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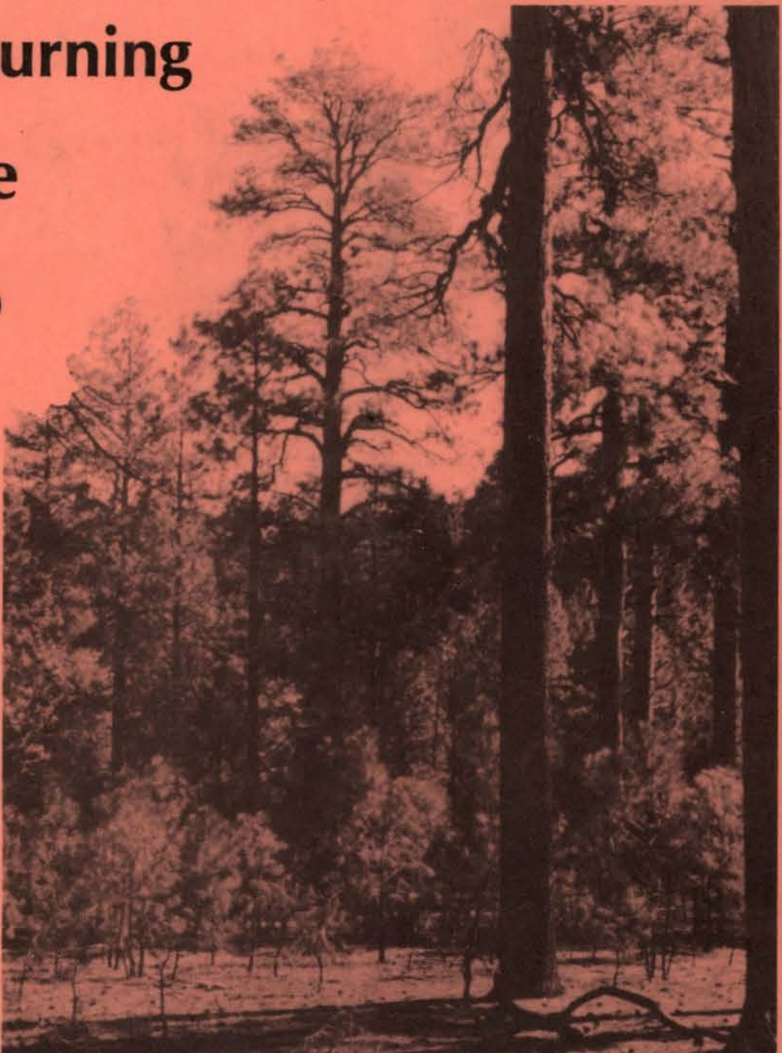

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Abstract

Planning the use of prescribed fire in ponderosa pine (Pinus ponderosa) *communities often requires an estimate of tree mortality. A logistic regression model was developed to estimate survival of fire-injured ponderosa pine from prescribed burning. Scorch height and diameter at breast height estimate the probability of survival. Once a ponderosa pine exceeds 45 cm in diameter, it has a high probability of survival for the range of intensities within this study. Since the model is based on scorch height, Van Wagner's (1973) scorch height predictive equations were tested using data collected from 21 experimental fall fires. The range of data includes fireline intensities from 16 to 860 Kcal/sec/m, ambient air temperatures from 13 to 29°C, and average scorch heights from 1 to 17 m. Van Wagner's second equation, where scorch height is a function of fireline intensity and ambient air temperature, should be used to predict scorch height. Regression coefficients should be developed for different tree species. The regression coefficient for ponderosa pine developed in this study is lower than the average value of other tree species. Fireline intensity and ambient air temperature account for only 68% of the variability in scorch height for ponderosa pine in this study. Large fuels or heavy duff loadings that provide ventilation and heat for extended periods of time may help further explain the variability.*

Predicting Mortality and Scorch Height from Prescribed Burning for Ponderosa Pine in Northern Idaho

