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Evaluation of a Passive Flame-Height Sensor To Estimate Forest Fire Intensity

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Abstract

The length of flames of wildland fires is a relative indicator of fireline intensity and an important index to fire effects and difficulty of control. A technique for measuring flame height and flame-tilt angle for the purpose of calculating flame length is described.

Laboratory tests determined the feasibility of using cotton string treated with ammonium phosphate fertilizers to measure flame height. Ammonium phosphate treatments with an effective P_2O_5 equivalent greater than 10 percent by weight prevented the string from sustaining combustion above the zone of contact with flames. Treated strings were completely decomposed to a height 5 to 7 percent above the visually estimated average flame height.

The strings were evaluated in nine prescribed fires in Douglas-fir logging residues. Operational use of the flame-height sensor is discussed.

KEYWORDS: Fire intensity, fire retardant treatments.

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Introduction

The length of flames in wildland fires is a relative indicator of fireline intensity and, as such, is an important index to fire effects and difficulty of control. No instruments are available, however, to directly measure fire intensity or flame length in the field. The use of trained observers can be costly and hazardous. Also, the highly variable and transient nature of flames makes it difficult to get a large number of estimates of flame length from observers, and it is impossible to establish the accuracy and precision of the data collected. This note describes a technique for measuring flame height which, along with observation of flame-tilt angle, may be used to calculate flame length and infer a relative fire intensity.

The flame-height sensor was developed in the laboratory and evaluated in field burning experiments. Laboratory tests determined the feasibility of using cotton strings treated with fire retardant chemicals to measure flame height. Flame heights determined by use of strings were compared to visual estimates and a theoretical calculation of flame length.

The technique was refined and operational difficulties evaluated in nine prescribed fires. Retardant-treated strings were suspended vertically over the burn areas. Post-burn measurement of the height to which strings were charred to the point of disintegration provided an estimate of average flame height. Flame-tilt angle was measured so that flame length and fireline intensity could be calculated.

Background

Fireline intensity is the rate of energy release per unit of length of fire front (Byram 1959). The rate of energy release has significance in fire suppression, prescribed burning, and the study of the ecological effects of fire. Previous attempts have been made to quantify fireline intensity in field situations. In fire management and research, Byram's (1959) equation (1) has been used to estimate the intensity of the active flaming phase.

$$I_B = Hwr \tag{1}$$

where: I_B = Byram's intensity (Btu per ft/s)
H = heat yield (Btu/lb of fuel consumed)
w = weight of available fuel (lb/ft2)
r = rate of spread (ft/s)

Van Wagner (1973) used equation (1) to calculate fireline intensity and, in turn, to develop a model to predict the height of lethal crown scorch above forest fires. Field evaluation of equation (1) requires extensive inventory, and it is usually necessary to make assumptions about H and w. H is affected by physical and chemical properties as well as factors affecting the combustion efficiency but is generally assumed to be around 8,000 Btu per pound. The appropriate value for w is generally assumed to be a function of the size and moisture distributions of fuel particles present.

Because of the difficulty in measuring the three variables on the right-hand side of equation (1) and the absence of an instrument to directly measure fire intensity, it has been necessary to substitute other observable characteristics for the desired variable. Byram (1959) found a laboratory relationship between flame length and intensity. Thomas (1963, 1970) found a similar relationship between flame length and a related parameter, the rate of fuel consumption per unit length of fire edge. Byram's (1959) equation (2) tends to give realistic results over a wider range of fire intensities (Albini 1976).

$$L = 0.45\ I_B^{0.46} \tag{2}$$

where: L = flame length (ft.)
I_B = Byram's fireline intensity (Btu per ft/s)

Rearranging equation (2) to solve for intensity in terms of flame length yields equation (3):

$$I_B = 5.7\ L^{22} \tag{3}$$

Given an estimate of flame length, equation (3) may be used to infer approximate fireline intensity.

Because of the difficulty associated with measuring fireline intensity, observations of flame length have been used instead. In prescribed burning research, flame length has usually been estimated, both with and without reference markers in the field of view (Bevins 1976, Sneeuwjagt 1974, and Swanson 1974). Fireline intensity during prescribed burns is also commonly controlled by lighting patterns to attain the desired flame length.

