Fire Temperature Monitoring During Experimental Burns at Indiana Dunes National Lakeshore

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ABSTRACT: Fire temperature was measured during several prescribed fires in a mosaic of prairies and oak woods within the Indiana Dunes National Lakeshore using temperature-sensitive paints on aluminum tags and mica sheets. Aboveground temperatures were highest in the prairies, often exceeding the melting point of the aluminum tags, and lower in the oak woods. Belowground temperatures, measured by painted mica sheets, were higher in the oak woods than in the prairies. Tree crown mortality was correlated with fire temperature and tree diameter. The results demonstrate high spatial variability in temperature during single burns in this mosaic of plant communities. This variation results from differences in fuel characteristics and the pattern of fire spread. While each community type had its own distinctive temperature profile, temperatures were highly variable among plots within the same community type.

INTRODUCTION

Fire is now recognized as an important factor in maintaining many vegetation types, making prescribed burning an essential management tool for natural areas. However, to understand fire effects in areas of diverse vegetation one needs a detailed knowledge of the variation in intensity of fires.

The intensity of a fire can be extremely variable within and between burns, even when such factors as seasonality and vegetation type are constant. Weather variables preceding and during a fire can make the difference between a creeping, smoldering fire and a dangerous conflagration. Temperature can be highly variable even within a single fire event in vegetation with homogenous fuel loads, because of such factors as preheating of fuel, wind shifts, fire-generated winds, and hour-to-hour changes in temperature and humidity.

Measurements of Fire Severity

Variability within a fire complicates the analysis of its effects. Many different methods for monitoring fires have been developed, the most accurate of which is the direct and continuous temperature measurement using thermocouples (Wright and Bailey 1982). This method works best in documenting temperature effects in a small area and is ideally suited to the study of heat injury on individual plants. However, the necessary equipment for documenting the spatial variability inherent in a large fire is inordinately expensive.

Fireline intensity (heat flux in BTU per feet per second) can be calculated using variables such as fuel model type (vegetation type), weather, and fuel moisture content, or from estimations of observed flame lengths (Rothermel 1972, Burgan and Rothermel 1984). Fuel models are essential for quickly estimating the fireline intensities and rates of spread for wildfires. However, these models must assume that fuel loads have little spatial variability. In some plant communities—for example, homogenous stands of chamise (*Adenostoma fasciculatum*) or a flat prairie—these models work well. However, in a complex mosaic of different fuel types, they are not well suited for analysis of the spatial variability of fire effects.

Heat release from a fire also can be estimated using measures of fuel load before and after a fire (Brown et al. 1982, p.3), or from the effects on a passive heat absorber such as water cans (Moreno and Oechel 1988). These methods are well suited for fire measures within a complex habitat. However, taking these measurements at hundreds of locations would require a great investment of time.

An alternative to the above methods is the direct measurement of temperature at hundreds of points within the fire. Temperature-sensitive materials (Silen 1956), especially paints (Howard et al. 1960, Fonteyn et al. 1984, Hobbs et al. 1984, Stott 1986), have been widely used for these types of measures. Stinson and Wright (1969) report that values obtained in fires in natural fuels in this manner have a high correlation with values measured by thermocouples. We report the results of our efforts at Indiana Dunes National Lakeshore to quantify fire temperature using a series of temperature-sensitive paints. The method we describe is reasonably inexpensive, costing about $100 to produce about 500 temperature monitors. Positioning of hundreds of monitors could be accomplished in less than one day, enabling their use with only a 24-hour advance notice of a burn.