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Introduction

Fire is an important element of the environment for ponderosa pine (*Pinus ponderosa*). It plays a number of roles in the ponderosa community (Biswell et al. 1973) and provides the land manager with an opportunity to use prescribed fire to meet a variety of management objectives. Prescribed fire in ponderosa pine has been used mainly to reduce wildfire hazards (Weaver 1957, Knorr 1963, Kallander 1969, Truesdell 1969, Sackett 1980, Harrington 1981). It has also been used to improve range conditions under ponderosa pine (Cooper 1960, Biswell 1972, Hall 1976, Severson and Boldt 1977, Harris and Covington 1983, Oswald and Covington 1983, Gartner and White 1986). In addition, fire can be used to thin ponderosa pine (Weaver 1947, 1959, 1967, Morris and Mowat 1958, Lynch 1959, Pearson et al. 1972), prepare a seedbed for natural regeneration (Schubert 1974, Barrett 1979, Sackett 1984, Haase 1986), and restrict pine encroachment into grasslands (Gartner and Thompson 1973). When planning a prescribed fire, the land manager needs a reliable prediction of ponderosa pine mortality. This study provides the tools to predict mortality of ponderosa pine resulting from fall prescribed fires in northern Idaho. A mortality model based on scorch height was developed, and since the model requires scorch height as input, Van Wagner's (1973) scorch height predictive equations were tested.

Fire and Ponderosa Pine

Ponderosa pine has evolved with an average natural fire frequency of 6 to 19 years with a range of 2 to 48 years (Wright 1978, Wright and Bailey 1982). This tree species has very pronounced survival mechanisms within a highly flammable community (Mutch 1970). The fire-tolerant characteristics of ponderosa pine include thick exfoliating bark, high open crown, high foliar moisture content (28-36% free water), large buds, relatively deep roots, and the ability to self-prune. Flammable properties of the ponderosa pine community include annual production of fine fuel and abundant needle drop. Since they dry out quickly, the fallen needles are highly flammable, make up a porous fuel bed, and have a high ratio of surface area to volume.

The fire resistance of ponderosa pine is due mainly to a thick exfoliating bark that is accumulated at an early age. Hall (1976) reports a 0.3 to 0.6 cm thick dead layer at 5.1 cm diameter at breast height (dbh). Ponderosa pine has a thick outer bark of low density exfoliating material with a relatively low moisture content that does not readily conduct heat. In addition, the bark surrounds a very moist core of high density wood which is thermally conductive. The outer bark insulates the cambium from external heat, while the cambium tends to dissipate the heat energy it receives. Martin (1963) argues that these factors favor survival of cambium in large diameter trees because the bark is thicker and the internal moist wood volume much greater than in small diameter trees.

Dieterich (1979) concluded that recovery of southwestern ponderosa pine is dependent on the season when the fire occurs, the percentage of crown scorch, consumption of live crown, site conditions, available moisture the following growing season, and incidence of insect attacks. If a large portion of the crown was removed by scorching, growth usually decreased the first year following the fire, but returned to normal during the second and third growing seasons.

Prescribed understory burning has produced different results according to the season of year (Harrington 1987). Harrington (1987) found that ponderosa pine mortality was highest in summer, followed closely by spring. Mortality was lowest in the fall. Spring burning occurs during the most active growing period for all plants; thus, a plant's ability to recover from damage decreases because carbohydrate reserves are lowest at this time (Norum 1975). Additionally, crown damage is most severe in spring and early summer burning because of low foliar moisture content and the succulent nature of the buds and twigs (Wagener 1961, Norum 1975). Bark beetles are able to concentrate on damaged trees following early season burns. Following dormant season burns, insects cannot respond to the stressed conditions of the damaged trees until the following spring, an interval which allows surviving trees additional recovery time (Miller and Keen 1960, Fischer 1980, Mitchell and Martin 1980). Thus, when the objective of a prescribed fire is to minimize ponderosa pine mortality, fall burning is preferred over spring or summer burning, although spring and summer burning may be necessary to meet other objectives.

Mortality

Damage by prescribed burning to overstory trees is caused by accumulated heat sufficient to consume or desiccate the living tissue. Location of the heat source, duration, and intensity of fire in relation to living tissue are primary features affecting plants. A tree can be divided into three areas to assess tissue damage resulting from the heat of a fire: the crown, the bole, and the roots (Ryan 1982). The leaves of trees are most susceptible to heat damage; however, these tissues are located quite far from the heat source. Cambium existing at the base of the tree stem is insulated from the heat, but is very close to the heat source. Foliage and cambium are primary areas where tissue damage occurs during fires (Martin and Brackebusch 1974, Van Wagner 1973). Where much litter has built up around large ponderosa pines, bole and root damage is a significant factor in determining mortality (Sackett, in press).

Crown damage is a good predictor of ponderosa pine mortality following fire (Herman 1950, 1954, Wagener 1961, Dieterich 1979). Wagener (1961) reports that bud kill was important in determining the survival chances of ponderosa pine, and concludes also that season of year, tree age, and site are important in determining mortality. Herman (1950, 1954) found scorch height and mortality of poles and mature timber were closely correlated.