The Rothermel (1972) mathematical fire spread model predicts the reaction intensity (I_R) per unit area of the actively flaming zone. The product of I_R and the depth of the flaming zone (D) can be used to approximate Byram's intensity (Albini 1976). Hough and Albini (1978) used I_R, D, and equation (2) to predict flame length and found a good correlation with observed flame lengths of less than 3 feet. Sneeuwjagt and Frandsen (1977) used least squares regression to test the hypothesis that observed flame lengths do not significantly differ from those predicted by I_R, D, and equation (2). They found the observed data agreed with the predicted data for zero intercept, but the slope was significantly less at the 95-percent confidence level. Whether the lack of agreement resulted from the model or the visual observations could not be determined.

Visual estimates of flame length are not as easy to make as might seem apparent. This is especially true for fires on steep slopes. The problem is largely one of logistics and training. Flame lengths can easily vary from less than 1 foot to over 20 feet in heterogeneous fuel beds. It takes many observers to get an adequate sample of such flame lengths. Having a large number of observers near the fire's edge is hazardous. There is also potential for bias between observers, due to errors of interpretation and viewing angle. An observer standing on a line of sight with the fire's edge has a good view of the flames in the foreground. The observer can estimate the height from a reference marker and measure the tilt angle of flames but cannot view the variation in flame length farther away. An observer standing perpendicular to the fire's edge can view some of this variation but has a viewing angle which approaches infinity as fireline intensity and slope increase.

Photography can aid in measuring flame length, but the logistics become prohibitive when successive photo points must be established as the fire spreads. Proper exposure of film varies with fire intensity and background light and is determined largely by trial and error. Photography is not well suited for night fire observations. The complexities of triangulation associated with photographic measurement of fire behavior have been reviewed by Pickford and Sandberg (1975).

Evaluation

Laboratory

Four fire-retardant chemicals were tested for effectiveness in retarding the combustion of cotton strings and manageability in field use. A standard method for comparing retardant effectiveness is on a P_2O_5 equivalent basis. One concentration each was used of AS (ammonium sulfate — $[NH_4]_2SO_4$) and DAP (diammonium phosphate - $[NH_4]_2 HPO_4$) crystalline fertilizer. Two concentrations each were used of Pyro, a liquid concentrate ammonium phosphate fertilizer with an N-P-K analysis of 11-37-0, and APP (ammonium polyphosphate). The APP was in the form of Fire Trol 934G[1] which is formulated using Allied Arcadian Poly-N 10-34-0.

The AS and DAP were mixed to 4-to-1, water-to-salt, concentrations by weight. The Pyro and APP were used in pure concentrate form (Pyro-high and APP-high, respectively) and mixed 1-to-1 with water by volume to give Pyro-low and APP-low, respectively (table 1). Number 2 cotton 6/16-ply wrapping twine was treated by soaking in the salt solutions for 24 hours in a plastic-lined trough. Plastic was used to prevent possible reaction of salt solutions with metals, with resulting effects on retardant capabilities (George et al. 1977). Strings were air dried by suspending them horizontally to insure a uniform salt concentration over the entire length.

When the strings had dried, a sample from each treatment was ignited by a Bunsen burner then removed from the flame to assure that the sample would not sustain combustion in the absence of an external heat source.

[1]Fire Trol 934G is a liquid concentrate fire retardant manufactured by Chemonics Industries, Phoenix, Arizona.

Table 1 —P_2O_5 equivalents of retardant treatments 1

Chemical treatment	Percent P_2O_5 equivalent by weight
1. AS (4 water: 1 AS crystals by weight)	7.2
2. Pyro-low (1 water: 1 liquid concentrate by volume)	21.4
3. Pyro-high (liquid concentrate)	37.0
4. APP-low(1 water: 1 liquid concentrate by volume)	19.6
5. APP-high (liquid concentrate)	33.0 2/
6. DAP (4 water: 1 DAP crystals by weight)	10.8

1/ The P_2O_5 equivalent assumes: (1) DAP to be 1V2 times more effective than AS, and (2) the ammonium phosphate formulation's effectiveness to be directly related to the P_2O_5 content. The latter has been found to be generally true; however, impurities can reduce the effectiveness of the solution 10 percent or more. (Personal conversation with Charles W. George, Northern Forest Fire Laboratory, Missoula, MT.)