The Study Area

Howes Prairie is an area of high species and community diversity in the Indiana Dunes about 1 km south of Lake Michigan and southeast of the town of Dune Acres. The vegetation in the burn area is a complex mosaic of wet prairie, mesic prairie, oak savanna, and oak forest communities on sand dunes at the southern end of Lake Michigan. The wet prairie is often flooded in the spring and dominated by bluejoint grass (*Calamagrostis canadensis*), meadowsweet (*Spiraea alba*), and willow (*Salix gracilis*) with scattered aspen (*Populus tremuloides*). The highly diverse mesic prairie contains abundant little bluestem (*Andropogon scoparius*), big bluestem (*A. gerardii*), Indian grass (*Sorghastrum nutans*), marsh blazing star (*Liatris spicata*), rattlesnake master (*Eryngium yuccifolium*), and tall coreopsis (*Coreopsis tripteris*). The oak woods range from savanna-like dry oak woods dominated by black oak (*Quercus velutina*) and sassafras (*Sassafras albidum*), to mesic woods with abundant white oak (*Quercus alba*), red maple (*Acer rubrum*,) and black cherry (*Prunus serotina*) (Cole and Pavlovic unpubl. data). The understory vegetation in the oak woods and mesic woods is predominantly Pennsylvania sedge (*Carex pennsylvanica*) and late low blueberry (*Vaccinium vacillans*). Taxonomic nomenclature in this paper follows Swink and Wilhelm (1979).

METHODS

Prescribed Fires and Plot Design

Between 1986 and 1990 eight prescribed research fires were studied using the temperature monitors described herein. This article focuses on the results of two 18-ha burns that took place at Howes Prairie on April 18, 1986 and April 9, 1988.

The burn area is located near a forested residential development, yet because of the high quality of this rare habitat, it is not desirable to use mechanized fire suppression and maintain firebreaks. Despite these limitations, the resource management staff from Indiana Dunes National Lakeshore were able to plan and conduct safe burns with minimal disturbance to the prairie and to maintain the required smoke dispersal over Lake Michigan.

The fires were ignited by starting a backing fire at the northeast perimeter (see Figure 1) under the influence of a 2 to 4 mph southeast to southwest wind. Fire ignition teams gradually circled the east and west perimeters of the burn area, igniting flanking fires. After several hours the ignition teams met at the south perimeter and ignited a headfire. The backing fire, flanking fires, and headfire all converged near the south-central portion of the burn area. This ignition sequence was used to ensure fire safety rather than for any specific experimental reason. However, the variety of fire types created by this sequence produced the effects of different fire types, thereby simulating the variety inherent in wildfires occurring in the area.

Weather during the fires was continuously monitored using a portable weather station equipped to monitor wind direction, wind speed, temperature, and humidity. Temperatures recorded during the fires ranged from 18 to 24°C. Relative humidities ranged from 58 to 41%. The higher temperatures and lower humidities occurred in the early afternoon, late in the development of the fires and while the southern portion of the area was burning (Klick 1988).

Measurements of fire type, flame length, and rate of spread were made at many observation points along the fire perimeter. However, these measures could not be made at interior plots, especially within the intensely burning central portion. Small-scale wind shifts created occasional backing fires, flanking fires, and headfires in all portions of the study area, making fire type classification by area difficult.

The study area was stratified into four community types: wet prairie, mesic prairie, oak woods, and mesic woods. Within the burn area forty cylindrical (5.24-m radius, 100 m^2) permanent vegetation plots were randomly located within the four stratified community units. These plots were monitored annually, beginning in 1983, measuring the tree, shrub, and herbaceous vegetation. The complete vegetational effects of these fires (see abstract in Cole et al. 1990) will be the subject of future articles. Half of the burn area (low frequency treatment) was burned every other year (1986, 1988), while the other half (high frequency treatment) was burned annually (1986, 1987, 1988).

Aboveground Temperature Measurement

Aluminum tags (20 x 85 x .2 mm; available from Forestry Suppliers, Inc., and other sources) were painted with stripes of temperature-sensitive Tempilac® paint (available from Tempil, Big Three Industries, Inc., South Plainfield, NJ 07080) with temperature values arranged at intervals from 93°C to 538°C. The melting point of aluminum at 660°C provided an additional measure of temperature.