Dead cambium is a significant factor when found in all four quadrants of the stem cross section in conjunction with 50% or more of live crown scorched (Mann and Gunter 1960), yet a tree must be completely girdled to die by cambial damage alone. Fahnestock and Hare (1964) observed that cambium injury occurred in streaks and spots and covered appreciable areas only on the leeward side of some trees burned in headfires. Any fire that is intense enough to girdle a large ponderosa pine will probably scorch all its foliage as well. However, it may be possible to have low intensity fires that produce low scorch heights and completely girdle the tree if the fire burns for a long duration at the base. Since crown damage adequately predicts mortality for ponderosa pine, and cambial and root damage are difficult and expensive to detect, the initial purpose of this study was to provide a reliable mortality model based on crown damage.

Crown damage has been assessed a number of different ways, including measurement of percentage of the crown volume scorched (usually referred to as percent crown scorch), percentage of buds and twigs consumed, percentage of crown length scorched, and the maximum height above ground of scorched foliage (usually referred to as scorch height). Percent crown scorch predicts tree mortality better than scorch height (Peterson 1985, Peterson and Arbaugh 1986, Ryan et al. 1988). However, percent crown scorch is of little value for predicting tree mortality to plan prescribed fires. Peterson (1985) found that calculated crown scorch volume based on scorch height and tree dimensions was significantly greater than observed crown scorch volume. On the other hand, scorch height can be related to predicted fire intensity. Thus, mortality models based on scorch height are useful for planning prescribed fires, whereas models based on percent crown scorch would be more appropriate for conducting salvage operations after a wildfire. Since the purpose of this study was to develop a mortality model for use in planning prescribed fires, the model is based on scorch height rather than percent crown scorch. Including dbh in the model allows for direct comparison with Bevins' (1980) mortality model for interior Douglas-fir (*Pseudotsuga menziesii* var. glauca).

Bevins (1980) utilized a logistic regression model to estimate survival of fire-injured Douglas-fir using data from Norum's (1975) study as input to the logistic regression routine, and RISK (Hamilton 1974) to obtain tree survival predictions within the probability interval (0,1). Stem dbh and crown scorch height predicted survival better than any other combination of variables.

Scorch Height

The height at which lethal foliage temperature is reached or exceeded above a flaming front is dependent upon fireline intensity, ambient air temperature, and wind speed (Van Wagner 1973). The basic theoretical models for prediction of scorch height are given by Taylor (1961) and Thomas (1964). Van Wagner (1973) adapted the equations for low wind conditions.

Equation 1 $$H_s = K_1(I)^{2/3}$$

Equation 2 $$H_s = K_2\frac{(I)^{2/3}}{(60 - T)}$$

Equation 3 $$H_s = K_3\frac{(I)^{7/6}}{[.107(I) + W^3]^{1/2}\,(60 - T)}$$

where,

H_s = scorch height (m)
K_i = constant generated from regression analysis
I = fireline intensity (Kcal/sec-m)
T = ambient air temperature (°C)
W = windspeed (m/sec).

Equation 1 relates scorch height to the ⅔ power of fireline intensity (I). Fireline intensity equals rate of spread multiplied by fuel weight consumed per unit area multiplied by heat of combustion (Byram 1973). Equation 2 involves fireline intensity and ambient air temperature (T) in degrees Celsius. The third equation introduces the wind (W) in meters per second. The regression coefficients (K_i) are determined empirically. When investigating different temperatures at different heights, Van Wagner (1975) reports an average value of K_2 equal to 8.9, with a range of values from 5.2 to 14.2.

Site Description

This study was conducted on land owned or managed by the Coeur d'Alene Indian Tribe/Bureau of Indian Affairs in Benewah and Kootenai counties of northern Idaho. Four locations were selected in mature, seral ponderosa pine stands of the Douglas-fir/ninebark (*Pseudotsuga menziesii/Physocarpus malvaceous*) habitat type (Daubenmire and Daubenmire 1968). Two of the research areas located near Tensed, Idaho, supported a mixed stand of ponderosa pine with occasional Douglas-fir. These areas were selectively harvested during the summer of 1978, just prior to burning. The remaining sites, one near Plummer, Idaho, and the other near Worley, Idaho, consisted of pure ponderosa pine stands surrounded by agricultural land. Both of these sites were selectively harvested prior to 1975.

