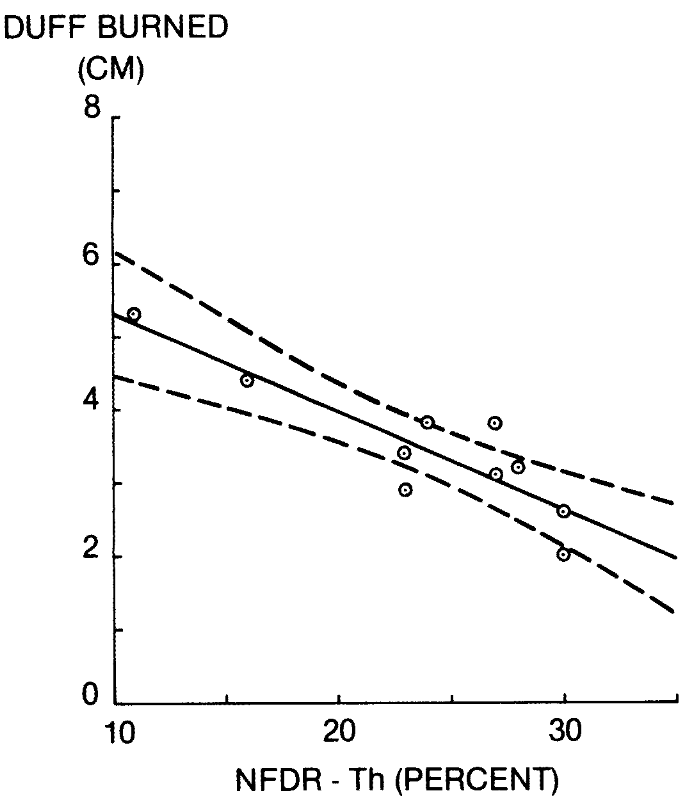

Figure 6.--Duff consumption in prescribed underburning experiments plotted against NFDR-Th fuel moisture content.

Duff Remaining

Regression Analysis.--The duff layer thickness remaining after fire is commonly specified in prescribed burning objectives. Duff remaining, AFTDUFF (centimeters), was regressed on NFDR moisture contents and duff moisture contents. When preburn duff thickness, BEFDUFF (centimeters), is used as an independent variable, the best fit is obtained in combination with NFDR-Th moisture content:

$$\text{AFTDUFF} = -6.76+0.99 \text{ BEFDUFF} +0.14 \text{ NFDR-Th (centimeters)}. \quad (9)$$

$$(N = 10;\ r^2 = 0.97;\ s_{\hat{y}.x} = 0.45 \text{ cm}).$$

Units where duff burned independently (H2, P1) or where rainfall interrupted burning (TB) are excluded. Equation 9 is essentially a prediction of duff consumption similar to equation 8 because the regression coefficient on BEFDUFF is near unity. When preburn duff thickness is not used, it is necessary to exclude units (TB, A) where duff thickness exceeds 10.5 centimeters (4.1 inches) to obtain a regression significant at the 99-percent level (equation 10, fig. 7).

$$\text{AFTDUFF} = 1.24 +.02\ M_{L_D} \text{ (centimeters)}. \quad (10)$$

$$(N = 10;\ r^2 = 0.81;\ s_{\hat{y}.x} = 0.78 \text{ cm})$$

The constant term in equation 10 is significant at the 95-percent level only.

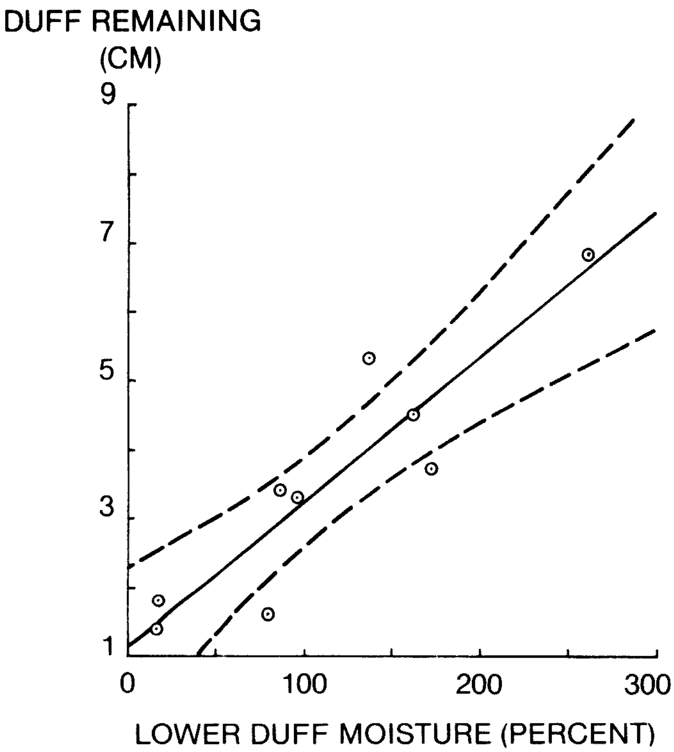

Figure 7.--Duff thickness remaining after fire plotted against moisture content in the lower one-half of the duff layer.

