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Comparison of Fuel Consumption Between High Intensity and Moderate Intensity Fires in Logging Slash

Abstract

Slash burning is an integral tool of forest management in the Pacific Northwest. The purpose of this study was to determine if mass-ignited, high intensity fires had less fuel consumption than moderate intensity fires. There was 23 percent less woody fuel consumption in high intensity burns than in moderate intensity burns. A hypothetical maximum consumption rate model was derived for high intensity fires. High intensity fires could be used to reduce emissions from slash burning, thereby diminishing one of its adverse effects.

Introduction

Thousands of acres in the Pacific Northwest are burned each year as an integral part of forest management. Slash burning is used to prepare harvested sites for planting and to reduce wildfire hazards.

Air quality is directly impacted by smoke from slash fires. As a result, several studies have been undertaken to predict the consumption of fuels during slash burning. Emissions that are released into the air during slash burning can be controlled by understanding and manipulating fuel consumption.

Certain ignition techniques are shown to decrease fuel consumption (National Wildfire Coordinating Group 1985) and to improve air quality by decreasing emissions. In a 1984 pilot study, the Fire and Air Resource Management Project, Pacific Northwest Research Station, USDA Forest Service, measured fuel consumption in rapidly ignited, high intensity fires. Results from the pilot study indicated that high intensity fires consumed less fuel than did lower intensity fires, with the majority of consumption taking place during the flaming phase.

The purpose of this paper was to further investigate fuel consumption during high intensity fires. The objective was to determine if high fire intensities significantly reduce fuel consumption as compared to moderate fire intensities.

A model was developed to determine if differences in the thermal environment could explain differences in fuel consumption between high and moderate intensity fires.

Literature Review and Background

The majority of slash burns in the Northwest are ignited with hand-held torches, using strip headfires. This ignition techique involves igniting one to several adjacent strips of fuel at one time. As the fire spreads, these strips burn together in the flaming stage which is characterized by the movement of visible flame through the fuel. As the flaming front passes and the fire "dies-down," entering the smoldering stage (National Wildfire Coordinating Group 1985), the next successive strips are ignited. The process is slow, and only small areas of the unit are in the flaming stage at one time. Fire intensities (heat release per area per time) range from low to moderate, depending on the ignition rate. This paper refers to such burns as moderate intensity fires.

High intensity fires differ from moderate intensity fires in several ways, the most obvious being the method of ignition. A unit must be mass-ignited to achieve a high intensity fire (Countryman 1964). Mass ignition can be accomplished by handlighting or by helitorch; the ignited strips interact quickly, and the entire unit is simultaneously in flames. The result is longer flame lengths, which result in violent fire behavior, fire whirls, and high intensities. Brown and Davis (1973) discuss fire intensities in terms of "stair-step or a discontinuous-type" scale. They suggest this discontinuous scale occurs because fire intensity increases rather abruptly from one level to another level of considerably higher intensity. Above this abrupt step is the region of high intensity fires, often accompanied by large convection columns (Byram 1957). This paper refers to such burns as high intensity fires.

Most of the prior slash-burn consumption studies have investigated woody fuel and duff (consisting of the fermentation and humus layers) consumption from moderate intensity fires. Woody fuel consumption studies have been completed in Idaho, Montana, and Ontario (Norum 1977, McRae 1980, Brown *et al.* 1985, Reinhardt *et al.* 1989). Duff consumption studies have been undertaken in different geographic locations and forest types (Van Wagner 1972, Shearer 1975, Norum 1977, Sandberg 1980, Brown *et al.* 1985).

The Fire and Air Resource Management Project, Pacific Northwest Research Station, has conducted several woody fuel and duff consumption studies for logging slash using moderate intensity fire in western Oregon and western Washington (Sandberg and Ottmar 1983, Ottmar 1984, and Ottmar *et al.* 1985). These studies provide a baseline against which the fuel consumption data for this study of high intensity fires will be compared. Data collected in the Fire and Air Resource Management Project studies were the most relevant to the area and conditions under which the high intensity fires were studied. To simplify the comparison between moderate intensity fires and high intensity fires, the same variables were measured and the same methodology was used.