The understory vegetation was locally dominated by a mixture of shrubs characteristic of the ninebark union (Daubenmire and Daubenmire 1968); however, the low rhizomatous shrubs of snowberry (*Symphoricarpos albus*) and wild rose (*Rosa* spp.) had a greater cover. Native and introduced grasses were abundant. A diverse mixture of forbs was conspicuously present, but their cover was low.

The soils of the Tensed units were classified as loamy skeletal, mixed, frigid Dystric Xeroochrept of the Minaloosa series. The Plummer and Worley sites were a fine-silty, mixed, mesic argiaquic Xeric Argialboll of the Southwick series (U.S. Soil Conservation Service, St. Maries, Idaho). All locations were relatively flat with slope gradients ranging from 0 to 30%. Elevations above mean sea level ranged from 790 to 880 m.

Mean annual precipitation was 56 to 66 cm. Air temperature averaged 6.9°C at the nearest weather station, Tensed, Idaho (U.S. Dept. of Commerce 1976-1978). Annual precipitation measured at this station for 1978 was 69.6 cm. Although long-term averages were not kept at Tensed, the annual precipitation for the entire north Idaho area was 14% below normal in 1978. The study areas had below average precipitation for 1976 and 1977 (16% and 20% below normal, respectively), thus the trees may have been under drought stress at the time of the burn.

Methods

Four locations were divided into 16 (0.2 - 1.0 ha) burn plots each, for a total of 64 plots. To determine the effects of understory burning, plots were assigned one of four treatments: 1) control (no burn), 2) backfire, 3) single headfire, and 4) strip headfire, and were burned with different fuel loads, fuel moistures and weather conditions (Bakken 1981). The strip headfires had 2 to 6 m spacing, which prevented fire intensity from reaching its potential maximum. The total of 64 treatments were distributed as follows: 16 controls, 15 backfires, 17 single headfires, and 16 strip headfires. All burning was conducted between the hours of 1:00 and 6:00 p.m. during September and October 1978.

In order to verify Van Wagner's work, mean scorch height was determined from three or more trees with a clear demarkation of scorch. Fireline intensity was calculated as the product of rate of spread, fuel weight consumed per unit area, and heat of combustion (4500 cal/gram). Units of measure were Kcal/sec-m- ^{0} C. With these restrictions, only 5 of the 15 backfires, 9 of the 17 headfires, and 8 of the 16 strip headfires were available for the regression analysis. One additional strip headfire was deleted because it fell outside Van Wagner's range of intensities. Most backfires were eliminated because they did not result in detectable scorch over 1 m. Table 1 gives a summary of scorch height from the 21 fall fires.

Data were collected during three time periods: preburn (site description and fuel loading variables),

Table 1. Variability of scorch height from different ignition techniques for 21 fall fires.[1]

	Mean Scorch Height (m)	Standard Error	Minimum Scorch Height (m)	Maximum Scorch Height (m)	Number of Trees Per Fire
Backfires	4.0	1.00	3	6	4
	2.2	0.30	1	4	11
	4.5	2.18	2	11	4
	1.0	0.00	1	1	4
	2.3	0.47	1	5	7
Strip Headfires	2.9	0.35	2	4	8
	3.7	0.68	1	6	7
	5.4	1.45	1	12	7
	6.3	0.57	4	8	7
	7.4	0.97	2	11	10
	8.0	1.78	5	13	4
	6.5	1.66	2	10	4
Single Headfires	6.5	0.89	4	9	6
	7.3	0.62	6	10	6
	10.5	1.71	6	14	4
	4.5	1.10	1	12	11
	16.7	2.40	12	20	3
	4.6	1.21	1	10	7
	6.9	0.80	2	14	17
	12.8	1.11	10	15	4
	6.6	3.37	1	26	7

[1] Data from Bakken (1981).

burn (fire behavior and weather variables), and postburn (changes in fuel loading and overstory damage due to treatments). During each burn, temperature, flame length, rate of spread, relative humidity, and windspeed were recorded three times.