Tests in a muffle furnace demonstrated that the thin tags warmed to near the ambient temperature in less than one minute (Cole 1986). However, because aluminum is a heat conductor, the temperatures recorded on the tags incorporate both temperature and a small element of residence time required to heat the tag. Although the heating of the aluminum tag and the large intervals between paint strips make this method less accurate than thermocouple measurements, the tags provide an inexpensive quantitative measure of temperature that can be used to compare different locations within a fire.

The aluminum tags were attached to sampling stakes at 15.24-cm intervals. In our initial efforts (1986), we transported metal stakes to plots and attached the tags using metal wire. However, experimentation demonstrated that fresh-cut saplings did not burn in the fires and were easier to transport to the plots. Furthermore, the tags could be quickly attached to the sapling stakes with a staple gun, and the removal of saplings of woody species furthered our management objectives elsewhere in the park. Suitable stakes were derived from straight saplings of sassafras, aspen, cherry, and oak cut from thickets outside of the study plots. Three stakes were placed along the perimeter of each of the 40 vegetation plots and at other critical points within the burn area.

Nested analysis of variance (Sokal and Rohlf 1981) was used to test for temperature effects (1988 burn) between communities (wet and mesic prairie, and oak and mesic woods), between fire frequency treatments (burned in 1986 and 1987 versus 1986 only), and among plots (nested factor). Temperature values in this analysis of variance were the average of four values between 15 and 107 cm above ground. A nonparametric Mann-Whitney U test was used to analyze the variability in temperature between communities. A probit analysis (Sokal and Rohlf 1981) was used to determine temperature effects on crown mortality of trees of different diameters.

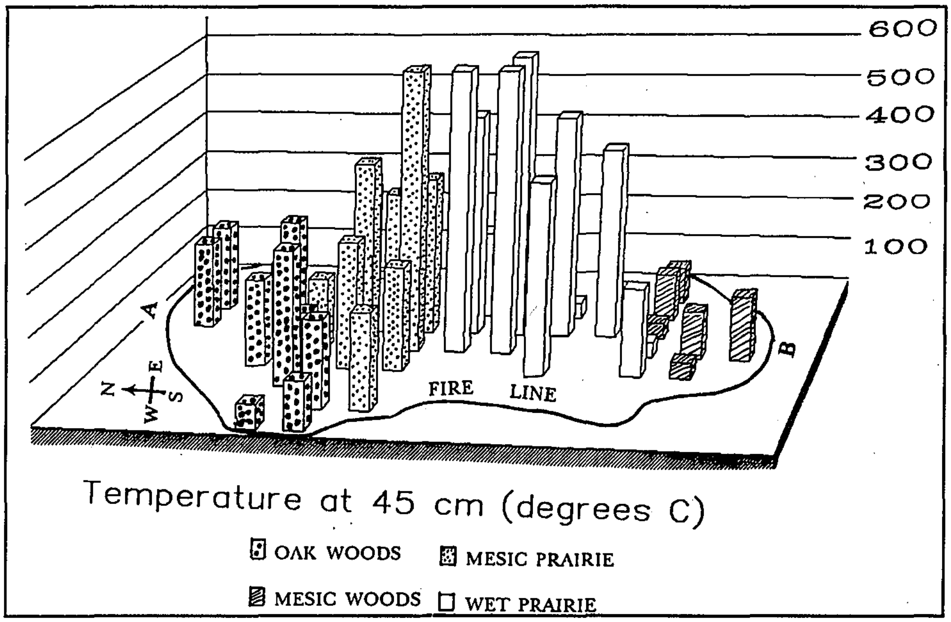

Figure 1. Three-dimensional view of an 18-ha burn area showing mean temperature recorded at 45 cm height in four different natural communities in an April 9, 1988 fire. Each column represents the mean of the peak temperatures recorded by three sensors within a vegetation plot. Ignition was initiated at point A. Flanking fires were set around the circumference to point B. Wind was from the southeast until late in the fire when it shifted to a northwesterly direction.

