Fire Intensity-Fuel Reduction Relationships Associated With Understory Burning in Larch/Douglas-Fir Stands

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INTRODUCTION

FIRE has been called everything from bad to good, from friendly hero to villainous foe. Sometimes, it is too naively called natural. The simple fact is that fire *is*. As long as our climate in the Northern Rocky Mountains remains essentially unchanged, we will have photosynthesis working to produce biomass at rates greater than decomposition can convert that biomass. The result is an accumulation of fuels, the stuff of which fire is made. Fire is natural, and through time it has become biologically correct because plant species have adapted to recurring fires.

Can fire then be rated as good or bad, a friendly hero or villainous foe? The answer must be yes because man needs and uses parts of the forest. It would be pleasantly simple if we could be scientifically pure and aloof and view fire simply as an amoral physical force that, by virtue of being natural, is biologically correct wherever and whenever it occurs. To view fire in this way presupposes that man's only interest in the forest lies in his appreciation of nature. Man is obviously interested in the forest for many other reasons. All attempts to manage forest lands are ultimately for man's benefit. We manage forests for man to look at, saw down, hunt in, grind up, hike in, just think about, produce water, and so on. Considering man's interests, it would be irresponsible for scientists or managers to say any fire anywhere is good, simply because it is biologically correct. Fire is a force that cannot be denied, and in the wrong place or at the wrong time is not alined with man's chosen wants, needs, or objectives for the land. We can deal with this dilemma, however, by using this unrelenting force to maintain ecosystems which we wish to use for our various purposes.

Fortunately, fire is immensely variable; a fuel complex can burn in many ways, yielding many different results. Consequently, it seems that the obvious thing to do is intentionally burn an area when the fire will favor those aspects of the ecosystems we value, need, or desire to emphasize. The ecosystem will not be destroyed when burned; it will only respond. Of course, it will respond differently to different kinds of fire; so the key is to provide a fire treatment that will produce optimum results.

To get the kind of fire needed to produce certain results, we must know what causes a fire to be the kind of fire it is and, often, how it acts as a process. Prescribed fire can never be successfully employed on a try-it-and-see basis. Fire must be quantified to the point where measurable prefire factors can be used to predict and so to produce the kind of fire needed to achieve a desired or acceptable set of results. It is toward this state of precise, quantified understanding that fire effects research should be working. We must quantify prefire variables, the kind of fire resulting, and postfire results so that we can say certain prefire conditions yield predictable results.

This paper describes one positive, probing step on what is a long path of research leading to the answers needed to use fire precisely in many forest types. The goal is true fire management, which is the right fire in the right place at the right time.

Increased use of partial cutting of timber, coupled with the recognition of natural fuel accumulations, leads us to conclude that fuel treatment is needed in living stands. Fire remains a strong candidate in the choice of treatments. Fuel treatment must preserve or enhance desirable portions of the biological community. If timber production is the major concern, residual trees must be left healthy and proper conditions must be provided for seedling establishment. Similar care must be exercised where understory grasses, forbs, and shrubs are important for browse and forage. Site productivity must not be degraded, so the nutrient status of the soil demands attention. And, all of this must be done in a way that avoids air pollution.

THE STUDY

The 22 experimental fires upon which this study is based were conducted in 1972 and 1973 in a mature stand of Douglas-fir and western larch. The study site is on the University of Montana Lubrecht Experimental Forest at an elevation of 4,800 ft m.s.l. Study plots are on east to northeast exposures. Slopes range from 20 to 50 percent. The stands are strongly dominated by Douglas-fir, but have a component of western larch and a few scattered lodgepole and ponderosa pines.

Thirty-two experimental plots were established that averaged 0.35 acre. Plot size was not considered to be a factor in treatment or results because of the ignition technique used. Fuels in 5-meter-wide strips were totally ignited along the contour beginning at the upslope perimeter of the plot and proceeding in 5-meter increments to the downslope plot boundary. A 25-point grid on 5-meter spacings was located in the center of each plot to establish fixed points for sampling.