Fuel loading was determined by two methods, dependent upon the type and size class of fuel. Fuel loads were measured preburn and postburn to determine fuel reduction. Large down woody fuels were sampled using Brown's (1974) planar intersect method. These included 100-hour fuels (2.5 cm to 7.6 cm dia.) and 1000-hour fuels (7.6 cm dia.). Litter, duff, herbaceous grasses and forbs, 1-hour fuels (0 to 0.6 cm dia.), 10-hour fuels (0.6 to 2.5 cm dia.), and shrubs were sampled by direct weight collections using 0.1 m^2 quadrats (5 quadrats per plot). Fuel loadings on the four locations ranged from 35,090 Kg/ha at Tensed to 58,200 Kg/ha at Plummer. The partially decomposed duff was the dominant fuel component on all sites, constituting between 50 and 59% of total fuel loading (Bakken 1981).

Fuel moisture at the time of the burn was taken directly for litter, duff, herbaceous grasses and forbs, 1-hour, and 10-hour woody fuels. The moisture content of the shrubs was not taken. The forest floor quadrat samples were weighed, oven-dried at 70°C for 24 hours, then reweighed and converted to fuel moisture. Table 2 summarizes the burning conditions.

Mensurational and tree damage data were acquired together in the spring of 1979 after budbreak. One hundred-ninety-four ponderosa pine trees were sampled. Stem dbh was rounded to the nearest 5 cm increment. Total tree height and average crown scorch height were measured to the nearest whole meter with a clinometer and 100-m measuring tape. Seedlings less than 0.5 m tall were not measured. Mortality was determined by assessing the presence or absence of new growth the following spring.

Statistical Analysis

A logistic model is often used to predict individual tree mortality (Hamilton and Edwards 1976, Hamilton 1986). The RISK logistic regression routine (Hamilton 1974) predicted tree survival in the interval 0 (dead) to 1 (alive). Regression coefficients were tested for significance using Student's t test. The regression routine fits the data to a logistic function of the form:

$$P(s) = [1 + e^{(a + bx)}]^{-1}$$

where,

$P(s)$ = estimated probability of survival in the interval (0,1)
e = base of the natural logarithms
a = regression constant
b = vector of regression coefficients
x = vector of independent variables.

Table 2. Mean, range, and coefficient of variation of preburn fuel loadings, moisture content, weather measurements, fire behavior variables, and fuel consumption for 21 fall fires (September 16-October 19, 1978).

	Mean	Range	C.V.
Preburn Fuel Load (kg/m²)			
litter	0.383	0.129 - 0.927	45.3
duff	2.097	0.650 - 3.689	41.5
1 hour	0.064	0.007 - 0.396	131.1
10 hour	0.187	0.000 - 1.906	216.5
100 hour	0.055	0.000 - 0.191	121.1
1000 hour	0.886	0.000 - 5.100	124.4
herbaceous	0.044	0.012 - 0.132	66.1
Moisture Content (%)			
litter	0.14	0.09 - 0.22	29.3
duff	0.22	0.09 - 0.46	45.7
1 hour	0.11	0.08 - 0.19	24.6
10 hour	0.14	0.09 - 0.24	30.0
100 hour	0.17	0.16 - 0.18	4.6
1000 hour	0.20	0.18 - 0.23	7.1
herbaceous	0.74	0.36 - 1.11	40.0
Weather			
temperature (°C)	19	13 - 29	21.9
relative humidity (%)	0.38	0.24 - 0.50	19.1
wind (m/sec)	0.8	0.00 - 1.8	56.8
Fire Behavior			
rate of spread (m/min)	1.4	0.1 - 3.0	69.7
flame length (m)	0.75	0.2 - 1.7	57.1
intensity (kcal/sec/m)	221.6	15.8 - 857.0	113.9
Fuel Consumed (kg/m²)			
litter and duff	1.507	0.129 - 3.023	58.6
total	1.967	0.208 - 5.355	63.7

An analysis of variance F-ratio was used to test whether the model explained a significant portion of the variation in the data.

To test the scorch height predictive equations, data were fitted using least squares regression to Van Wagner's (1973) equations and arranged to pass through the origin. The dependent variable was scorch height. Independent variables were Van Wagner's (1973) Equations 1, 2, and 3. Student's t test was used as the test statistic to determine if each coefficient was significantly different from zero. Results of all statistical tests were considered significant if $P<0.05$.

Results And Discussion

Mortality

Of a total of 194 ponderosa pine examined for this study, 81 (42%) were determined to be dead in the spring following the fall fires. As expected, surviving trees tended to be taller, have greater stem diameters, and lower percentage of live crown scorched (Table 3). When compared to data for Douglas-fir (Bevins 1980), a higher percent crown scorch was required to kill smaller ponderosa pine trees.

