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Burning Rate of Smoldering Peat[1]

Abstract

Smoldering ground fires spread slowly (about 3 cm h^{-1}) and can raise mineral soil temperatures above 300°C for several hours with peak temperatures near 600°C, resulting in decomposition of organic material and the death of soil organisms. Smoldering ground fire has potential for reigniting surface fire long after the main front has passed. The rate of smoldering was examined with Canadian sphagnum peat moss as a representative fuel. The time to burn a known amount of organic mass was monitored for different organic bulk densities and moisture and inorganic contents. Organic bulk densities were comparable to the field and ranged from 90 to 180kg m^{-3}. Moisture and inorganic contents were expressed as mass ratios relative to the organic mass and covered the range of sustained smoldering combustion. Moisture ratios, R_M, ran up to 0.8 and inorganic ratios, R_I, up to 4.0. The burning rate is independent of the organic bulk density. A universal burning rate, the unit area burn rate (UBR), was obtained by normalizing the burning rate to the area of the burning surface. It is expressed as follows:

$\text{UBR} = 0.27 - 0.097\ R_M - 0.033(R_I - D)$ g cm^{-2} h^{-1}, where $D = R_I$ if $R_I < 1.0$, and $D = 1.0$ if $R_I \geq 1.0$.

Introduction

Smoldering, although not as visually dramatic as flaming combustion, is an important component of forest fires. It is common in the duff of the coniferous forest that is derived from the accumulation of detritus. The duff includes the fermentation and humus layers or the O_e and O_a soil horizons that lie between the surface litter and the mineral soil (Brady 1984). The rate of smoldering—mass loss over time—and its dependence on organic bulk density, moisture, and inorganic content of the duff is the topic of this manuscript.

Smoldering is a form of fire spread that generally occurs in fuel arrays that are more tightly packed than those that sustain flaming. A transition from flaming to smoldering is expected when fuel particles are thin or very small in diameter and occupy more than approximately 10 percent of the volume. Rothermel (1972) shows a decreasing reaction intensity, the rate of heat release of spreading fire per unit area of the forest floor, that extrapolates to very low values when the packing ratio or fractional volume occupied by fuel approaches 10 percent. Forest duff, which has packing ratios greater than 10 percent, exhibits only smoldering, while litter, with packing ratios less than 10 percent, exhibits only flaming. (A form of smoldering does occur in large fuels independent of packing during the glowing phase in large fuel pile burning, but is not addressed here.)

The ground fire, as the smoldering fire is named by fire control specialists, presents no threat in terms of its rate of spread. However, it can persist for days or weeks and later can initiate a flaming surface fire if it is fanned into flames by a chance gust of wind (Wein 1981). This potential has branded the ground fire as the "hold-over fire." Smoldering duff temperatures in excess of 300°C have been observed for up to 12 hours under a mixed overstory of western larch (*Larch occidentalis* Nutt.) and lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) (Hartford and Frandsen, in press).

The duff presents an effective barrier to the transfer of heat to the mineral soil during passage of a surface fire. However, if the duff is ignited, the resultant smoldering fire is likely to be brought into direct contact with the mineral soil raising its temperature above 300°C for several hours. Flora and fauna of the duff are consumed along with roots and seeds. Organic material in the upper portion of the mineral soil is oxidized, and roots, seeds, and soil organisms necessary for recycling nutrients are killed and possibly consumed. Smoldering duff can also contribute more than 50 percent of the air pollutants produced from a fire (Sandberg 1983). If, on the other hand, the moisture and inorganic content of the duff exceeds the limits for combustion then the duff is likely to remain unburned and not act as a source of heat (Frandsen 1987). Under these conditions the smoldering combustion zone is prevented from coming into

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[1] Based on Ph.D. dissertation submitted to the University of Montana.

direct contact with the mineral soil. However, the moisture limit may be overcome. A flow of heat from an abundance of surface fuels (slash) burning at the surface can dry the fuel and bring it within the combustion limits.