Sandberg and Ottmar (1983) found that the best predictor of large, woody fuel[1] consumption, measured by diameter reduction, is the internal moisture of large logs. In attempting to predict fuel consumption by combustion stages (flaming and smoldering), Ottmar (1984) did a preliminary study of woody fuel that focused on predicting consumption during the flaming stage. Ward (1983) had already found that emission factors differ for flaming combustion and smoldering combustion.

Ottmar (1984) speculates that consumption of small fuels occurs mostly during the flaming stage; and that diameter reduction of large, woody fuels during the flaming stage is dependent on the amount of small fuels consumed. Ottmar suggests that the ratio of flaming versus smoldering consumption (flaming proportion) for large logs is dependent on the 100-hour[2] fuel consumption.

Consumption of duff was found to be affected by the burning of woody fuels, depending on duff moisture (Ottmar *et al.* 1985). Two different moisture conditions were found to describe two duff consumption conditions. Duff reduction for wet duff (less than 25 days since 1.3 cm of rain) is dependent on the total heat load supplied by the combustion of large woody fuels. Duff reduction for moist duff (more than 25 days since 1.3 cm of rain) is dependent on fire duration, which is determined by diameter reduction of the large fuels. Preliminary results from flaming duff consumption studies suggest that flaming duff reduction is dependent on flaming diameter reduction of woody fuel (Ottmar 1984).

Fuel consumption during high intensity fires is not well documented and is primarily qualitative rather than quantitative. The reviewed literature contains discrepancies in whether high intensity fires have more or less fuel consumption than moderate intensity fires. Several early workers observed that almost all fuel was consumed on high intensity fires (Clar and Chatten 1966, Byram 1966, Brown and Davis 1973). Other observations suggest that less fuel is consumed on high intensity fires (Hurley and Taylor 1974, Ottmar [personal communication]) or that there is no difference in fuel consumption between high intensity and moderate intensity fires (McRae [personal communication]).

What factors might exist in the thermal environment of a high intensity fire that would cause a difference in fuel consumption? One possible factor is the duration of heat supplied to woody fuel. Fire duration on several high intensity fires has been observed as being very short: from 1 to 2 hours for units ranging from 24 to 200 ha (Finnis 1970, Hurley and Taylor 1974, and Ottmar [personal communication]). Fire duration for moderate intensity fires ranges between 4 to 36 hours, with an average of 8 to 12 hours, depending on fuel moisture and time of year (Ottmar [personal communication]).

The rate of consumption could be another factor influencing fuel consumption during high intensity fires. The rate of woody fuel consumption has been measured in laboratory and field experiments, and there appears to be a wide range of consumption rates for both moderate intensity and high intensity fires per 2.5 cm of diameter reduction. Laboratory consumption rates varied from 52 minutes (Schaffer 1967) to 8 minutes (Anderson 1969, and U.S. Forest Products Laboratory 1974). Field observations of consumption rates ranged from 3.8 to 11 minutes on moderate intensity fires, to 2.5 minutes on high intensity fires (Ottmar [personal communication] and Countryman 1969).

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[1] Large, woody fuels will refer to dead woody material between 7.6 and 22.9 cm in diameter.

[2] 100-hour refers to a timelag fuel class for roundwood diameters of 2.5 to 7.6 cm (Deeming *et al.* 1977).

There is a disparity in previous study results concerning fuel consumption and rates of fuel consumption in high intensity and moderate intensity fires. This study seeks to resolve that disparity by determining whether there is a difference in fuel consumption between moderate intensity fires and high intensity fires.

Study Areas and Methodology

Sites were selected using the criteria of Sandberg and Ottmar (1983) and Ottmar *et al.* (1985). Sixteen clearcut units were selected for high fire intensity broadcast burns, which included three units that were burned for the 1984 pilot study on high intensity fires. Sites were located on lands belonging to the U.S. Forest Service, the U.S. Bureau of Land Management, the Oregon Department of Forestry, and cooperating private companies. One site was located in Idaho, one in Montana, six in Oregon, and eight in Washington.

Thirteen units were cable-yarded and the remaining three were tractor-logged. Second-growth Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) and western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) were the main species on 13 of the units. Two units consisted of lodgepole pine (*Pinus contorta* Dougl.) and one unit was predominantly subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.).

The same variables collected in the Sandberg and Ottmar studies (Sandberg and Ottmar 1983, Ottmar 1984, and Ottmar *et al.* 1985) were collected for this study of high intensity fires. These variables were moisture content of woody fuel material; diameter reduction for both flaming and total consumption; large and small woody fuel consumption; and duff reduction, during both the flaming stage and in total.