The resulting mortality equation for ponderosa pine is:

Equation 4 $P(s) = [1 + e^{(2.33-.37DBH + 36H_s}]^{-1}$

where,

DBH = diameter at breast height (cm)
H_s = scorch height (m).

The combined use of stem dbh and crown scorch height as independent variables in the logistic regression routine allows direct comparison with Bevins' (1980) results for interior Douglas-fir. Since Bevins' (1980) results are in English units and the conversion is difficult, the equation for ponderosa pine in English units is:

Equation 5 $P(s) = [1 + e^{(2.33-.95DBH + .11H_s}]^{-1}$

where,

DBH = diameter at breast height (in.)
H_s = scorch height (ft.).

Equation 4 suggests that ponderosa pine is very resistant to mortality from scorch (Figure 1). The steep slope of the scorch height curves shows that probability of survival decreases with increasing scorch height for small diameter trees. Once a tree exceeds 45 cm in diameter, it has a high probability of survival for the range of intensities within this study.

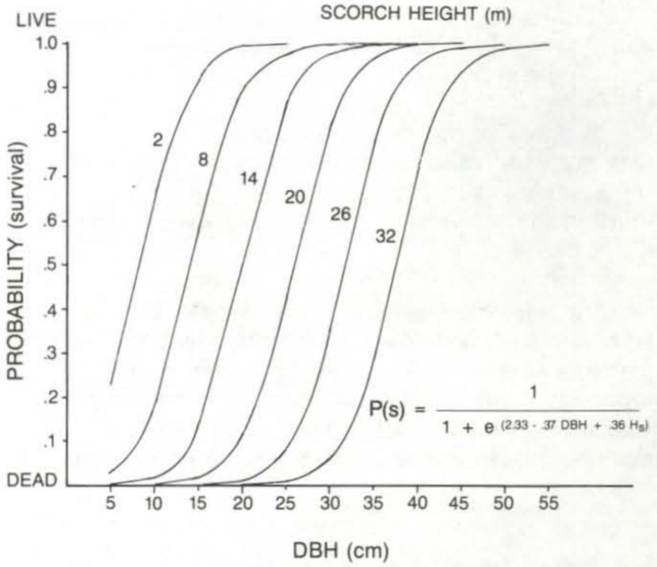

Figure 1. Plot of mortality equation (Equation 4) for ponderosa pine based on diameter at breast height and scorch heights from 2 to 32 meters.

Scorch Height

In order to predict mortality before the burn, scorch height must be predicted. Van Wagner's (1973) third equation is usually used to predict scorch height. Table 4 compares the regression coefficients (K_i) in Equations 1, 2, and 3 found by Van Wagner (1973, 1975) and the coefficients generated from this study. Similar to Van Wagner's results, the third equation (which includes

Table 3. DBH, tree height, scorch height, and crown scorch for ponderosa pine tree condition (live vs. dead) with minimum, mean, and maximum values.

Tree Condition	Number of Trees	Stem DBH			Tree Ht.			Scorch Ht.			Crown Scorch		
		Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
		Centimeters			Meters			Meters			Percent		
Dead	81	5	7	30	1	3	17	1	3	15	0	90	100
Live	113	5	22	70	1	12	32	1	7	26	0	34	100
Total	194	5	16	70	1	7	32	1	5	26	0	58	100

Table 4. Comparison of regression coefficients in Equations 1, 2, and 3 between Van Wagner (1973 and 1975) and results from this study.

	K_1	r^2	K_2	r^2	K_3	r^2	n
Van Wagner (1973)	.385	.98	11.6	.98	3.94	.98	13
Van Wagner (1975)			8.9				6
Ponderosa Pine in Northern Idaho	.163	.65	6.9	.68	2.26	.66	21

wind) does not improve the reliability of the prediction. Van Wagner (1973) stated that the third equation rests on a weak theoretical basis compared to the still air case. His main conclusion was that scorch height varies with the ⅔ power of fireline intensity (Equation 1). Also, the range of wind values in this study and Van Wagner's (1973) study is very limited. All things considered, the third equation involving wind should not be used to predict scorch height.

The regression coefficients for ponderosa pine in Equations 1, 2, and 3 are consistently lower than reported for other species (Van Wagner 1973). Van Wagner (1975) reported a wide range of values for K_2(5.2 to 14.2). Thus, scorch height varies by tree species. This variation can be dealt with by developing different regression coefficients for different species instead of relying on an average.