Down and dead woody fuels were sampled before and after burning by using the two length planar intersect technique described by Brown (1974). Freshly fallen needles and duff were intensively subsampled for depth and weight, and a weight-to-depth relationship was computed. All inventory and instrumented sampling of duff was by depth, and the duff weight was calculated. Dead, down woody fuels and duff were sampled on 13 of the 25 grid points, and three duff depth measurements were taken at each inventory point. In addition, duff depth and depth reduction due to fire treatment were measured at 100 points in each fire by using 18-cm bridge spikes driven to the upper surface of the duff.

All trees over 5 inches d.b.h. were mapped for location. Trees smaller than 5 inches d.b.h. were intensively sampled on 13 circular (4-meter-diameter) subplots in each study plot. All trees were recorded by diameter, height, species, and as to whether they were alive or dead. Woody shrubs were sampled on 26 quarter milacre subplots in each study plot, and the number of each species was recorded by stem diameter. Grasses and forbs were lumped and sampled by a relative plot estimate procedure.

Down,dead, woody fuels were divided into the following diameter size classes:

0 to ¼ inch (0 to 0.635 cm)
¼ to 1 inch (0.635 to 2.54 cm)
1 to 3 inches (2.54 to 7.62 cm)
3 inches (7.62 cm) or larger rotten material
3 inches (7.62 cm) or larger sound material

All inventory sampling was replicated after burning.

Fifty fuel moisture samples were gathered and sealed within 1 hour of ignition time. Ten samples of fuel in the 0- to ¼-inch-size class, ¼- to 1-inch-size class, upper duff, lower duff, and herbaceous vegetation were collected from each experimental plot. Sample collection points on the experimental plots were distributed evenly from top to bottom.

An on-site weather station recorded temperature, humidity, and windspeed during the fires. Windspeeds used in the data analysis are those measured 4 feet above the ground at each fire. Each fire was instrumented for temperature and intensity at 13 points corresponding to the fuels inventory points. Temperature sensitive paints were used to measure temperatures in litter and soil and passive heat flux sensors (Smith and Kelley, 1969) were used to measure fire intensity (unit area energy release rate). In addition, heights of crown scorch, percent of crowns scorched, and heights of bole scorch were measured on all trees within the 25-point sampling grid. After fire treatment, all trees larger than 5 inches d.b.h. were tested for amount of cambium killed. Four cores were taken from each tree at 4 feet above the ground and tested with a 1 percent solution of ortho-tolidine and hydrogen peroxide. When so treated, live cambium is stained blue.

FIRE TREATMENTS

Nine of the 20 prescribed fires in 1973 were conducted from early May to the first of July. The remaining 11 were burned from early September to mid-October. Average dead fuel moisture contents ranged from 8.5 to 35.0 percent. Total dead fuel loadings ranged from 5.5 to 50 tons per acre. Windspeed varied from 0 to 15 miles per hour. Ranges of other variables are:

	Plot averages	
	Minimum	Maximum
0 to 1/4 inch (0 to 0.635 cm) preburn fuel weight (kg/m^2	0.052	0.148
1/4 to 1 inch (0.635 to 2.54 cm) preburn fuel weight (kg/m^2)	.047	.359
1 to 3 inches (2.54 to 7.62 cm) preburn fuel weight (kg/m^2)	.150	1.243
3 inches (7.62 cm) or larger rotten preburn fuel weight (kg/m^2)	1.006	9.413
3 inches (7.62 cm) or larger sound preburn fuel weight (kg/m^2)	.000	3.443
Total preburn fuel weight (kg/m^2)	1.228	11.057
0 to 1/4 inch (0 to 0.635 cm) fuel moisture content (percent)	8.0	35.2
1/4 to 1 (0.635 to 2.54 cm) fuel moisture content (percent)	8.4	42.5
Upper duff moisture content (percent)	9.8	115.4
Lower duff moisture content (percent)	22.8	145.1
Herbaceous moisture content (percent)	91.5	343.3
Slope (percent)	20.0	51.0
Windspeed (mi/h)	00.0	15
Preburn dead fuel depth (cm)	7.0	34.3
Average diameter of small-stemmed trees (inches)	.60	2.33
Preburn grass and forb weight (kg/m^2)	.0261	.2462
Preburn woody shrub weight (kg/m^2)	.0291	.2748
Duff depth, preburn (cm)	4.3	10.8
Fire intensity (kcal/sec/m)	23.	214.
0 to 1/4 inch (0 to 0.635 cm) percent fuel reduction (percent)	1.0	68.0
1/4 to 1 inch (0.635 to 2.54 cm) percent fuel reduction (percent)	~00.0	85.0
1 to 3 inches (2.54 to 7.62 cm) percent fuel reduction (percent)	~00.0	85.0
3 inches (7.62 cm) and larger percent fuel reduction (percent)	12.0	97.0
Percent total fuel reduction (percent)	~.00	96.00
Percent of small stemmed trees killed (percent)	14.00	88.00
Percent of large stem cambium killed (percent)	1.14	73.08
Percent duff depth reduction (percent)	14.3	71.8
Crown scorch height (m)	1.6	10.6