Smoldering can be initiated in the duff after a fire spreads through the forest litter if the duff is capable of sustained smoldering (Frandsen 1987). Larger litter fuels that sustain burning, such as twigs and cones, are ignited and act as centers to propagate the fire down into the duff. Once the fire is established, it propagates horizontally and vertically until it reaches conditions that will not sustain smoldering.

If heat from the smoldering combustion wave is not sufficient to overcome the heat of vaporization required by moist fuel, smoldering must cease. Furthermore, inorganic materials within the fuel matrix can absorb heat but not oxidize to produce more heat. Thus, the amount of heat produced per unit volume is reduced. Both moisture and inorganic content should reduce the effectiveness of the available heat to propagate the smoldering fire. Smoldering is expected to proceed with the greatest rate when these inhibiting variables have their minimum values.

The factors that may affect the rate of burning are the moisture and inorganic content of the duff and its organic bulk density. Both the moisture and the inorganic content hinder the smoldering process and therefore are viewed as slowing down the rate of burning. Increasing the bulk density may slow down the supply of oxygen to the combustion interface and also slow the rate of burning. However, Ohlemiller *et al.* (1979) found with flexible polyurethanes that "the smolder process is flexible enough to adapt to a wide range of oxygen supply levels, including extraordinarily low levels." The following procedure outlines an experiment to measure the dependence of the mass consumption rate of smoldering peat on the above factors.

Methods

Canadian sphagnum peat moss was selected as a representative fuel for examining the rate of smoldering in the laboratory under simulated field conditions. It has similar particle sizes and bulk and particle densities as duff, is an important ground cover in the wet boreal forest that supports smoldering combustion (Wein 1983), and is a uniform fuel that is commercially available. The range of organic bulk densities varied from 90 to 180 kg m^{-3}. This corresponds to the range that is normally found in duff (Woodard and Martin 1980; Harrington 1986). Results are related to smoldering in the absence of wind and slope.

The moisture and inorganic contents were expressed as mass ratios relative to the organic mass. The moisture ratio, R_M, ranged from 0 to 0.8 at 0.2 intervals and inorganic ratio, R_I, from near 0 (natural peat inorganic ratio) to 4 at intervals of 1. All combinations were sampled except those that were outside the smoldering limit given by Frandsen (1987) (Figure 1), as

$$R_M + (R_I/4) < 1.1 \qquad (1)$$

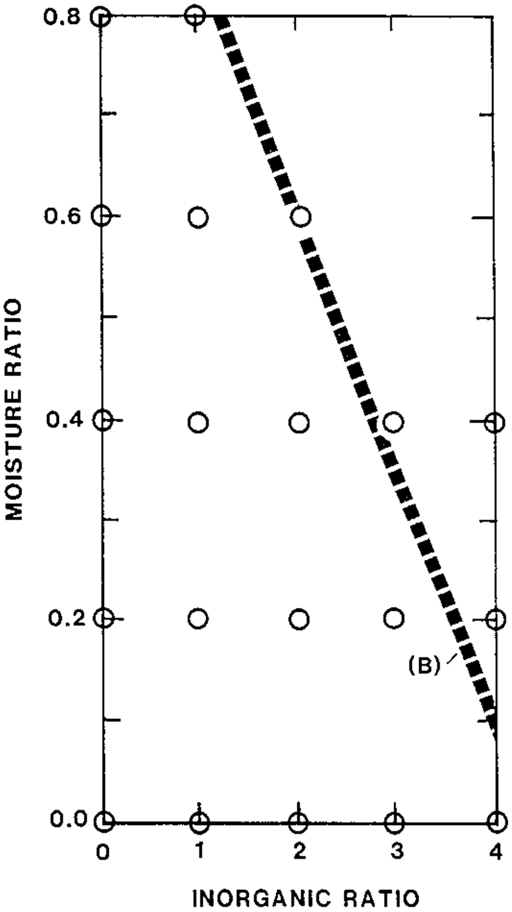

Figure 1. Sampling design. Each circle designates a sampling combination of moisture and inorganic ratios for each organic concentration. Each combination was replicated three times. Few observations were attempted beyond the expected smoldering limit (B).