Figure 2 compares the value of K_2 for ponderosa pine developed in this study with the average values for K_2 for red pine (*Pinus resinosa*), white pine (*Pinus strobus*), jack pine (*Pinus banksiana*), red oak (*Quercus rubra*), and aspen (*Populus tremuloides*) developed by Van Wagner (1973, 1975). Ponderosa pine with a gentle slope (K_2 = 6.9) is resistant to scorch. Van Wagner (1975) recommends using the average value of K_2 = 10.0 from his 1973 and 1975 studies. Using this value will overestimate scorch height for ponderosa pine, except at very low intensity and temperature combinations. The reduced value of K_2 is due possibly to foliar moisture content which affects the specific heat of needles. Ponderosa pine has a high foliar moisture content (about 106% for the lower branches), with about 28 to 36% free water, a water content much higher than for other northern Rocky Mountain conifers (Jackson 1978).

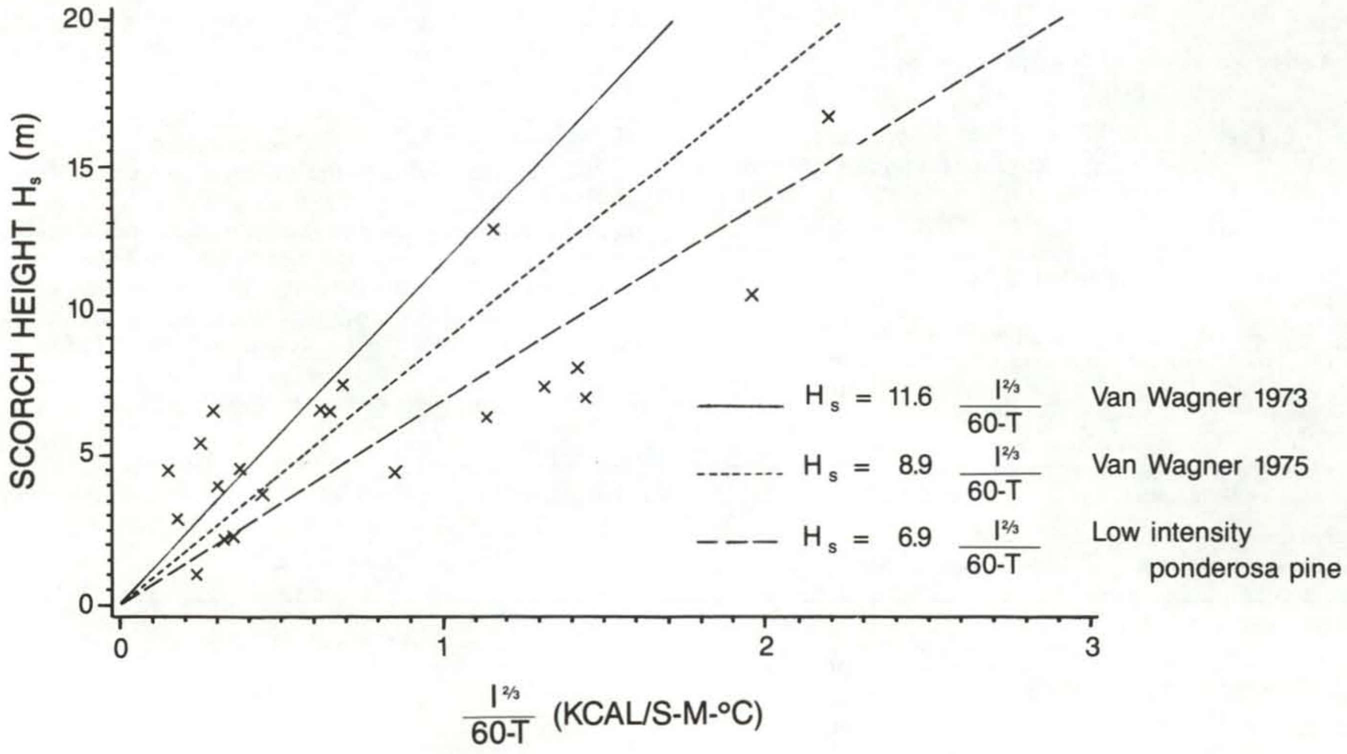

Figure 2. Comparison of this study's average K_2 value from Equation 2 for ponderosa pine and average values for red pine, white pine, jack pine, red oak, and aspen, developed by Van Wagner (1973, 1975).