2/ When other ingredients are added to Fire-Trol 934G, the P_2O_5 equivalent is reduced to approximately 33 percent.

A test burn was conducted on the burning table in the University of Washington fire science laboratory. Thirty samples of each treatment were tested. A 12-by-15 grid with 2-inch by 2-inch spacing was constructed by tying the strings to numbered tags which were then clipped to a wire mesh. The mesh was suspended 5 feet above the burning table. Small weights were tied to the bottom of the strings to keep them vertical during passage of the flaming front. The treatments were ordered randomly and placed systematically, starting with a random treatment and spot in the grid. This resulted in a diagonal pattern and assured an even distribution of each treatment throughout the grid.

A crib was constructed on the burning table from 1-inch by 3/8-inch lath. The resulting fuel bed was 3 feet^2 and 2 inches deep. The loading was 1.65 pounds per foot^2, surface area-to-volume ratio was 88 feet-^{1}, and moisture content was 8 percent. The crib was ignited at one end and burned without slope or wind, so flame height and length were essentially the same. Flame height was estimated ocularly. Accuracy was probably no better than ±3 inches. Flame height was defined as height from flame base to top of continuous flame. Estimates of flame height were made from positions both parallel and perpendicular to the direction of fire spread. The average of all visual estimates was assumed to be the true average height. The rate of spread, depth of the flaming zone, and residence time were also estimated.

After the fire, the strings were removed and inspected to determine the point at which scorching first appeared and where the fibers were charred to the breaking point. Completely charred string is brittle and will shatter when bent. The measurement technique involved running two fingers firmly down the string to the point where the fibers disintegrated. This length and length to the point where light scorching was apparent were measured to the nearest 0.5 inch. The observed flame length was compared to the string measurement and the flame length predicted by equations (1) and (2).

Samples of treated strings were placed in a muffel furnace to determine the time-temperature relationship at which scorching and charring occur. Strings were removed from the furnace and inspected to determine when light scorching began and when charring was complete.

Field

Strings treated with fire retardant have since been used to measure flame height on nine research burns in Douglas-fir *(Pseudotsuga menziesii* [Mirb.] Franco) partial cuts in western Washington and Oregon. Ten-foot strings tied to numbered metal tags which could be quickly fastened to wire supports were suspended over inventoried fuel plots (fig. 1). Bulldog paper clips were attached to string bases and at midpoints to keep strings vertical during passage of the flaming front. An observer was positioned on a line of sight parallel to the flaming front to measure the tilt angle with a clinometer (fig. 2).

Under field conditions, flame length on low-intensity backing fires and narrow-strip headfires can be estimated visually to an accuracy circa 1 foot. The strings treated with fire retardant are capable of measuring flame height to at least this level of accuracy. The accuracy of calculations of flame length, then, depends largely on the accuracy of the flame-tilt measurement.

On a number of prescribed burns with backing fires and narrow-strip headfires, there was little variation in the flame-tilt angle along the line of fire. It was also possible for several observers to measure the tilt angle with clinometers and consistently agree within 5 degrees. Most of the slopes (A) on the nine burns were around 20 degrees. The flame-tilt angles ($) (measured from the horizontal) were generally 40 to 50 degrees. Thus, the angle (0) needed to solve for flame length was usually in the 20- to 30- degree range. Due to the nonlinearity of the function, a 5-degree error in measuring tilt angle in the 20- to 30-degree range results in an error of approximately 20 percent in the calculated flame length. This accuracy is similar to that of direct observation of flame lengths in the 2- to 5-foot range. As the angle *6* approaches 90-degrees, measurement errors have an insignificant effect on calculated flame length.