Percent Duff Reduction

Comparison with Prior Work.--Shearer (1975) and Norum (1977) presented prediction equations for percent duff reduction based on lower duff moisture content. The two algorithms are plotted in figure 7, along with results of this study. The two equations are similar at moisture contents less than 110 percent, while Norum's predicts less duff reduction at higher moisture contents. Our data tends to substantiate their results, except at very low moisture contents. Agreement was best with Shearer's equation, most likely because the range of preburn duff thickness is similar for the two studies. No improvement in fit was possible by adding fine fuel consumption as an independent variable. Units (TB, A) where duff thickness was greater than 10.5 centimeters (4.1 inches) were excluded from figure 8, and the maximum of upper and lower duff moisture was used as our independent variable for this plot.

Regression Analysis.--Regression of percent duff reduction on duff moisture content provided no substantial improvement over the predictive algorithm provided by Shearer (1975), so we recommend that equation for use in Douglas-fir underburning.

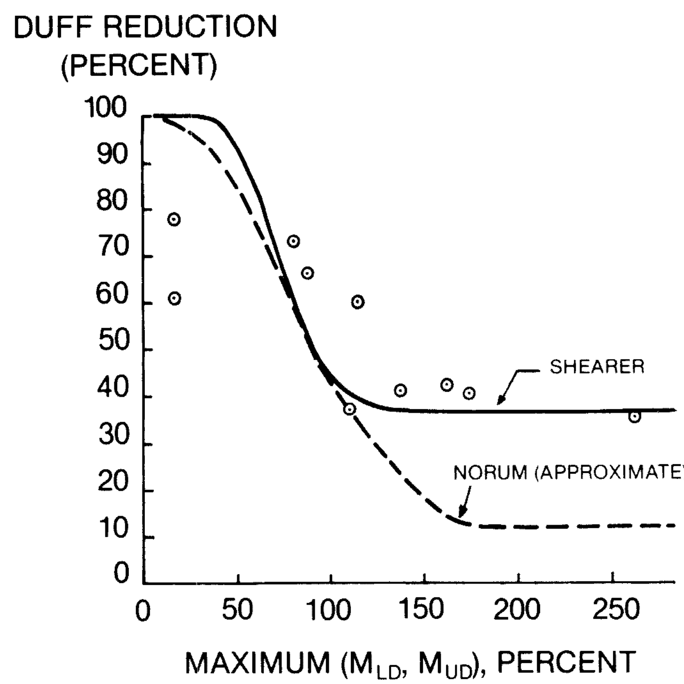

Figure 8.--Comparison of percent duff reduction with prediction algorithms by Shearer (1975), and Norum (1977). Duff thickness less than 10.5 cm.

The relationship between percent duff reduction, %D (percent), and NFDR-Th (percent), is demonstrated by figure 9. Units were excluded from analysis if preburn duff thickness exceeded 10.5 centimeters (TB, A), or where rainfall interrupted burning (TB, H2). The simple linear regression can be improved, albeit slightly, if the information is available to add NFDR 100-hour timelag fuel moisture in the NFDR-Hu (percent), or preburn duff thickness, BEFDUFF (cm), as an independent variable. All terms in the resulting predictive equations are significant at the 1-percent level.