ANALYSIS AND RESULTS

Few kinds of experimental treatments offer as great a probability of interaction between variables as does fire. Many variables are involved, and many were measured for this study. Grosenbaugh's (1967) REX—Fortran—4 system for combinatorial screening or conventional analysis of multivariate regressions was used to order the data into meaningful relationships.

Fuel Reduction

Interest in fuel reduction includes overall fuel consumption and fuel consumption by size class and fuel type. Therefore, fuel reduction was analyzed by individual size classes and then by groups of size classes. Further, it is important to know how much actual fuel weight burned, what percent of each fuel class was consumed, and what measured variables best explain each. Consequently, fuel consumption was analyzed by the following groupings:

Dependent variables:

Y1=0 to ¼ inch (0 to 0.635 cm) diameter dead fuel weight loss (kg/m^2)
Y2=¼ to 1 inch (0.635 to 2.54 cm) diameter dead fuel weight loss (kg/m^2)
Y3=1 to 3 inches (2.54 to 7.62 cm) diameter dead fuel weight loss (kg/m^2)
Y4=3 inches (7.62 cm) diameter and larger dead fuel weight loss (kg/m^2)
Y5=0 to 3 inches (0 to 7.62 cm) diameter dead fuel weight loss (kg/m^2)
Y6=Total dead fuel weight loss (kg/m^2)
Y7=0 to ¼ inch (0 to 0.635 cm) diameter dead fuel percent weight loss (%)
Y8=¼ to 1 inch (0.635 to 2.54 cm) diameter dead fuel percent weight loss (%)
Y9=1 to 3 inches (2.54 to 7.62 cm) diameter dead fuel percent weight loss (%)
Y10=3 inches (7.62 cm) diameter and larger dead fuel percent weight loss (%)
Y11=0 to 1 inch (0 to 2.54 cm) diameter dead fuel percent weight loss (%)
Y12=0 to 3 inch (0 to 7.62 cm) diameter dead fuel percent weight loss (%)
Y13=Total dead fuel percent weight loss (%)

These dependent variables were regressed against the following set of measured independent variables. All combinations of variables were screened up to sets of five. Only statistically valid pairings were considered and correlations between independent variables were computed to assure maximum independence. All regression equations reported have an F test significance level of ≥ 0.99.

Independent variables:

X1=0 to ¼ inch (0 to 0.635 cm) preburn dead fuel weight (kg/m^2)
X2=¼ to 1 inch (0.635 to 2.54 cm) preburn dead fuel weight (kg/m^2)
X3=1 to 3 inches (2.54 to 7.62 cm) preburn dead fuel weight (kg/m^2)