In low-intensity fires, the strings remain intact and the clips rarely come off. When they do come off, the strings tend to be lifted by the convection column. This usually does not occur until after fireline intensity has peaked and the secondary combustion associated with larger fuels is taking place. Peak intensity and longest flame are usually associated with passage of the flaming front. When fuels are concentrated in a plot, however, the burnout time is increased. After the flaming front passes, the flame-tilt angle approaches the vertical and burn height measured on the strings may differ from the flame height associated with tilt angle measured during peak intensity. Examination of fuels on the plot gives a good indication of which plots are likely to burn longer, and the observer can pay special attention to these plots.

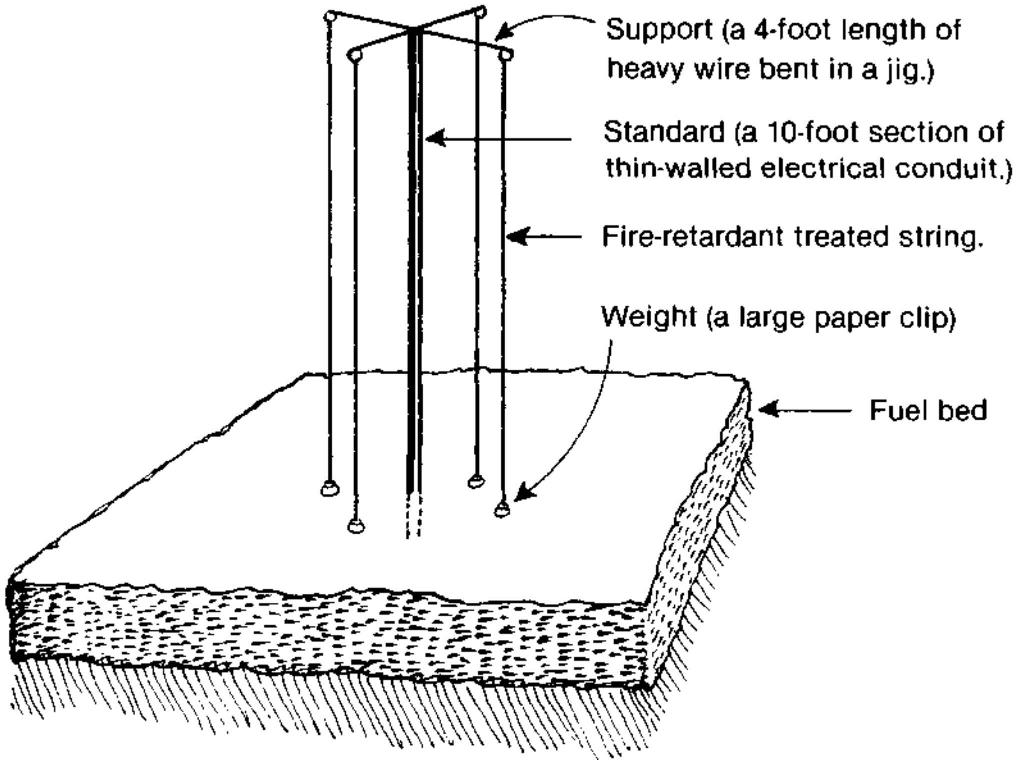

Figure 1.—Configuration of a flame-height sensor.

