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Measuring Fire Behavior with Photography

Targets imaged in the photographs are used to scale fire dimensions.

Abstract: *Photography is practical for recording and measuring some aspects of forest fire behavior if the scale and perspective can be determined. This paper describes a photogrammetric method for measuring flame height and rate of spread for fires on flat terrain. The flames are photographed at known times with a camera in front of the advancing fire. Scale and perspective of the photographs are determined by including two targets a known distance apart in the camera view field and applying simple geometry.*

Introduction

Flame height, rate of spread, intensity, and fuel comsumption are important attributes of forest fires, but they are often difficult to measure. A series of photographs taken as a fire advances can record fire behavior for subsequent computations if the scale and perspective can be determined. This paper describes a photogrammetric method for measuring flame height and rate of fire spread. The measurements are made from a time-series of photagraphs of the flames taken in front of the advancing fire and compared with measurements by conventional techniques. Scale and perspective of the photographs are determined by including two targets a known distance apart in the camera view field and applying simple geometry.

These photographs provide a permanent record of fire movement and size. Measurements made from the photographs can help to correlate fire behavior with such variables as windspeed, fuel moisture content, and fireline intensity.

Background

Byram (1959) defined fireline intensity, I, as the energy released per unit length of fireline and proposed the equation

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

where

I = fireline intensity (kw/m),
H = heat value of fuel (kJ/kg),
w = fuel consumed (kg/m^2), and
r = rate of fire spread (m/sec).

Byram (1959) also described the relationship between flame height, h, and fireline, I, intensity as

$$h = 0.0775\, I^{0.46}\ (\text{m}). \tag{2}$$

Thus, estimates of fireline intensities can be calculated by applying Equation 2 to measurements of flame height. Combining Equations 1 and 2 and then solving for w, gives

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$$w = \frac{260\, h^{2.174}}{Hr} \qquad (3)$$

Equation 3 can be used to estimate fuel consumption, which can in turn be used to compute emission factors for combustion products in air pollution assessment.

Adkins and Clements (1976) determined flame heights from photographs of forest fires at a distance over flat terrain. The method described in this paper is a modified extension of their work. The distance from the fire's front to the camera was determined for each photograph. These distances, along with the times of the photographs, allow calculations of fire spread rate.

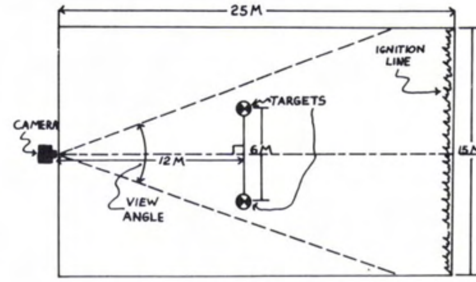

FIG. 1. Plan view of the area used for the experiment showing the positions of the camera and targets relative to the ignition line. The distances in this figure are nominal values and need not be strictly adhered to.

EXPERIMENTAL METHODS

Our photographic procedures are demonstrated for a test fire at the Holt-Walton Experimental Forest near Cordele, Georgia. A 35-mm camera with a 55-mm lens was mounted on a stepladder with its optical center 3 meters above ground. The camera was in front of and facing the ignition line. The camera's optical axis was approximately horizontal and normal to the ignition line. The camera was focused at 10 m with settings of *f*8 and 1/60 sec. The two targets were mounted 1 meter above ground on vertical stakes, and placed on a line perpendicular to the camera's line of sight at positions that resulted in the targets appearing near the left and right edges of the photographs (Figure 1).

Ten photographs were taken at arbitrary times during the test fire. A digital watch-lens assembly was mounted on the camera's base plate so that an image of the watch appeared on each photograph.

Data on photographs were transformed to digital data on a Hewlett-Packard* 9874A electronic digitizer interfaced with a HP 2647A graphics terminal. Hand digitizing of photographs would have been too tedious and time consuming.

The digitizer's platen in a vertical position served as a screen for rear projection of a 35-mm transparency with a slide projector. Data were digitized from the projected images with a digitizing cursor and passed to the graphics terminal that stored it on magnetic tape cassettes. Computer programs were written in terminal Basic language for scaling, computation of perspective, and statistical analysis of results.

SCALING AND PERSPECTIVE

Adkins and Clements (1976) described a simple method for scaling photographs of fires over flat terrain and for finding distances from the camera to the fire. They assume that the height from the base of the flames to the horizon on the film is the image of the camera's height above the ground at the fire's distance. Their method requires that the horizon be included in the photographs. Our method substitutes a virtual horizon for the real one.

The virtual horizon can be found graphically on the photographic image by laying out a vertical distance equal to the camera height's image, C_i, from the base of a target, as shown in Figure 2. The camera height's image from the base of the target is given by the relationship

$$C_i = C_o \, ({}^{T_i}/_{T_o}) \qquad (4)$$

where

C_i = camera height's image,
C_o = actual camera height,
T_o = actual distance between targets, and
T_i = image of distance between targets.

Placing only one target at camera height so that it appears in the photograph simplifies the procedure. The target's image is the virtual horizon.