X4=3 inches (7.62 cm) or larger rotten preburn dead fuel weight (kg/m^2)
X5=3 inches (7.62 cm) or larger sound preburn dead fuel weight (kg/m^2)
X6=X1+X2
X7=X3+X6
X8=X4+X5
X9=X7+X8
X10=Moisture content of 0 to ¼ inch (0 to 0.635 cm) dead fuels (%)
X11=Moisture content of ¼ to 1 inch (0.635 to 2.54 cm) dead fuels (%)
X12=Moisture content of upper duff (%)
X13=Moisture content of lower duff (%)
X14=Moisture content of herbaceous vegetation (%)
X15=1/X10
X16=1/X11
X17=1/X12
X18=1/X13
X19=1/X14
X20=Preburn weight of woody shrubs (kg/m^2)
X21=Preburn weight of grasses and forbs (kg/m^2)
X22=Preburn dead fuel depth (cm)
X23=Average slope (%)
X24=Windspeed (mi/h)
X25=Preburn duff depth (cm)
X26=Average diameter of small stemmed trees (inches)
X27=Fire intensity (kcal/sec/m)

The following regression equations were selected from some 70,000 combinations tested. They were further selected as the most meaningful or useful of several "best" equations. The user must be warned that these are not cause and effect equations, but merely products of the data-fitting process called regression analysis. Where the sign of a coefficient made a variable's relationship with the dependent variable appear illogical, the simple linear correlation coefficient was computed to assure that no experimental bias was present and that the polarity of the variable was the result of the fitting process. Each variable was tested for its individual contribution in explaining variance.

0 to ¼ inch (0 to 0.635 cm) dead fuel weight loss (kg/m^2)
$\hat{Y}1 = 0.13 + 0.87\ X1 + 0.0021\ X11 + 0.66\ X15 \quad R^2 = 0.75$
Standard error of the estimate is 0.0147

¼ to 1 inch (0.635 to 2.54 cm) dead fuel weight loss (kg/m^2)
$\hat{Y}2 = 0.21 + 1.05\ X2 + 0.0062\ X11 - 0.00088\ X12 + 0.90\ X15 \quad R^2 = 0.90$
Standard error of the estimate is 0.027

1 to 3 inches (2.54 to 7.62 cm) dead fuel weight loss (kg/m^2)
$\hat{Y}3 = 0.32 + 0.97\ X3 - 0.064\ X5 - 0.01\ X10 + 38.62\ X19 \quad R^2 = 0.85$
Standard error of the estimate is 0.013

3 inches (7.62 cm) or larger dead fuel weight loss (kg/m^2)

$\hat{Y}4=-2.55+30.0\ X1+1.1\ X4-0.018\ X13 \quad R^2=0.92$

Standard error of the estimate is 0.90

0 to 3 inches (0 to 7.62 cm) diameter dead fuel weight loss (kg/m^2)

$\hat{Y}5=-0.14+1.24\ X1+1.21\ X2-0.025\ X5 \quad R^2=0.83$

Standard error of the estimate is 0.05

Total fuel weight loss (kg/m^2)

$\hat{Y}6=-2.5+31.7\ X1+1.1\ X4-0.019\ X13 \quad R^2=0.92$

Standard error of the estimate is 0.88

As could be expected, the preburn fuel weight was the most prominent variable in describing how much of a size class burned. After all, we know without statistics that what burns is what is there. However, upon careful examination, the equations show the interacting influence of different size classes in the fire process. The equations also indicate the most important moisture contents. The persistent appearance of the herbaceous moisture content as an important descriptor was an unexpected occurrence.

Percent fuel weight reduction tends to normalize the influence of preburn fuel weights and allow the influences of other variables to be more fully expressed.

The following equations for percent fuel loss are stratified into spring and fall fires.

SPRING FIRES

0 to ¼ inch (0 to 0.635 cm) diameter dead fuel percent weight loss (%)

$\hat{Y}7=-203+3872\ X1+8.77\ X4-4.32\ X22-11.6\ X24$

$R^2=0.98$

Standard error of the estimate is 4.7

¼ to 1 inch (0.635 to 2.54 cm) diameter dead fuel percent weight loss (%)

$\hat{Y}8=473-20\ X5-1974\ X15+7.47\ X22-9.84\ X23$

$R^2=0.96$

Standard error of the estimate is 8.9

1 to 3 inches (2.54 to 7.62 cm)diameter dead fuel percent weight loss (%)