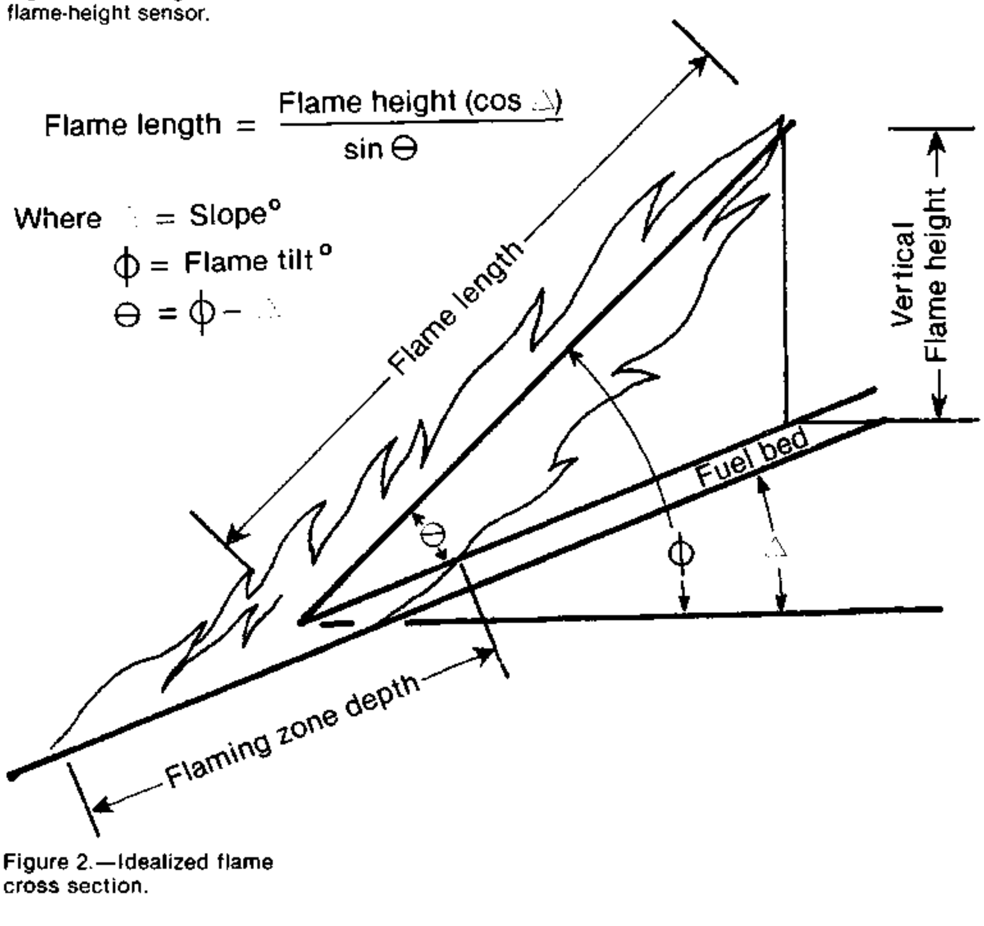

Figure 2.—Idealized flame cross section.

Results

The laboratory fire spread across the 3-foot crib in 17 minutes, with an estimated flaming zone depth of 14 inches and residence time of 4 minutes. Flame height became steady as soon as the flaming zone was fully developed and maintained a nearly uniform height as long as fuel lasted. Flame height was lower in the center of the fuel bed than on the sides. The average flame height in 27 observations was 29 inches. Because interpretation of flame height is somewhat subjective, no attempt was made to calculate variance.

When heat content of 8,000 Btu per pound (Rothermel 1972, Albini 1976) and available fuel of 1.65 pounds per foot^2 are assumed, Byram's (1959) equation (1) predicts a fireline intensity of 38.3 Btu per second per foot for a fire spreading at 2.9 x 10^{-3} feet per second. Equation (2) predicts flame length or height for vertical flames of 28.9 inches. This result comes fortuitously close to the observed flame height of 29 inches.

The strings were noticeably scorched several inches above the height to which they were charred to disintegration (table 2). Height of complete charring of strings treated with the two APP and the DAP solutions, was only slightly higher than the observed height of 29 inches. The AS and both Pyro treatments, however, resulted in charring 4 to 5 inches higher than the observed flame height. Despite having passed the Bunsen-burner test, samples of strings receiving these three treatments sustained glowing combustion after the flaming front had passed. For these reasons, the AS and Pyro treatments were excluded from further analysis. Bartlett's test for homogeneity of variance and analysis of variance revealed no difference for the means and variances of the char height of the remaining three treatments.

Table 2—Mean ($\bar{x}$) and standard error ($S\bar{x}$) of the scorch and char height above the fuel bed

Chemical treatment	Height (inches)			
	Scorch		Char	
	$\bar{x}$	$S\bar{x}$	$\bar{x}$	$S\bar{x}$
AS	41.3	1.0	33.1	0.8
Pyro-low	40.8	0.8	33.3	0.8
Pyro-high	40.3	1.0	34.1	1.0
APP-low	34.6	1.0	30.4	0.8
APP-high	42.6	1.2	30.9	0.9
DAP	41.3	1.1	30.9	0.8

The retardant-treated strings were scorched and charred in relation to the amount of energy absorbed. A sample of APP-low string was analyzed in a differential scanning calorimeter to determine the amount of energy required to raise the string temperature. Approximately 270 calories per gram were required to raise the sample to 400° C, or about twice the energy required for similar untreated samples. The muffel furnace test demonstrated that the strings did not provide a unique measure of time or temperature (fig. 3). There was, however, a fairly narrow band of scorch separating the uncharred string from string charred to the point of disintegration.