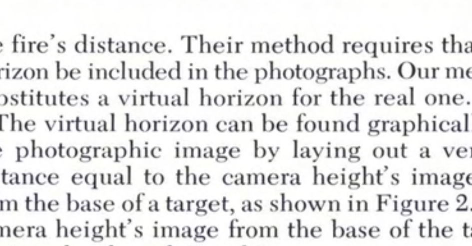

FIG. 2. Drawing of camera's view of plot showing the relationship among the camera height, the distance between targets, and the virtual horizon.

Flame heights can be measured along the fire front in each photograph. Consider the two sets of similar triangles in Figure 3: *acd* and *a'c'd*, and *abd* and *a'b'd*. Flame height is found from the ratio of sides of these sets of similar trangles, as

$$F_o = F_i \, ({}^{C_o}/_{C_i}) \qquad (5)$$

where

F_o = actual flame height and
F_i = image of flame height.

* Mention of trade names throughout this paper does not constitute endorsement by the U.S. Department of Agriculture.

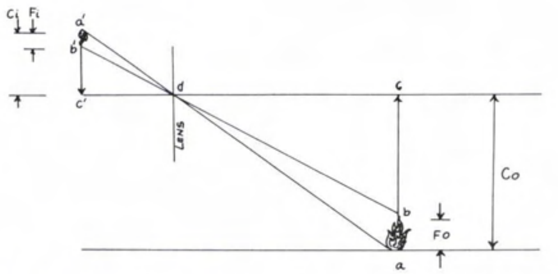

FIG. 3. Side view of optics of camera aimed at a fire on flat terrain showing the relationships of camera height, C_o, and flame height, F_o, with their images in the focal plane. Triangle *acd* is similar to *a'c'd* and triangle *abd* is similar to *a'b'd*.

Equation 5 depends on the camera's optical axis being horizontal. For example, an angle of declination of the optical axis of 10 degrees will introduce a 2 percent error in flame height measurements.

The mean distance from the fire's front to the camera was estimated for each photograph. These distances, along with the times between photographs, allowed calculation of rate of fire spread. An equation for the distance from the camera to the fireline's base can be derived by considering the two sets of similar triangles in Figure 4: *acd* and *a'c'd,* and *bed* and *b'c'd*. One triangle from each set share a common side, namely the lens-image distance, v. Thus, by similar triangles the distance from the camera to the fireline's base is given as

$$D_F = v\frac{C_o}{C_F} \tag{6}$$

and also

$$v = D_T\ ({}^{C_T}/_{C_o}) \tag{7}$$

and combining these yield

$$D_F = D_T\ ({}^{C_T}/_{C_F}) \tag{8}$$

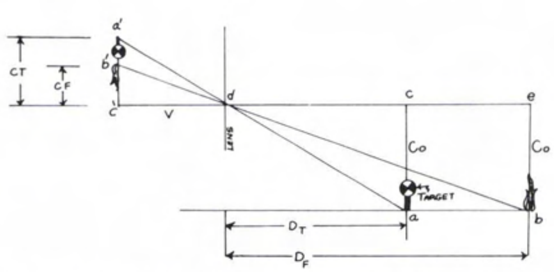

FIG. 4. Side view of optics of camera aimed at target and fire on flat terrain showing relationships through similar triangles of real distances or heights with their images in the focal plane.

where

C_T = image height of camera at target,
C_F = image height of camera at fire,
D_T = distance from camera to target line, and
D_F = distance from camera to fireline base.

Equation 8 depends on the camera's optical axis being parallel to the surface. For example, if the land surface has a 20 degree slope and the camera's optical axis is horizontal, an error of 6 percent on distance measurements would occur. Steeper slopes would yield more serious errors.

To obtain a graphical plan view from the oblique photographic view requires correcting the perspective by a shift of the lateral coordinate values for each distance from the camera. Consider the plan view (Figure 5). Calculate the camera's view width, W_v, at the distance, D_F, to a point on the fireline by similar triangles.

$$W_v = \frac{W_i}{v} D_F \tag{9}$$

where

v = lens-image distance

and

W_i = width of photographic image.

The shift or offset of the lateral coordinate value from the edge of the rectangular plot is calculated by

$$S = (W_p - W_v)/2 \tag{10}$$

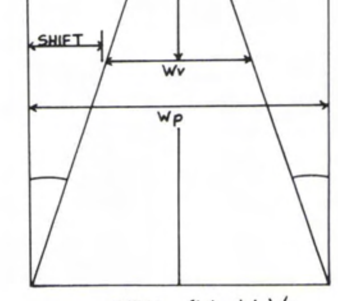

FIG. 5. Plan view of area for experimental fire showing corrected perspective and relationships between the offset shift and camera's view width and plot width.

where

W_p = width of the plot.

Results and Discussion

Equations 2 and 3 allow calculation of values for fireline intensity and fuel consumption from measurements of flame height and rate of fire spread along with the fuel's heat value. Flame heights were calculated for a series of positions along the fireline and the x-y coordinates of the base of the flame at those positions. From one slide, a three-dimensional graph of 134 flame heights at their positions along the fireline is shown in Figure 6. Each vertical line represents the flame height at that position; blank spaces indicate no data. Some blank spaces are due to tree trunks blocking the camera's view. The flame heights ranged from 0.019 to 0.285 metres with a mean of 0.131 metres and a standard deviation of 0.062 metres. The base of the flame shows how the flame front's position varies along the fireline. Frequency and cumulative frequency polygons can be plotted from these same data.