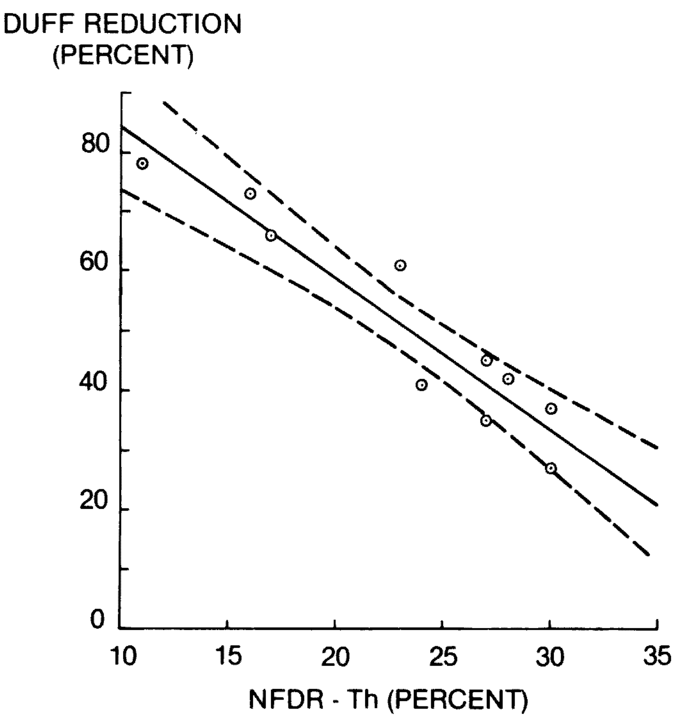

Figure 9.--Percent duff reduction during prescribed underburning experiments plotted against NFDR-Th fuel moisture content. Preburn duff thickness averaged 5.3 to 10.5 centimeters.

%D = 110 -2.54 NFDR-Th (percent),
(N = 10; r^2 = 0.89 $s_{\hat{y}.x}$ = 6%)
%D = 133 -2.05 NFDR-Th -2.54 NFDR-Hu (percent),
(N = 8; r^2 = 0.91; $s_{\hat{y}.x}$ = 5%)
%D = 126 -2.46 NFDR-Th -2.33 BEFDUFF (percent).
(N = 10; r^2 = 0.95 $s_{\hat{y}.x}$ = 4%)

Mineral Soil Exposure

Comparison with prior work.--Attempts by Van Wagner (1972) and Chrosciewicz (1978) to predict mineral soil exposure by regression analysis were largely unsuccessful. Norum's (1977) procedure is based on the assumption that duff is removed in an even layer all across a burned area; an assumption he substantiates by reporting typical standard deviations of duff depth reduction on the order of 2 centimeters (0.8 inches). We were unable to substantiate his results, however; no doubt because of the greater disturbance by logging in our stands, which resulted in more variable duff consumption. Standard deviations of duff reduction in the partial cut stands averaged about 4 centimeters (1.6 inches).

Regression analysis.--The percentage of mineral soil exposed increased an average of 22 percent by burning. Soil exposure, %B (percent), was regressed on NFDR-Th (fig. 10). Units with thick duff (≥10.5 cm) (TB, A) and those where rainfall interrupted burning (TB, H2) were excluded:

%B = 79 -2.27 NFDR-Th.

(N = 10; r^2 = 0.76; $s_{\hat{y}.x}$ = 9%)

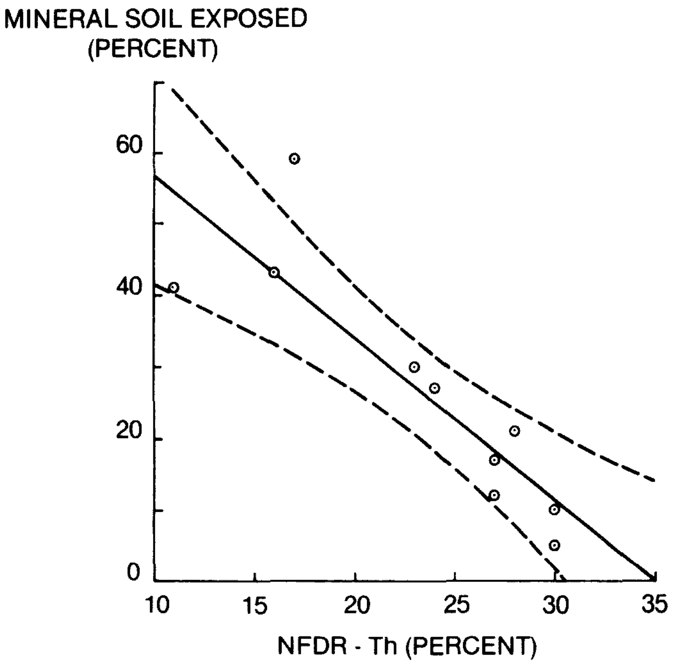

Figure 10.--Percent mineral soil exposed by prescribed underburning, plotted against NFDR-Th fuel moisture contents. Preburn duff averaged 5.3 to 10.4 centimeters thick.