Peat was moistened or dried to reach the selected moisture ratios. Inorganic material in the form of 240 mesh (56 μ particle size) powdered silica was added to moist peat to obtain inorganic ratios higher than the inherent inorganic content of peat. Silica was used to ensure that there would be the least amount of chemical interaction between the added inorganic material and the combustion process. It is speculated that natural inorganic material occurring in peat may react in a manner to alter the combustion process. More detail on sample preparation can be found in Frandsen (1989).

The experimental sample was contained within a noncombustible insulated box with an open top. The box was placed in a sealed glass cylinder. The cylinder was sealed except for an inlet and exit to allow for a flow of air. The flow was held constant at 3.5 g min^{-1} (near 3.5 ℓ min^{-1}), an amount that was determined to be sufficient to maintain smoldering without oxygen starvation, as experienced in the field. The sample volume within the insulated combustion box was 5 cm x 5 cm in cross-section and 4 cm deep. The walls were 2.5 cm thick. The insulating material was ceramic board with thermal properties similar to peat (Frandsen 1987). Consequently, the heat transferred to the walls was not greatly different from the heat transferred within the peat. This allowed the burning peat to approximate part of an expanded volume. There was no excessive heat loss or cooling at the walls of the container, as evidenced by the absence of unburned peat adjacent to the walls.

The upper exposed surface of the peat was ignited by four rows of resistance coils heated to a red glow. The glowing area approximated the area of the peat surface and was held within 5 mm of the surface for 2 minutes. Prior experimentation indicated that 2 minutes was sufficient to ignite peat at all combinations up to the highest moisture and inorganic ratios. The amount of organic material consumed under enhanced burning during the ignition period is small compared to the total mass consumed. Consequently, there is little error in the total burn time of the sample that ranged from 80 to 257 minutes.

The igniter coils were lifted away from the peat surface within 15 seconds of switching off the igniter. The duration of smoldering was taken from the time the igniter was switched off until smoldering stopped as evidenced by the absence of carbon monoxide in the air flowing from the cylinder containing the smoldering peat. Carbon monoxide was considered absent when the volumetric concentration was less than 0.0005 V/V.

Results

Data were obtained from 172 sample observations. This includes additions to the original design for comparison samplings and losses due to those conditions that would not sustain combustion.

The average smoldering burn rate was calculated by dividing the organic mass (sample mass−inorganic mass) by the duration of smoldering. The organic mass was equivalent to the total mass lost because all of the organic mass was consumed during smoldering.

There is a general trend toward lower burn rates with increasing inorganic ratios above 1.0 for each moisture ratio (Figure 2). Burn rate variations within replications of the organic bulk density were as great or greater than variations between organic bulk densities. Hence, there is no dependence on the organic bulk density. Because of this independence, one may view each combination of the moisture and inorganic ratios as replicated by as much as 12 times if all burns were successful.

Two commercial varieties of peat were used. The original choice was used for all pilot experiments and initial observations at moisture ratios of 0 and 0.2. When additional peat was needed, no more of that variety was available. A replacement was used at moisture ratios of 0.4 through 0.8. The search for the replacement included those peats having similar bulk physical properties and the lowest inorganic content approaching that of the original peat. Comparisons of the burn rates showed the two peats to be equivalent at 0 moisture ratio, but the burn rate of the original peat was 20 percent greater at the larger moisture ratios (0.4 to 0.8). Observations with the replacement peat were adjusted upward by 20 percent so that they could be used to complement the original observations (Frandsen 1989).