Equation 2 has an r^2 of 68% for ponderosa pine. Thus, the high initial heat pulse accounts for only two-thirds of the variation in scorch heights encountered. Several factors may help explain the variation. Van Wagner (1973) reports the difficulties created by wind speed because of its opposing effects on several aspects of fire behavior. As wind speed increases, the convection column is deflected. Cooler air enters into the plume, and the effective distance to the crown canopy is increased. This tends to reduce the temperature at any vertical height above the ground. Ventilation is the ability of cool air to enter the stand and replace the heated air. Topography, unit layout, and stand density all affect wind flow through the canopy. Scorch height can be expected to increase when wind flow through the canopy is restricted. Wind speed also increases intensity by increasing the combustion rate, thereby increasing the temperature in the convective plume.

The accumulated heat necessary to kill plant tissue is a time-temperature relationship: a high temperature exposure for a short period of time, or a lower temperature exposure for a long time period can have the same result. Kayll (1968) and Hare (1961) report that conifer foliage is killed by a 1-minute exposure to 60° C or a 10-minute exposure to 50° C. The intensity measured in this and similar studies (Van Wagner 1973, 1975) is gross intensity, which accounts for the high initial convective heat pulse but makes no allowance for radiant heat and delayed combustion. If the moisture content of duff and large fuels is low enough and there is a substantial amount of duff or large fuels, they may provide radiant heat for extended periods of time, thereby increasing scorch height.

Conclusions

Mortality from fire is a function of percent crown scorch, cambial damage, consumption of twigs and buds, season of fire, site condition, tree age, tree vigor, available growing season moisture, and incidence of subsequent insect and disease attacks. In order to better prepare for fall understory burning in ponderosa pine, a mortality model based on scorch height and diameter at breast height was developed to predict postfire survival. Scorch height and diameter at breast height are easily measured and adequately predict survival. The model demonstrates that fire will thin from below, killing the smaller trees. When compared to the mortality model for Douglas-fir (Bevins 1980), smaller ponderosa pine have a higher probability of survival than larger Douglas-fir. This is because ponderosa pine possesses certain fire survival mechanisms, primarily a thick exfoliating bark and high open crown with moist, long needles.

For the mortality model to be useful for predicting the results of understory burning before ignition, an accurate means of predicting scorch height is required. When examining the variance, minimum height, and maximum height of scorch (Table 1), one finds that scorch height can be highly variable within a stand. Although the predictive equations developed in this and other studies may be helpful, there is no substitute for understory burning experience (Kilgore and Curtis 1987). Ignition method, for example, can control intensity, which in turn affects scorch height, and fuel and stand conditions are usually highly variable. Hence, experience in conducting prescribed fires is essential in order to successfully meet burning objectives.

Scorch height is a function of fireline intensity, ambient air temperature, windspeed, availability of large fuels, tree species present, and season of year. This study confirms Van Wagner's (1973, 1975) work in that scorch height is correlated to the ⅔ power of intensity (where intensity equals rate of spread multiplied by total fuel consumed multiplied by heat of combustion). Van Wagner's (1973) second equation, not the third, should be used to predict scorch. Regression coefficients should be determined for individual tree species rather than relying on an average. Fireline intensity and ambient air temperature account for only 68% of the variability in scorch height for ponderosa pine in this study.

The heat which produces scorch is a time-temperature relationship. Duff and large fuels may provide radiant heat for a longer period of time if their moisture content is low enough to burn. For land managers to predict scorch, they must deal with both the initial high convective heat pulse and the lower radiant heat that lasts for extended periods of time. Ventilation may be important in determining the length of time that heat may reside in the stand, hence wind flow through the canopy should be examined when preparing for understory burning. In all of these areas, further research is necessary.

The mortality model and predictive scorch height equations developed in this study should be valuable tools for planning prescribed understory fires, allowing the land manager to use fire to meet a variety of management objectives. Predicting ponderosa pine mortality is essentially a three-step procedure. First, predict fireline intensity using nomograms (Albini 1976) or the computer program BEHAVE (Andrews 1986). Second, use the intensity and ambient air temperature in Van Wagner's Equation 2 to predict scorch height. Use a value of 6.9 for K_2 under ponderosa pine, and Van Wagner's suggested average of $K_2 = 10.0$ for other tree species that may be present. Subjectively assess how wind, available large fuels, and ventilation will affect scorch height. Third, use the predicted scorch height and diameter at breast height in Equation 4 (or use Figure 1) to obtain the probability of ponderosa pine survival. Subjectively assess how the site condition, tree vigor, pre- and post-fire moisture regimes, and insect and disease conditions will affect mortality.

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