Five of the sixteen units were eliminated from the study after the burns were carried out because of high fine fuel moistures which impeded the spread of the fire; or because of sustained winds during the smoldering stage, which increased fuel consumption (Sandberg and Ottmar 1983). The remaining eleven burns were used for statistical comparisons of fuel consumption between high intensity, moderate intensity, and non-attainment fires. Non-attainment fires are fires that did not reach high intensities. These fires are defined as non-attainment fires until it can be determined statistically if they are moderate intensity fires or outliers. The moderate intensity fires used for fuel consumption comparisons are from studies by Sandberg and Ottmar (1983), Ottmar (1984) and Ottmar *et al.* (1985).

Averages for each of the four variables in the high intensity, moderate intensity, and non-attainment fires were determined. These averages were then tested for significant differences using the 2-tailed, t-test at $\alpha = 0.05$ between non-attainment and moderate intensity fires, and between high intensity and moderate intensity fires.

The procedures from Ottmar and Sandberg (1981) and Ottmar (unpublished manuscript. Flaming consumption rates for moderate intensity fires. *On file with,* USDA For. Ser., Fire and Air Res. Mgmt. Proj., Seattle.) were used to measure flaming duration and flaming consumption rates. Flaming duration was determined by visually estimating the percentage of the area involved in the flaming stage and the time that the area was flaming. Flaming consumption rate was calculated by dividing flaming duration by flaming diameter reduction.

A hypothetical maximum flaming consumption rate for high intensity fires was derived from the conduction equation discussed in Jakob and Hawkins (1957). The measured high intensity and moderate intensity fire consumption rates were compared to the hypothetical maximum consumption rate. If the measured high intensity fire rates approach the hypothetical maximum consumption rate but do not exceed it, and there appears to be a break or step between the moderate and high intensity fire consumption rates, there would appear to be a difference in the thermal environment for high intensity fires.

Results

Of the 11 fires used for this study, 7 burned at high intensity. The remaining four fires did not burn at high intensity, and are referred to as non-attainment fires. Fuel consumption and flaming consumption rates for the high intensity and non-attainment fires are reported in Table 1.

The objective of the statistical analysis was to determine (1) if the four non-attainment fires had the same fuel consumption as the moderate intensity fires, and (2) if the seven high intensity fires had different fuel consumption from the moderate intensity fires. Woody and duff consumption from the two groups of fires, high intensity and non-attainment, were compared to the woody and duff consumption data from the moderate intensity fires.

TABLE 1. Summary of woody fuel and duff consumption.

Name	Diameter Reduction (cm)	Flaming Proportion (%)	Duff Reduction (cm)	Flaming Duff Reduction (%)	Flaming Consumption Rate (minutes/2.5 cm)
High Intensity Fires					
Little Deschutes	1.8	1.0	3.0	1.2	*
Twin Harbors	4.0	1.0	4.0	1.9	*
High Divide	2.3	1.0	1.6	0.6	*
Winston #5	2.7	1.0	1.8	*	*
Summit Lodgepole	7.4	0.9	3.6	2.4	3.1
Low Donovan	4.7	0.9	2.5	1.0	2.8
Sprucedale	4.8	1.0	4.9	2.0	2.8
AVERAGE	4.0	1.0	3.1	1.5	2.9
Non-attainment Fires					
Davis Creek	4.7	0.6	2.9	0.9	5.0
Sweethome Area #2	4.8	0.6	3.9	1.5	*
Sweethome Area #3	8.1	0.9	4.5	1.9	*
Creel Rock	6.2	0.5	4.4	1.4	4.3
AVERAGE	6.0	0.7	3.9	1.4	4.7

*Data not collected

The four fuel consumption variables used for comparison between the groups were diameter reduction, flaming proportion (proportion of flaming diameter reduction to total diameter reduction), duff reduction, and flaming duff reduction. Diameter reduction is dependent on fuel moisture, flaming proportion is dependent on 100-hour timelag fuel consumption, duff reduction depends on large woody fuel consumption, and flaming duff reduction is dependent on flaming diameter reduction. Because of these dependencies, only those moderate intensity fires which fell within the range of the independent variables for either high intensity fires or non-attainment fires were used.