Noting that the burn rates at inorganic ratios near 0 and at 1 show little difference at moisture ratios 0 through 0.4 (Figure 2), we can linearize the burn rate by combining the burn rates at 1 with those near zero and giving the combined inorganic ratio a dummy value of 0 and reducing all the higher inorganic ratios by 1. (This is not the case for moisture ratios 0.6 and 0.8 but the data at moisture ratio 0.6 account for only 14 percent of the data and only 2 percent at 0.8 moisture ratio.)

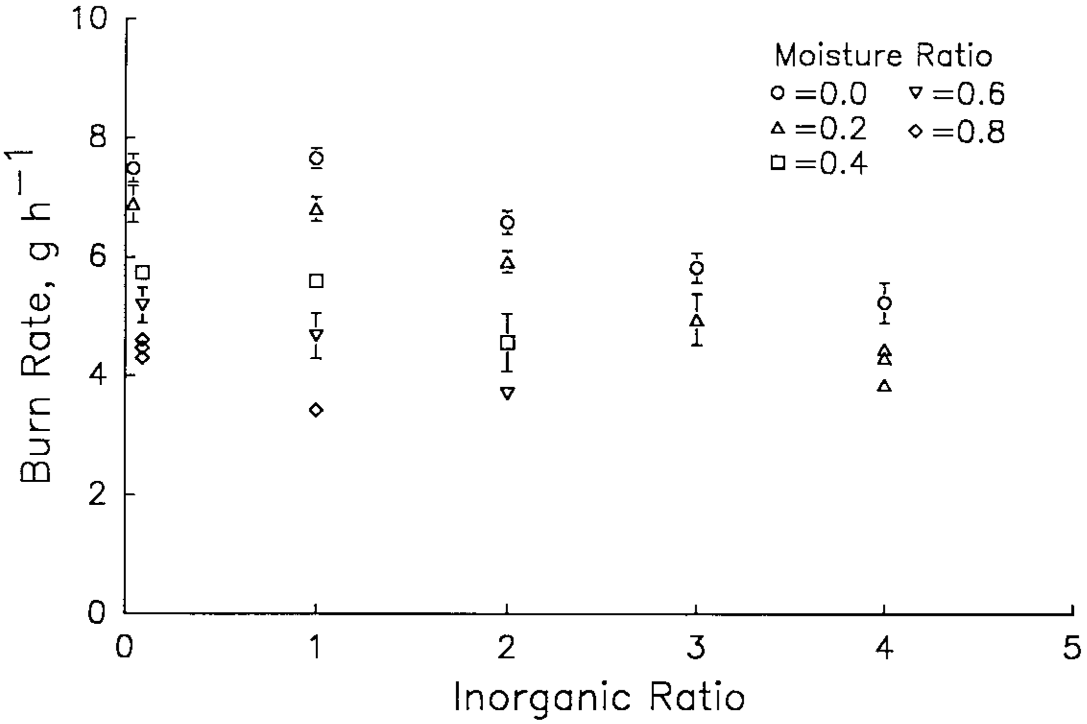

Figure 2. Burn rate dependence on the inorganic ratio at moisture ratios of 0 to 0.8. Note the decline of the burn rate with increasing inorganic ratio beginning at 1. Error bars relate to the standard deviation, n = 6 to 12 observations. Since observations have no error bars except for moisture ratio 0.4 at inorganic ratios of 0.09 and 1 where the error is less than the symbol size. ($1\ g\ h^{-1} = 2.78 \times 10^{-7}\ kg\ s^{-1}$)

The modified data have the appearance of being linear in both the inorganic and moisture ratios. A linear model developed by applying a least squares fit to the modified data is shown below. It also embraces the shift in the inorganic axis discussed above.