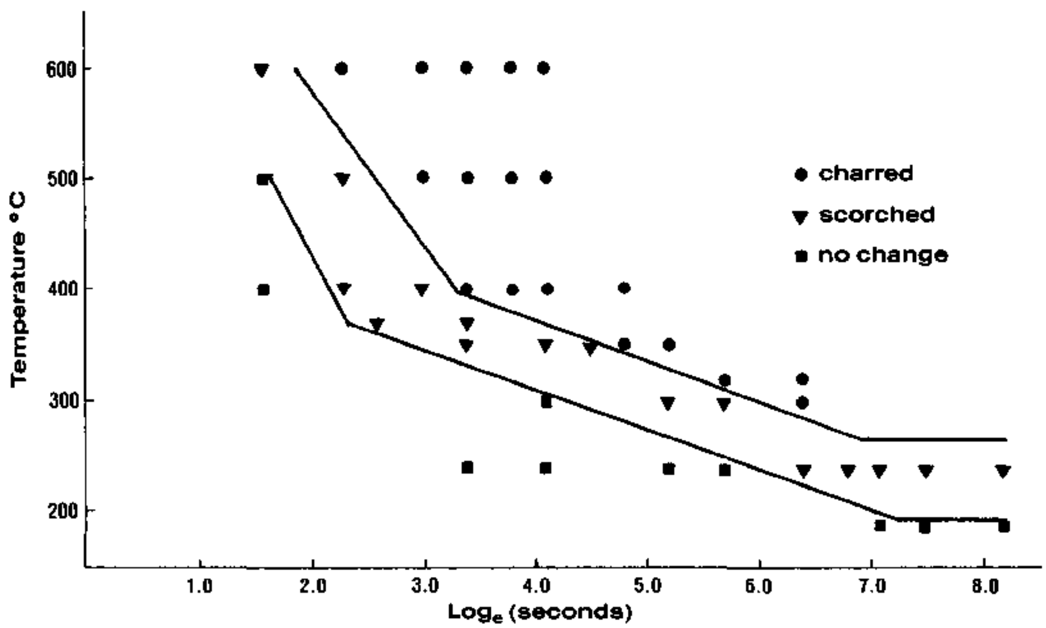

Figure 3.—Change in retardant-treated strings as a function of temperature and time.

Discussion

Visual estimates of flame heights were slightly lower than those measured by the complete charring of treated strings. The average height for strings treated with DAP and APP was 5 to 7 percent greater than the average observed. Considering the relative accuracy of the ocular estimates, this difference does not appear significant.

Ammonium sulfate and ammonium phosphate solutions lower the ignition temperature. Thus, fuels treated with these compounds undergo pyrolysis and combustion at lower temperatures than do untreated fuels (George and Susott 1971). AS compounds are completely decomposed at about 425°C and are not available to retard glowing combustion (George and Blakely 1972). Also, on a P_2O_5 equivalent basis, AS is less effective than DAP (table 1). This may explain why the AS-treated strings sustained glowing combustion after passage of the flame front. Ammonium phosphate compounds, on the other hand, are not completely decomposed at temperatures below 675°C (George and Blakely 1972).

Based on the P_2O_5 equivalent, strings treated with Pyro should have had greater retardant properties than those treated with DAP and APP. The fact that the Pyro treatment did not retard combustion as well as the DAP and APP treatments may have been related to the fact that salt crystals in the Pyro liquid concentrate began to precipitate out of solution and salt crystals were found clinging to the Pyro-treated strings. Since the retardants coat the fibers rather than penetrate them, it is possible that "salting out" reduced effectiveness of the coating. This could explain the glowing combustion observed in the Pyro-treated strings.