All four consumption variables for non-attainment fires were determined to have no significant differences from moderate intensity fires (Table 2), and are assumed to belong to that group. High intensity fires had significantly higher flaming proportion and significantly less diameter reduction than moderate intensity fires (Table 2). Hence, woody fuel consumption was 23 percent less for high intensity fires than for moderate intensity fires. Flaming and total duff consumption for high intensity fires are statistically the same as those for moderate intensity fires for the range of large woody fuel consumption investigated.

Discussion

Flaming proportion was higher for high intensity fires than for moderate intensity fires. This suggests there is very little smoldering during high intensity fires because flaming proportion is dependent on 100-hour consumption, which primarily takes place during the flaming stage. Yet, the statistical analysis suggests that total fuel consumption is less (Table 1). What is limiting fuel consumption during high intensity fires? Brown and Davis (1973) suggest that heat conduction controls consumption of fuel in logging slash. Based on this assumption, a model of heat conduction into large fuels during high intensity fires was developed for this study.

The variables that control conduction on an infinitely thick wooden slab during a sudden change in temperature are time, temperature, and diffusivity (Jakob and Hawkins 1957). It is assumed that diffusivity will not change between moderate intensity fires and high intensity fires. Average surface temperatures of logs fluctuate in high intensity fires, which affects the conduction equation, but the equation is not overly sensitive to changes in temperature. Therefore, it is hypothesized that time—how long heat is supplied to the surface of the large fuel—must be the main limiting variable.

TABLE 2. Summary of statistical t-test results.

	Sample Size	Mean (cm)	Significant Difference (alpha = 0.05)
Diameter reduction			
Non-attainment fires	4	5.9	no
Moderate intensity fires	14	6.3	
High intensity fires	7	3.6	yes
Moderate intensity fires	10	6.1	
Flaming Proportion			
Non-attainment fires	4	0.65	no
Moderate intensity fires	11	0.68	
High intensity fires	7	0.98	yes
Moderate intensity fires	17	0.53	
Duff Reduction			
Non-attainment fires	4	3.9	no
Moderate intensity fires	6	3.4	
High intensity fires	7	3.1	no
Moderate intensity fires	19	2.3	
Flaming Duff Reduction			
Non-attainment fires	4	1.4	no
Moderate intensity fires	9	1.5	
High intensity fires	6	1.5	no
Moderate intensity fires	13	1.4	

During a high intensity fire, a given amount of flaming consumption occurs during a shorter period of time than during a moderate intensity fire: the flaming consumption rate is faster. High intensity fires are mass-ignited, so small fuels burn rapidly, producing high intensities. Therefore, the surface of the large fuels is intensely heated for only a short time, creating a steep temperature gradient within the log. This steep temperature gradient causes moisture to be driven off and the log surface to be consumed almost simultaneously. Once the small fuels are consumed, the flaming stage is over and consumption of the large fuels stops because consumption to the depth to which moisture was driven off has already occurred. Because the flaming consumption rate is faster and consumption is limited to the flaming phase, there is less total woody fuel consumption.

Conversely, during a moderate intensity fire, a given amount of flaming consumption occurs during a longer period of time. Therefore, the flaming consumption rate is slower than during a high intensity fire. Heat is supplied to the surface of the large fuels over a longer period of time and a deeper temperature gradient is developed, drying the log to a greater depth. When the small fuels stop burning in the flaming stage, the larger fuels continue to smolder to the depth to which they have been dried. This is due to a slower flaming consumption rate, so consumption occurs not only during the flaming phase but during the smoldering phase as well. Consequently, there is more total fuel consumption.

A hypothetical maximum consumption rate model was developed for high intensity fires, using the Jakob and Hawkins (1957) conduction equation, to quantitatively determine if time is limiting consumption.

The equation is deemed appropriate for use with high intensity fires even though slash burning may violate some of the assumptions. For example, heat is not being conducted into an infinite slab. Also, the temperature at the log surface is not constant but is widely fluctuating. The equation is considered sufficiently robust to overcome these inconsistencies.