$$BR = 7.58 - 2.72R_M - 0.918(R_I - D) \quad g\ h^{-1}$$
$$(1\ g\ h^{-1} = 2.78 \times 10^{-7}\ kg\ s^{-1}) \qquad (2)$$

where BR = burn rate
and $D = R_I$ if $R_I < 1.0$
$D = 1.0$ if $R_I \geq 1.0$

The burn rate versus moisture ratio is shown in Figure 3, along with the linearized model. The percentage error (predicted−actual)/actual, is shown over the range of inorganic ratios at a moisture ratio of 0 in Figure 4. Estimates of the burn rate from the linear model indicate that 91, 89, and 90 percent of the predicted values lie within ± 10 percent of the actual value for moisture ratios of 0, 0.2, and 0.4. Errors are greater at moisture ratios of 0.6 and 0.8. Only about 70 percent of the predicted values were within ± 10 percent of the actual values. The lower predictive capability is not surprising considering the departure of these data from the form of the data at the lower moisture ratios in Figure 2. Furthermore, these data, as mentioned above, account for only 14 and 2 percent of all the observations.

Discussion

Many people think in terms of the linear spread rate of smoldering when reference is made to burn rate, rather than to the mass loss burn rate presented here. We gain insight into the spread rate if we convert the burn rate to a unit area burn rate by normalizing the burn rate to the area of the burning surface of the smoldering wave. The resulting unit area burn rate relates to the smoldering wave and is independent of the combustion box.

The cross-sectional area, A, of the burning volume of the combustion box (Figure 5) approximates the burning surface as it moves downward. The linear spread rate can be obtained by equating the mass loss burn rate, $\Delta m/\Delta t$, to the product of the organic bulk density, ϱ_o, and the volume

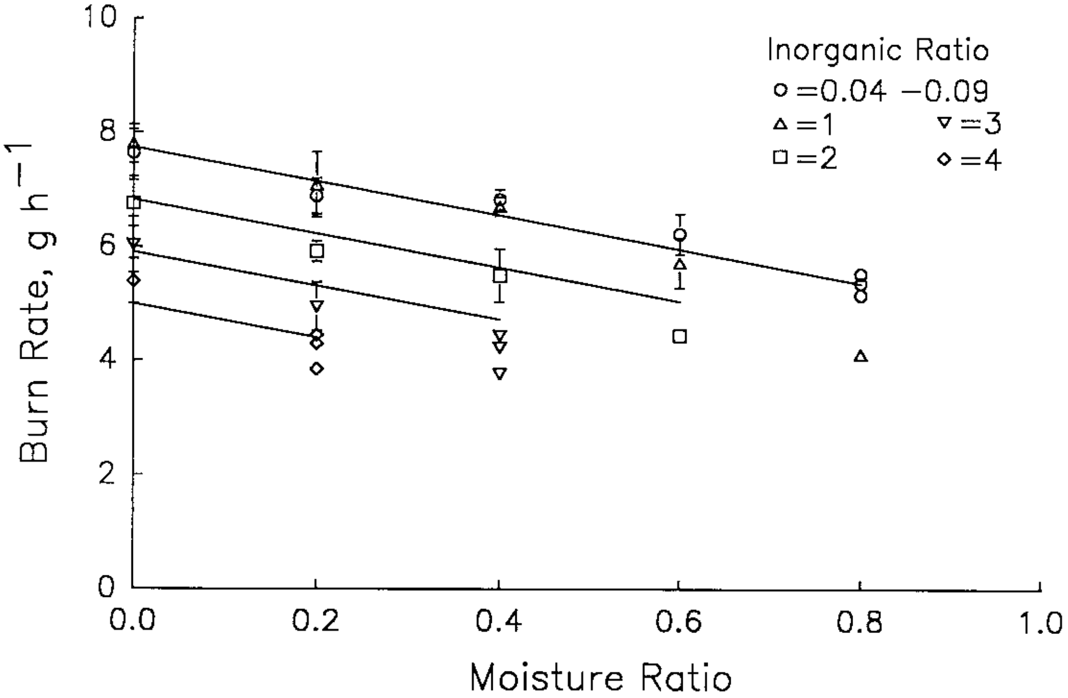

Figure 3. Linear least squares fit to observations. Error bars relate to the standard deviation, n = 6 to 12 observations. Single observations have no error bars. Note single linear fit to inorganic ratios from 0.04 to 1. (1 g h^{-1} = 2.78 x 10^{-7} kg s^{-1})