Belowground Temperature Measurement

Sheets of mica were cut into blocks measuring 20 X 6 cm, onto which a series of different paints with melting points ranging from 55°C to 538°C were striped. Eighty of these mica tiles were then inserted into the ground so that 2.54 cm remained above the litter–humus interface. Temperature was then measured as the distance below the humus surface that various temperature paints melted.

RESULTS

Spatial Variability of Temperatures

Temperatures varied greatly between fire events mostly because of changes in vegetation type and weather. However, temperatures also were highly variable within individual fires as parameters such as fire movement versus wind direction or slope direction changed (Figure 1). In general, within any specific community type, temperatures were higher within the fire center than near the perimeter, owing to preheating of fuel and winds generated by updrafts as the fire flanks converged at the center.

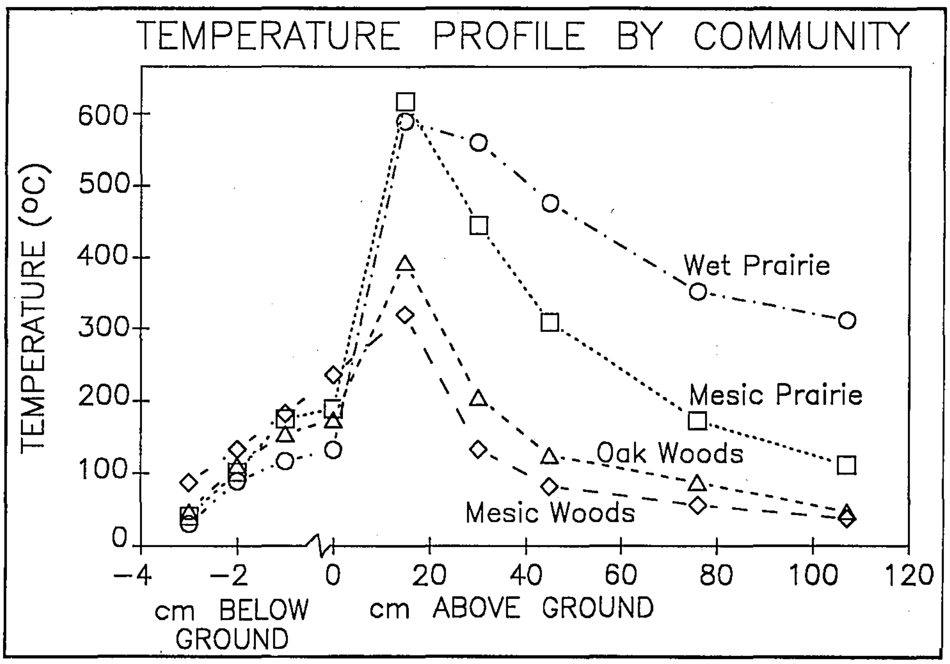

Figure 2. Profiles of mean peak temperature in four community types. Note scale change at ground level. The highest aboveground temperatures occurred in the wet prairie, while the highest belowground temperatures occurred in the mesic woods.

Nested analysis of variance demonstrated significant differences between communities ($F_{3,30}$=23.29, p<0.001) and among plots within communities ($F_{30,75}$=2.10, p=0.005). No significant differences in temperatures between fire frequency treatments ($F_{1,30}$=2.41, p>0.1) were detected.

Temperature Variability by Height and Community

The different fuel arrangements in distinct communities affected flame height and the consequent temperature profile (Figure 2). Tall grass cover in the wet and mesic prairies produced high temperatures, and aluminum tags sometimes melted at heights greater than 1 m. Low, creeping fires in oak woods often only burned leaf litter, sometimes producing no high temperatures above 20 cm when burning downhill.