$\hat{Y}9=-241+910\ X2+168\ X3+14.4\ X4-256\ X20$

$R^2=0.93$

Standard error of the estimate is 8.5

3 inches (7.62 cm) or larger dead fuel percent weight loss (%)

$\hat{Y}10=-2.5-99.6\ X3+7.13\ X4+2.5\ X22+7.68\ X24$

$R^2=0.97$

Standard error of the estimate is 6.24

0 to 1 inch (0 to 2.54 cm) diameter dead fuel percent weight loss (%)

$\hat{Y}11=-39+611\ X6+7.60\ X4-675\ X16-293\ X20$

$R^2=0.95$

Standard error of the estimate is 8.6

0 to 3 inches (0 to 7.62 cm) diameter dead fuel percent weight loss (%)
$\hat{Y}12 = 4.1 + 1904\ X1 + 10.1\ X4 - 696\ X16 - 2.99\ X23$
$R^2 = 0.95$
Standard error of the estimate is 10.1
Total dead fuel percent weight loss (%)
$\hat{Y}13 = 11.3 + 941\ X1 - 85.1\ X3 + 8.8\ X4 - 9173\ X19$
$R^2 = 0.97$
Standard error of the estimate is 6.8

FALL FIRES

0 to ¼ inch (0 to 0.635 cm) diameter dead fuel percent weight loss (%)
$\hat{Y}7 = 42 - 4.93\ X4 - 678\ X20 - 2.1X24 + 9167\ X19$
$R^2 = 0.95$
Standard error of the estimate is 8.5
¼ to 1 inch (0.635 to 2.54 cm) diameter dead fuel percent weight loss (%)
$\hat{Y}8 = 78 + 24.2\ X3 - 20\ X5 - 195\ X20 - 9.4\ X24$
$R^2 = 0.93$
Standard error of the estimate is 6.7
1 to 3 inches (2.54 to 7.62 cm) diameter dead fuel percent weight loss (%)
$\hat{Y}9 = -105 + 325\ X6 - 4.46\ X8 + 7319\ X19 + 10.2\ X24$
$R^2 = 0.94$
Standard error of the estimate is 10.15
3 inches (7.62 cm) or larger dead fuel percent weight loss (%)
$\hat{Y}10 = 9.1 + 408\ X1 + 2279\ X18 - 698\ X2 + 492\ X21$
$R^2 = 0.94$
Standard error of the estimate is 11.96
0 to 1 inch (0 to 2.54 cm) diameter dead fuel percent weight loss (%)
$\hat{Y}11 = 91 - 6.0\ X4 - 396\ X20 - 4.5\ X24 + 47\ X23$
$R^2 = 0.91$
Standard error of the estimate is 10.0
0 to 3 inches (0 to 7.62 cm) diameter dead fuel percent weight loss (%)
$\hat{Y}12 = 112 - 4.8\ X4 - 10.0\ X5 - 443\ X20 - 4.1\ X24$
$R^2 = 0.96$
Standard error of the estimate is 5.66
Total dead fuel percent weight loss (%)
$\hat{Y}13 = 28 + 395\ X1 + 719\ X17 - 688\ X20 + 467\ X21$
$R^2 = 0.94$
Standard error of the estimate is 12.2

Note how frequently X19, X20, and X21 appear as significant variables in describing dead fuel consumption. These variables are herbaceous moisture content (reciprocal), weight of woody shrubs, and weight of grasses and forbs. Heretofore, most prescribed broadcast burning has dealt with clearcut logging sites where fire activity depended almost entirely on dead fuels and their moisture status. Burning in living stands will require more attention to form, moisture status, and amounts of living vegetation. Woody shrub weight appears quite often as an important variable and always with a negative effect on fuel reduction. Whether this is a direct or interactive effect is not clear. Nevertheless, the presence of woody shrubs appears to be significant in this kind of burning. Grasses and forbs, on the other hand, appear to support the combustion of dead fuels in fall fires.