To develop the model of maximum consumption rate, a minimum depth or thickness must be determined to which a log must be preheated before the initiation of flaming combustion. Frandsen (1973) describes an effective heating number which yields the proportion of the particle (thickness of the shell) that has to be heated before ignition as a function of particle size. Frandsen's equation predicts that, as particle size increases, the effective heating number decreases. The proportion or thickness of the shell necessary to heat the particle can be graphed against the diameter of the particle using Frandsen's equation. As the size of the particle increases, the thickness of the shell rises sharply, peaks, then gradually decreases. However, Frandsen only collected data for particles less than 1.3 cm in diameter, the diameter at which the curve of the graph peaks. For the thickness to actually decrease does not make intuitive sense and was determined only mathematically, not empirically. I propose—in a physical sense of the problem—that the thickness sharply increases, reaches a peak, and levels off. At this leveling-off point, the thickness ranges from 0.08 to 0.18 cm, depending on whether the particle is heated from all sides or from one direction. Assuming that this value holds true for all particles larger than 1.3 cm, the average of 0.08 cm and 0.18 cm was used as the minimum thickness to be heated before ignition.

The conduction equation is as follows (Jakob and Hawkins 1957):

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

where the variables are as follows:

t_i is initial surface temperature before heating,
t_s is temperature to which the surface is raised,
t_x is temperature at the depth x in the log,
α is diffusivity of wood,
x is the radial distance into the log from the surface,
$\mathrm{erf}\left(\frac{x}{2\sqrt{\alpha T}}\right)$, is Gauss' error integral, and
T is the time it takes to reach x at a specified t_x.

To develop the maximum consumption rate, the following values are assumed:

t_i = 21 °C,
t_s = 925 °C, an estimated average temperature for the surface of the log during the flaming stage for high intensity fires,
t_x = 343 °C, minimum temperature at which flames appear when rapid heating takes place (Brown 1951),
$\alpha = 1.6 * 10^{-4} \mathrm{cm}^2$ per second (U.S. Forest Products Laboratory 1974).
$x = \frac{0.08 + 0.18}{2} = 0.13$ cm, minimum thickness needed before flaming combustion.

Since $\mathrm{erf}\left(\frac{x}{2\sqrt{\alpha T}}\right) = \frac{t_x - t_s}{t_i - t_s} = 0.6438$,

then $\frac{x}{2\sqrt{\alpha T}} = 0.65$.

Solving for T:

$$T \cong \frac{x^2}{1.69\alpha}$$

Substituting the values for x and α:

$T \cong 6.0$ seconds.

The hypothetical maximum consumption rate for high intensity fires is 0.13 cm of diameter reduction in 6.0 seconds, or 2.5 cm of diameter reduction in 2 minutes.

Plotting this maximum consumption rate on a graph with moderate intensity flaming consumption rates shows that the high intensity flaming consumption rates are approaching, but not exceeding, the maximum high intensity flaming consumption rate (Figure 1). As a group, moderate intensity rates are slower than the measured high intensity group and hypothetical maximum high intensity rates. There is, therefore, a different consumption rate—faster—for the group of high intensity fires than for the moderate intensity group. This supports the qualitative interpretation made previously. However, this model cannot be tested against the observed high intensity fire rates due to insufficient data.

No evidence was found for the discontinuous jump in intensity suggested earlier between moderate intensity fires and high intensity fires. Examining the graph shows no stair-step or break between the moderate intensity fires group and the high intensity fires group, but rather there seems to be a continuous range of variation. This indicates that, as the flaming rate of consumption increases, the total fuel consumption decreases, depending on a subjective classification of increasing intensities.

The results from this study were based on only seven high intensity fires. This small sample size suggests that it is difficult to achieve high intensity fires under the moderate moisture conditions used in this study. The reason for this may be that many variables affecting a burn cannot be controlled. One example is the difficulty in having a large area in the flaming stage simultaneously. Another example is that many weather variables, such as wind, rain, fuel moisture, and atmospheric stability, can affect the way a slash fire will burn.

Conclusion and Recommendations

Mass-ignited, high intensity fires are difficult to achieve. For this reason, the results of this study were based on a small sample size. Mass-ignited, high intensity fires are shorter in duration and have a faster flaming consumption rate than moderate intensity fires. This faster flaming consumption rate suggests that the thermal environment for high intensity fires differs from that for moderate intensity fires. Because of this difference, high intensity fires have less fuel consumption than moderate intensity fires.