Belowground temperatures were lowest in the prairie communities. Although abundant litter existed within the prairies, only the top surface was burned because of the moisture remaining from several rain events preceding the fire, especially in the wet prairie. In general, the closer the community to the water table, the wetter the litter and the less the humus was heated. Litter in the wet prairie, normally wet to flooded in the spring, was rarely charred in spring burns. In addition, fire may sweep through grasslands faster, resulting in less residence time and producing lower soil temperatures (Bentley and Fenner 1958).

The highest soil temperatures were obtained in portions of the mesic oak woods where high fuel accumulations caused intense, but highly variable soil temperatures. In these plots, most of the litter was burned off, and the temperatures averaged 133°C at a depth of 2 cm in the underlying humus.

Although each community type had a characteristic temperature profile, significant between-plot variability occurred within each type. Within-plot variability due to localized fuel accumulations and randomly blown flames touching the sensors was smoothed by calculating a mean from the three sensors at each height in each plot. These mean values from each plot were then used to obtain the between-plot mean and standard deviations shown in Figure 3. Despite the smoothing of the within-plot variability, significant between-plot variability within each community type is seen as the large standard deviations evident in Figure 3 and from the results of the analysis of variance. Statistical discrimination between prairie and wooded communities was possible at most heights, but differentiation between the mesic prairie and wet prairie, or between the mesic woods and oak woods, was less significant (see lowercase letters of Figure 3). Differentiation between the fire intensities in the mesic and wet prairies would probably have been improved if the tags had not melted at 660°C, imposing an artificial upper limit to the peak temperature measurements.

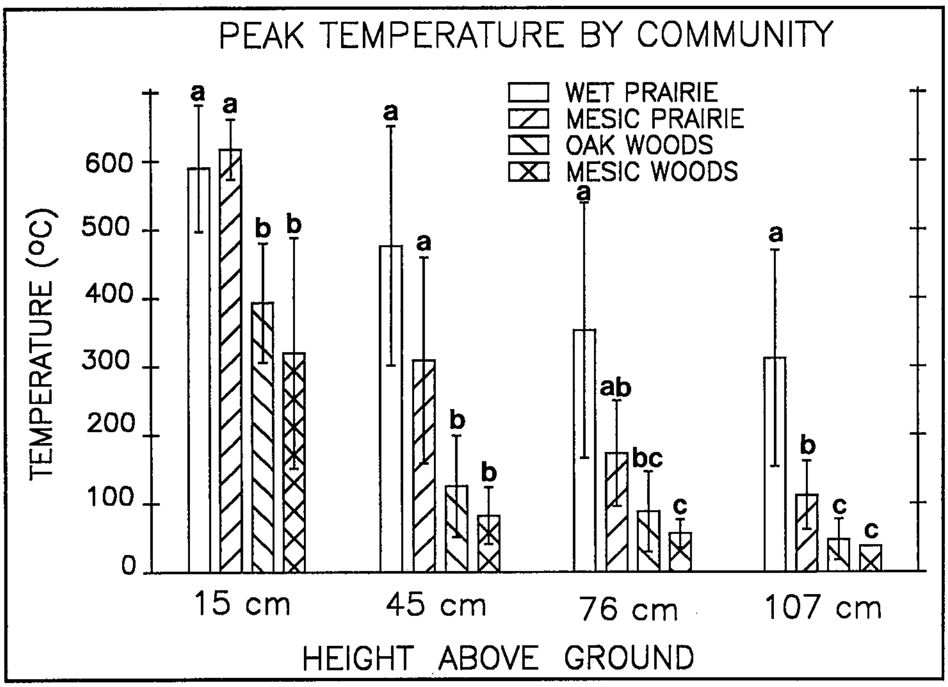

Figure 3. Between-plot means and standard deviations of peak temperatures within four community types. Lowercase letters denote significant differences at the 0.05% level as determined by application of the Mann-Whitney U test. This nonparametric rank test was used because of disparities in variances between the populations.