Two classes of dead fuels appear to dominate. Not surprisingly, the 0- to ¼-inch-diameter fuels appear frequently in the equations. However, the most persistently important variable is rotten fuel larger than 3 inches in diameter; it occurs in most fuel loss equations and is always highly significant. Again, understory burning in old, unmanaged stands differs from the burning of clearcuts. In clearcuts much of the large material is sound and contributes little to the fire.

Duff Reduction

Reduction of duff depth is an important result of any forest fire. Along with other factors, the remaining duff depth can be a strong selection pressure for species of seedlings germinating after a fire in a larch/Douglas-fir forest. Little or no duff favors larch seedlings, whereas Douglas-fir seedlings germinate and survive better in a moderate amount of duff.

In this forest type, duff rarely dries sufficiently for fire to carry in duff alone. Hence, the reduction of duff depends on those factors above its surface that influence fire intensity and residence time. Presumably, heat from above dries, ignites, and consumes the duff; one would expect duff moisture content to be a factor in this process.

Duff depth reduction and percent duff depth reduction were regressed against all combinations up to sets of four. Spring and fall fires were again sufficiently different to necessitate stratification. The best-fitted equations follow.

Duff depth reduction (cm) in spring fires

$$\hat{Y} = -2.0 + 0.433\ X25 + 31.5\ X18 - 2.0\ X3 + 7.5\ X20$$

$R^2 = 0.95$

Standard error of the estimate is 0.15

Duff depth reduction (cm) in fall fires

$$\hat{Y} = 1.03 + 0.77\ X25 - 0.0306\ X13 - 14.0\ X20 + 12.5\ X21$$

$R^2 = 0.93$

Standard error of the estimate is 0.6

Note that woody shrub weight (X20) appears in both equations with opposite signs and that grass and forb weight appears in the fall equation, presumably as a fuel.

Percent duff depth reduction (%) in spring fires

$\hat{Y}=44.0-0.216\ X13+148\ X20-2.13\ X24-0.814\ X22$

$R^2=0.97$

Standard error of the estimate is 1.58

Percent duff depth reduction (%) in fall fires

$\hat{Y}=52-1.28\ X12+3.34\ X10-253.0\ X20+612.0\ X21$

$R^2=0.90$

Standard error of the estimate is 6.0

Again woody shrub weight appears with opposite signs and grass and forb weight appears only in the fall equation. As expected, duff moisture content is important in all equations in some form. Of course, these relationships fit only within range of dead fuel loadings and burning conditions experienced in this study.

Fire Intensity

Fire intensity remains a remarkably elusive variable to accurately measure under field conditions. In the final analysis, the passive heat flux sensors were not accurate enough to provide intensity data. The reasons for this failing are not yet clear, but improper location and orientation are likely culprits.

In lieu of intensity data from that source, a theoretical intensity was computed from the measured crown-scorch heights on each study plot. Thanks to work by Van Wagner (1973), it is possible to relate the height of crown scorch to the intensity of a line fire. The ignition pattern we used provided a series of such line fires. Crown-scorch heights were measured, windspeeds and temperatures were recorded, and a minimum needle-scorching temperature of 140°F was assumed.

Van Wagner computed scorch height from fire intensity with good accuracy. We took advantage of his findings and reversed the process, computing line fire intensity from measured crown-scorch heights. The reader must be warned that, although Van Wagner's work is based largely on generally accepted physical theory, some empirical data were used to find a needed proportionality constant. His results were a remarkably close fit to the observed values, but present knowledge of foliage scorching and fire intensity is too limited to confidently describe the possible values of intensity that will produce scorching. Recognizing these possible limitations, the computed intensities (kcal/sec/m) were regressed against the set of prefire independent variables. Again spring fires were sufficiently different from fall fires to necessitate stratification.