Mineral soil exposure was also compared to percent duff reduction (fig. 11). The logarithm of mineral soil exposure was regressed on that of percent duff reduction:

$$\log_e (\%B) = -0.08 + 2.12 \log_e (\%D).$$

$$(N = 13;\ r^2 = 0.90,\ s_{\hat{y}.x} = 0.34)$$

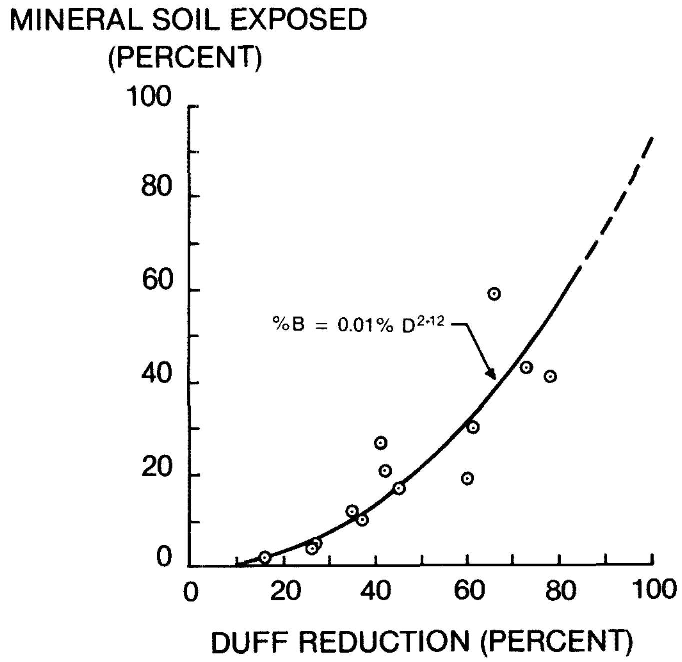

Figure 11.--Percent mineral exposure versus percent duff reduction.

No correction for possible bias was made in transforming this equation to the nonlinear form plotted in the figure. The figure may best be used to determine which objective is the greater constraint on planning a prescribed fire. For example, mineral soil to be exposed is typically specified as less than 20 percent. An objective to reduce duff by 50 percent or more would be in conflict with that specification.

Conclusion

The research reported here provides a means for prescribing weather and fuel moisture variables to attain a specified level of duff consumption. The amount (depth) of duff consumed or remaining, as well as the percentage of duff reduced or mineral soil exposed, may be specified. The NFDR-Th fuel moisture has the greatest utility as an independent variable. Predictability can be improved somewhat by adding preburn duff thickness, or duff (especially the lower one-half) moisture content as an independent variable.

The regression equations are generally valid for prescribed fires under partial cut Douglas-fir stands in western Washington and Oregon. Results were generally unpredictable if rainfall occurred within several hours after ignition. The equations predicting percentage duff reduction or mineral soil exposure are valid only where preburn duff is less than 10.5 centimeters (4.1 inches). Duff depth consumed or remaining after fire is underestimated by the equations when the duff is dry enough to burn independently of a surface fire. Prior research, substantiated here, suggests that this occurs when the upper duff moisture content is less than 30 percent, or when NFDR-Th is less than 18 percent. Evidence that less than 40 percent of duff is reduced with less than 15-percent mineral soil exposure and when lower duff moisture content exceeds 110 percent is corroborated.

Consumption of moist duff (greater than 30-percent moisture content) is dependent upon, and well correlated with, either the amount of woody fuel consumed or the duration of surface fire. Our results are best explained by the depth of heat penetration in a simple conducting solid during surface fire duration. The layer is apparently dried to a depth proportional to the square root of fire duration, then consumed to that depth by a smoldering fire.

The sensitivity of the results to NFDR-Th fuel moisture contents should facilitate prescribed fire planning and smoke management reporting. An average 0.13 centimeter (0.05 inch) of duff is consumed for each decrease of 1 percent in NFDR-Th. If the specific gravity of duff is 0.165, then 0.22 kilograms per square meter (1 ton per acre) additional duff is consumed. An average 2.5-percent additional duff is reduced, and 2.3-percent additional soil is bared. The difference between a spring and fall burn, with a typical difference of 15 to 20 percent in NFDR-Th, can result in as much as 4.4 kilograms per square meter (20 tons per acre) consumed and 45-percent mineral soil exposure. Obviously, specifying duff consumption when writing burning prescriptions can be the most important determinant of site preparation and off-site (i.e., air and water) effects.

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Predictive equations for duff reduction and mineral soil exposure by prescribed fire are presented. An explanation is suggested for the dependence of duff combustion on surface fuel combustion. Surface fire duration and fuel moisture estimates of the National Fire-Danger Rating 1,000-hour timelag are the best predictors for reduction in moist duff. Duff layers with less than 30-percent moisture burned independently of surface fires.

Keywords: Duff, fire effects, prescribed burning, site preparation.