Temperature Effects on Trees

Variations in fire temperature correlated with some vegetational effects, the most visible being top-killing of trees. The Howes Prairie area had not burned for over 20 years (Taylor 1990) when our first prescribed burn occurred in 1986. The abundant saplings that had invaded the prairie during those 20 years provided ample data on the relationship between fire temperature, tree diameter, and tree mortality. Most of these were top-killed by this first fire, so subsequent burns provided little additional data.

An analysis of the fire effects on 197 black oak trees demonstrated a correlation between peak temperature recorded on 37 plots, tree diameter, and the percentage of trees that were top-killed by the fire (Figure 4). Because low flames could melt even the highest temperature paint on the lowest tags (15 cm above the ground), these tags were an unreliable predictor of tree mortality. The highest tags (107 cm) were often unaffected by the flames. A better predictor of tree mortality was developed by averaging values from tags at four heights (15, 45, 76, and 107 cm) to calculate a "temperature index" used in the axis of Figure 4. This temperature index most likely corresponds to sustained high temperatures near the tree bole, but the melting of the lowest tags at 660°C necessitated its use.

Data on tree mortality and the calculated temperature index were used in a probit analysis (Sokal and Rohlf 1981) to calculate the LD50 (lethal dose for 50% of the individuals) for the tree size classes. The LD50 of the smallest trees (2.5 to 5 cm dbh) was calculated to be 183°C, while it was 366°C for the medium (5 to 10 cm dbh) trees. These measurements must be viewed as minimum measures because peak temperatures may have been higher than the highest melted paint, yet not high enough to melt the next paint in the series. No medium-sized trees (5 to 10 cm dbh) were

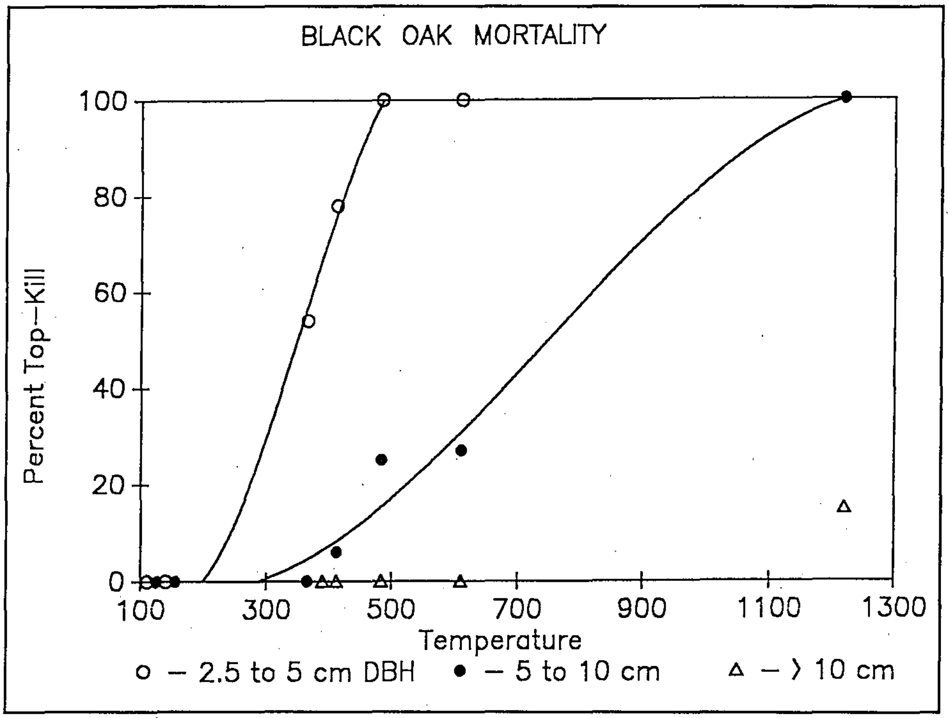

Figure 4. Probit analysis showing the percent of black oaks top-killed in an April 18, 1986 fire at Howes Prairie. Data is grouped into three tree size classes and six different classes of average temperature between 15 and 107 cm height (see text).

top-killed without the lowest tag (15 cm) exceeding the melting point of aluminum (660°C).