Anderson (1969) reported flame temperatures for pine needle fuel beds to be around 800°C. Assuming similar flame temperatures for the laboratory crib fire, it is possible that the ammonium phosphate retardants were decomposed and the strings charred slightly above the observed flame heights.

If string measurement is used to calculate flame length, and thence fireline intensity, the intensity of the laboratory fire would have been 44 Btu per ft/s. Considering the accuracy of equations (1) and (2), the assumed inputs, and measured rate of spread, the string-based calculation of flame height and fireline intensity agrees reasonably well with the observed flame height and intensity. Flame-height measurements can be combined with flame-tilt measurements to calculate a flame length for fires of similar intensity and duration. Longer duration of flaming may affect the height at which ammonium phosphate compounds decompose, resulting in slightly higher measurement.

Although the DAP and both APP treatments yielded string measurements which corresponded well with observed flame length, the APP-low strings were the most manageable. Other concentrations of ammonium phosphate fertilizer salts may work as well or better. Since the Pyro liquid concentrate used in this study appeared to be in poor condition, results from this study should not be interpreted as an indication that Pyro could not also be a suitable salt.

Other types of string might also work as well or better. Because retardants coat the fibers rather than penetrate them, it is desirable to use string formed from as many strands as possible, and one which is twisted loosely enough to allow salts to penetrate to the inner strands.

It is important to measure flame-tilt angle, slope, and decomposition height on the string as accurately as possible. As the flame-tilt angle approaches vertical, errors in measuring the angle have little effect on calculations of flame length unless the slope is also approaching vertical. Any error in flame-height measurements will result in a like error in calculating flame length. Because L in equation (3) is raised to the 2.2 power, any errors in determining flame length will result in a larger error in calculating fireline intensity.

Conclusions

The laboratory experiment and field trials indicate that the retardant-treated strings provide a reliable and inexpensive means of measuring vertical flame height. The flame height and measured tilt angle can be combined to calculate flame length, which is, in turn, a good indicator of fireline intensity.

A passive flame-height sensor has an advantage over direct observation in that it reduces the number of observers needed, reduces bias among observers, and increases the number of samples which can be taken. Flame-tilt angles can be measured from a greater distance with fewer observers than is possible with direct observation of flame length. One observer can collect data simultaneously on more than one plot. Observer bias is reduced because tilt angles and string lengths are easier to interpret and measure than a pulsating flame. Ocular estimates are restricted to one, or perhaps a few, observations of flame length, mentally integrated over an indefinite period. More samples can be taken with the passive flame-height sensor because a large number of strings can be suspended over a plot without affecting the fire. The observer can then devote time to measuring tilt angle, which is less variable and easier to define than length of flames. The strings will measure some of the variability in flame height.

In these tests, THE APP-low-treated strings gave the closest measure to ocularly estimated flame length and were more manageable than strings treated with DAP and APP-high. The Pyro-treated strings should have performed equally well with respect to retardation. It appears that ammonium phosphate compounds with a P_2O_5 equivalent greater than about 10 percent are potentially effective treatments. Above this concentration, the physical characteristics and ease of handling the strings appear to be the primary criteria for selecting a retardant.

The technique provides an economical and easy way to quantify fireline intensity. Because string absorbs very little retardant, the cost is minimal. The strings can be set up in minutes and can be put up ahead of time, provided they are not exposed to rain. Fire observation requires minimal effort, provided the flame-tilt, slope, and string height are accurately measured; and the technique yields precise estimates of flame length. These estimates can be used to calculate fireline intensity with sufficient accuracy to make relative comparisons between fires.

Metric Equivalents

1 foot = 0.304 8 meters
1 inch = 2.540 0 centimeters
1 acre = 0.404 7 hectares
1 pound = 0.453 6 kilograms
1 foot/second = 0.304 8 meters/second
1 pound/foot^2 = 4.882 4 kilograms/meter^2
1 B.t.u./pound = 2.234 4 joules/gram
1 B.t.u./pound = 0.555 6 calories/gram
1 B.t.u./foot per second = 0.826 8 kilocalories/meter per second
$\frac{5}{9}$(°F - 32) = °C

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