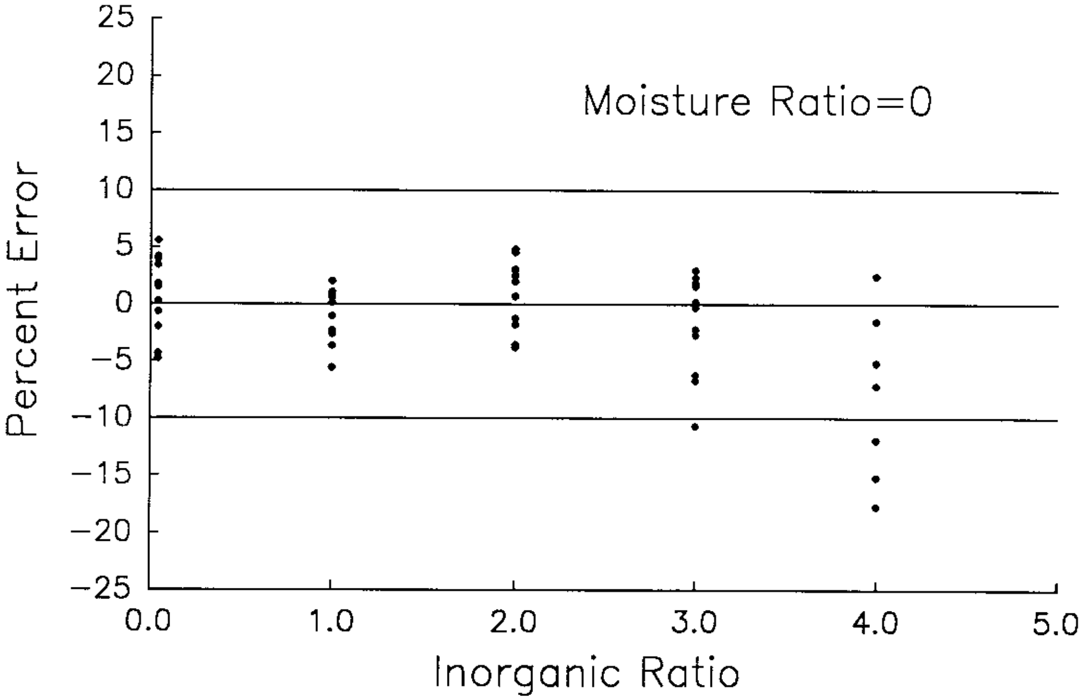

Figure 4. Errors in predicting the burn rate. N = 58.

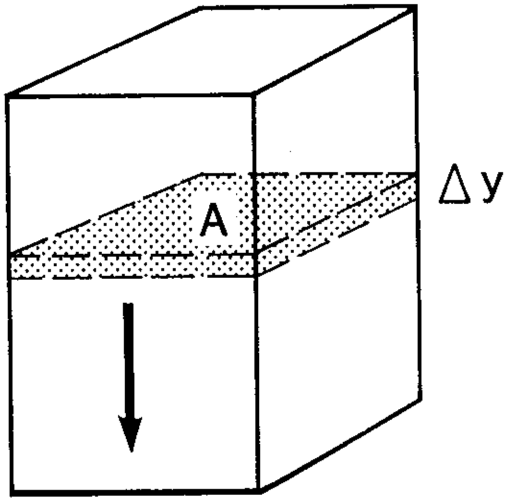

Figure 5. The burning volume within the combustion box showing the burning surface, A, as it moves downward a distance, Δy, sweeping out a volume element. ΔV = AΔy.