Fire intensity (kcal/sec/m) in spring fires

$\hat{Y}=914+853\ X6-6015\ X15-2110\ X17-83490\ X19$

$R^2=0.96$

Standard error of the estimate is 18.25

Fire intensity (kcal/sec/m) in fall fires

$\hat{Y}=54+174\ X3+9.5\ X4-4141\ X15+4810\ X17$

$R^2=0.89$

Standard error of the estimate is 18.6

The major difference between spring and fall fires is in the fuels that apparently dominate. Spring fires seem to derive most of their intensity from smaller fuels (0 to 1 inch diameter), but late summer and early fall fires involve the larger fuels (1 to 3 inches, and 3 inches or larger rotten fuels). Once again, reversing the process and using Van Wagner's relationship to compute crown-scorch height from the intensities provides an estimate of probable crown-scorch heights from prefire measurements.

Death of Small-Stemmed Trees

As could be expected, an overwhelming majority of the small-stemmed (<5 inches d.b.h.) trees were Douglas-fir. However, small trees of all species respond similarly to heat because important physiological differences that influence susceptibility to fire develop as trees mature. Therefore, all species were lumped together for analysis.

The dependent variable chosen is the percent of small-stemmed trees killed over the range of fire treatments. A moderately good relationship was found when spring and fall fires were used together, but considerable improvement was gained by stratifying by spring and fall fires. The percentage of small-stemmed trees killed by fire was found to be related to fire measurements in the following ways:

Percent of small stemmed-trees killed (%) spring fires

$\hat{Y}=-40.5+19.6\ X26+0.465\ X27+640\ X1-188\ X20$

$R^2=0.97$

Standard error of the estimate is 5.23

Percent of small-stemmed trees killed (%) in fall fires
$\hat{Y} = 70.9 - 133.5\ X2 + 4.29\ X4 + 2.4\ X11 - 0.987\ X13$
$R^2 = 0.93$
Standard error of the estimate is 7.13

The major apparent difference between the spring and fall fires is the appearance of heavy rotten fuels (X4) in the fall equation. Since it is a combination of temperature and time that kills trees, one would speculate that the long duration of fire in heavy fuels is responsible for its importance in fall when these fuels are dry enough to burn. Also, the presence of woody shrubs is less influential in reducing the death of small trees in fall than it is in spring.

Cambium Damage

The effects of fire on the timber overstory is of primary concern. Crown scorch and the killing of cambium are perhaps the most important factors. Both have been thoroughly analyzed in this study, but only one will be reported here. All trees larger than 5 inches d.b.h. were systematically tested for live cambium at four points around the tree. One simple but meaningful measure of tree damage is the percent of dead cambium sampled.

Percent dead cambium (%) in spring fires
$\hat{Y} = -311 + 3016\ X1 + 8.5\ X22 + 8.28\ X23 - 1688\ X18$
$R^2 = 0.88$
Standard error of the estimate is 7.74
Percent dead cambium (%) in fall fires
$\hat{Y} = -82 + 399\ X1 + 49\ X3 + 255\ X20 + 363\ X11$
$R^2 = 0.99$
Standard error of the estimate is 4.47

The strong influence of fuel weights, depths, and moisture contents is readily apparent here. Also, the importance of understory vegetation (X20) emerges as it has in every analysis performed thus far in the study.

CONCLUSIONS

Given correct preburn measurements and using proper ignition techniques, it is possible to achieve desired objectives through the use of carefully prescribed fire in standing Douglas-fir and western larch. Otherwise, the stand can be severely damaged.

This research was designed to sample a wide range of burning conditions; seemingly that was accomplished. Fuel consumption ranged from zero to near complete, yet complete control of the fires was retained. However, as fuel consumption increases, so does damage to the stand in the form of cambium death and crown scorch.

Nevertheless, reasonable trade offs are possible. Several fires were conducted that consumed as much as 80 percent of the fuel, burning 25 to 35 tons per acre of down dead woody material and killing no more than 10 percent of the trees larger than 5 inches d.b.h. Five fires killed no trees of this size, which shows that significant fuel reduction can be accomplished without undue damage to trees. Estimates of fuel consumption, fire intensity, crown-scorch height, degree of cambium damage and duff depth reduction, and other important fire results can be made from preburn measurement of fuels, burning conditions, and tree characteristics. An acceptable set of tradeoffs in desired objectives will have to be based on such estimates, and the fires conducted accordingly.

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