A plan view of the plot is shown in Figure 7 with the digitized positions of the base of the flame front from ten slides taken at different times during the fire. The dotted lines are coordinates of the flame front's base. The dashed lines indicate the camera's view angle. The mean distances for each slide are plotted as asterisks along the left axis and a relative time-scale is given on the right axis. This figure is in effect a map of the movement of the fire's front.

Figure 8 shows the mean distances for the fire front plotted against time with a linear regressed line for the data. The slope of the line gives the average rate of fire spread for the fire of 0.17 m/min with an R^2 of 0.993 for the regression. The rate of spread value by this method agreed closely (6.3 percent difference) with a value of 0.16 m/min found from the average of three measurements made by timing the flame front's travel between two stakes. Using 16,800 kJ/kg for the fuel's heat value and the average values found for fire spread and flame height, the fuel consumption during flaming combustion was 0.12 kg/m² (0.55 ton/acre) and the fireline intensity was 3.13 kJ/m-sec $(9.73\ \frac{\text{Btu}}{\text{ft-sec}})$.

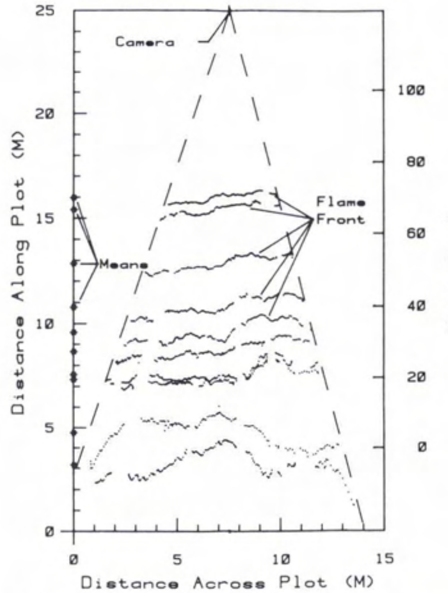

FIG. 7. Plan view of area for experimental fire showing relationship of flame front position with time and distance.

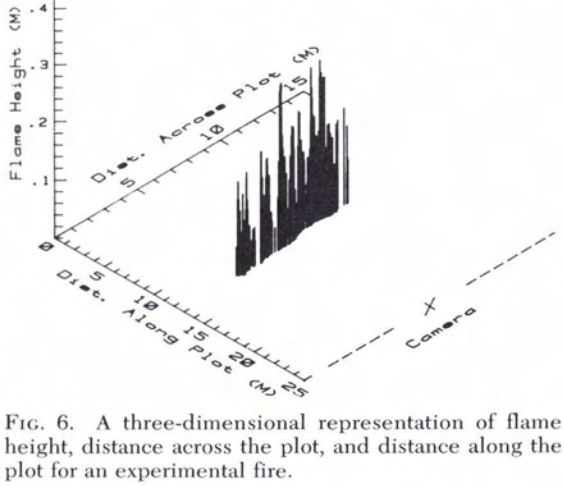

FIG. 6. A three-dimensional representation of flame height, distance across the plot, and distance along the plot for an experimental fire.

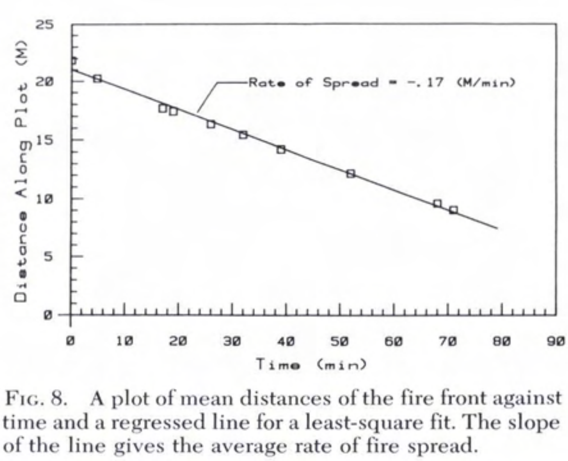

FIG. 8. A plot of mean distances of the fire front against time and a regressed line for a least-square fit. The slope of the line gives the average rate of fire spread.

Conclusions

It is expected that the method described in this paper will find its main usefulness as a research tool applied to prescribed fires. Application is limited to fairly flat but not necessarily horizontal terrain. For example, if 6 percent errors can be tolerated, then a relatively flat site with a moderate slope is suitable. A tree stand with high density may further limit the method by blocking the camera's view through the stand.

The chief benefit of this method is that it allows multiple measurements of impotant fire behavior characteristics at chosen places and times. For example, flame height, and thus fireline intensity, varies both along the fireline and with time. The method thus allows a comprehensive examination of these variations in fire behavior.

References

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(Received 27 February 1982; revised and accepted 10 September 1982)

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