These units were operational burns where a fire manager had determined the burn plan. As in all operational burns, it is difficult to control all the variables that determine whether a high intensity fire will be achieved. Evidence of this fact was that only 7 out of 16 burns reached high fire intensities.

Still, I believe that the method of burning with high intensity fire is a viable tool which the land manager can use to reduce fuel consumption. It could be possible for the manager to evaluate several variables that would determine what level of intensity is needed to achieve a high intensity fire.

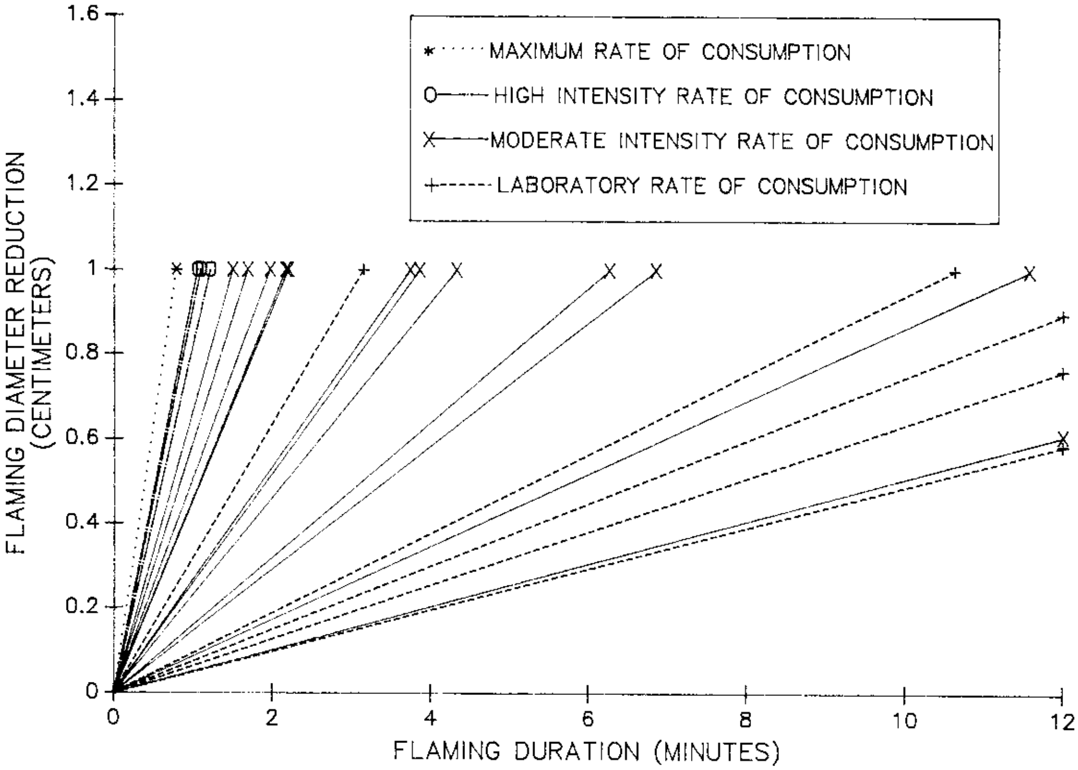

Figure 1. Flaming consumption rates.

From these variables, a classification of intensities could be determined which would be a factor in the calculation of fuel consumption. Size of unit, ignition method, length of time to ignite unit, fine fuel moisture, and the formation of a large convection column are the variables needed. Because there is less fuel consumption during high intensity fires this would lead to a reduction in the reported total fuel consumption. Since this method reduces fuel consumption, this burning technique could be used by air quality personnel to give credit for less emissions.

Several of the assumptions made in this study could be further investigated. One such assumption was the minimum thickness derived from Frandsen's effective heating number. A better approximation of minimum thickness needs to be investigated because the number was extrapolated from particles that were smaller than those used in this study. I would suggest conducting a laboratory study for determining the minimum thickness needed to be heated before ignition for larger particle sizes.

Since the measure of intensities was very subjective, another approach for determining fire intensities should be studied. A more quantitative approach for determining the thermal environment surrounding large, woody fuels should be developed. One possible approach would be to measure the radiation to which the log is subjected and from this measurement the intensity of the fire could be determined.

Knowledge of a fire's intensity would provide managers with yet another tool to estimate fuel consumption for prescribed burning.

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