consumption rate, AΔy/Δt, as swept out by the burning surface in Figure 5.

$$\Delta m/\Delta t = \varrho_o A \Delta y/\Delta t \quad \text{g h}^{-1} \tag{3}$$

Transposing, we have the linear rate of spread

$$\Delta y/\Delta t = ((\Delta m/\Delta t)/A)/\varrho_o \quad \text{cm h}^{-1} \tag{4}$$

where Δm/Δt is the burn rate, BR
and (Δm/Δt)/A is the unit area burn rate , UBR

Although the box was designed for a cross-sectional area of 25 cm^2, the actual area increased slightly from deterioration of the walls with each burn. Three boxes were used during the experiment to ensure that the area did not depart greatly from the designed area of 25 cm^2. The area ranged from 26 to 30 cm^2. The median, 28 cm^2, was used to approximate the area of the burning surface. Refinements in estimating the area are precluded by uncertainties in the shape of the surface. The unit area burn rate is a universal parameter that relates only to the burning surface of the smoldering wave and is expressed as the mass loss rate per unit area of the burning surface.

UBR = BR/28
Replacing BR with equation (2)

$$\text{UBR} = 0.27 - 0.097\, R_M - 0.033 R_I - D) \quad \text{g cm}^{-2}\ \text{h}^{-1} \tag{5}$$

$$(1\ \text{g cm}^{-2}\text{h}^{-1} = 2.78 \times 10^{-3}\ \text{kg m}^{-2}\text{s}^{-1})$$

where UBR = unit area burn rate

and D = R_I if $R_I < 1.0$
D = 1.0 if $R_I \geq 1.0$

UBR ranges from about 0.15 to 0.30 g cm^{-2} h^{-1}. Using a common value for the organic bulk density, 0.1 g cm^{-3} in Eq. (4), we arrive at a range of 1.5 to 3.0 cm h^{-1} that is in the right order of magnitude for smoldering (Wein 1983).

Note that in Eq. (4) the burn rate is related directly to the linear spread rate through the organic bulk density (A is constant). If the density is halved, the linear spread rate must be doubled to maintain the same mass loss rate. This is reasonable when you consider that a combustion front must pass through a less dense fuel array faster than through a more dense array to consume mass at the same rate. It should be clear that the linear spread rate may be thought of as volumetric burn rate as the burning surface sweeps out volume, but it cannot be thought of in the same sense as the mass burn rate.

Probable error analysis was employed to examine the variability of the independent variables (Frandsen 1989). Traditional statistical methods are not applicable when the sample is prepared to achieve preselected values of the independent variables as designed in Figure 1. Based on this analysis, the moisture ratio has an error that is no greater than 3.2 percent, the error in the organic bulk density is no greater than 3.5 percent, and the inorganic ratio has an error no greater than 2.6 percent.

Approximately 90 percent of the predictions from the linear model are within ±10 percent of the actual value at moisture ratios of 0, 0.2, and 0.4. Nearly all errors greater than ±10 percent are at the higher inorganic ratios. The predictive capability drops to around 70 percent at moisture ratios of 0.6 and 0.8. The preponderance of data are at the lower inorganic ratios, at and below 1. This is a reflection of limited sustained smoldering and uncertainties when approaching the combustion limit (Frandsen 1987) at moisture ratios at and above 0.4. It is likely that whatever orderliness there may be in the relationship breaks down as that boundary is approached.

The results of this study define the dependence of the rate of burning on the moisture and inorganic content of smoldering duff-like material and show a lack of dependence on the organic bulk density. A simple model capsulizes these characteristics so that inferences can be made about the rate of smoldering. These results contribute to a better understanding of the combustion of smoldering duff.

Acknowledgements

The author wishes to thank Prof. Donald F. Potts of the School of Forestry at the University of Montana for his encouragement to pursue this line of investigation.

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