Low fires with flame lengths less than 15 cm rarely killed any but the smallest seedlings and saplings. Saplings with a dbh of 2.5 to 5 cm were easily killed in moderate fires with flame lengths around 30 cm, whereas larger trees (5 to 10 cm dbh) required a hotter fire. Mature trees (> 10 cm dbh) were only top-killed by the most intense fires where flame lengths were not observable but temperatures exceeded 660°C above 107 cm.

Total mortality of trees (both shoots and roots killed) was rare compared to top-killing (crown mortality) of trees. During a four-year period, areas with two and three burns averaged 3.7% and 3.6% total mortality of black oaks per year, respectively. These numbers can be compared to 2.1% mortality per year on an unburned control area during the same period. Tree mortality in the burn areas may have increased after the 1988 summer drought (Cole and Pavlovic unpubl. data).

Comparison with Fuel Load Sampling

Measures of fuel loading were taken adjacent to several of the study plots. Five measurements of herbaceous fuel loading in the wet prairie (reported by Konz and Stanley 1988) were taken adjacent to five plots. This portion of the wet prairie burned at some of the highest temperatures recorded in this study. The herbaceous fuel loading averaged 2.99 kg/m^2 (1.21 tons/acre). Almost all of the herbaceous matter burned in the fires, but very little of the moist litter was consumed. No postfire sampling was conducted in the prairie.

Pre- and postfire sampling of woody material and litter was conducted in the mesic woods. Total downed woody material and herbaceous material (including litter) was sampled using the methods described in Brown (1974) and was reported by Stanley (1988a and 1988b). Preburn (18 days before the fire) woody fuel loading at eight stations in the mesic woods averaged 22.7 kg/m^2 (9.22 tons/acre), and postburn measures (two days after the fire) averaged 27.1 kg/m^2 (11.0 tons/acre). Preburn herbaceous (litter) samples in the mesic woods averaged 2.51 kg/m^2 (1.02 tons/acre) and postburn samples averaged 0.61 kg/m^2 (0.25 tons/acre).

Comparison of the fuel load measurements with fire temperatures was possible for three study plots adjacent to the fuel sampling stations in the mesic woods (Figure 5). These measurements suggest that there was a high correlation between the amount of leaf litter in a plot, the percentage of this leaf litter consumed by the fire, the woody fuel load, and the temperature measured at the plot, although additional measurements would be beneficial.

The significant combustion of fine fuels in both the prairie (herbaceous fuels) and the forest (leaf litter) seem to contradict the comparatively low consumption (or surprising increase) in woody fuels. This is explained by the brief warm-dry burning periods that usually occur in northern Indiana. If a burn is planned, any brief warm-dry spell must be used because extended dry spells are rare. A few days of warmth will dry out the fine fuels, but larger woody fuels remain moist. Following the initial fuel load measurements (and perhaps after the fire), branches can fall off of trees, potentially making the postfire measurements higher than the prefire ones. Because only 24- to 48-hours' notice is possible before a fire, extensive measurements of fuel immediately prior to a fire cannot be taken. During this hectic period, most personnel are busy preparing the fireline.

DISCUSSION

Effective temperature monitors

The variability in temperatures measured during these studies emphasizes the need for an accurate method of monitoring fires at remote sites, that is, sites that cannot be visually assessed during large burns. The statistical analysis of fire "treatments" assumes that all the vegetation within the experimental treatment receives similar impacts. This is rarely true, because fire behavior in all but very small fires is quite complex, complicating the task of statistical comparisons between different treatments (e.g., seasonality).

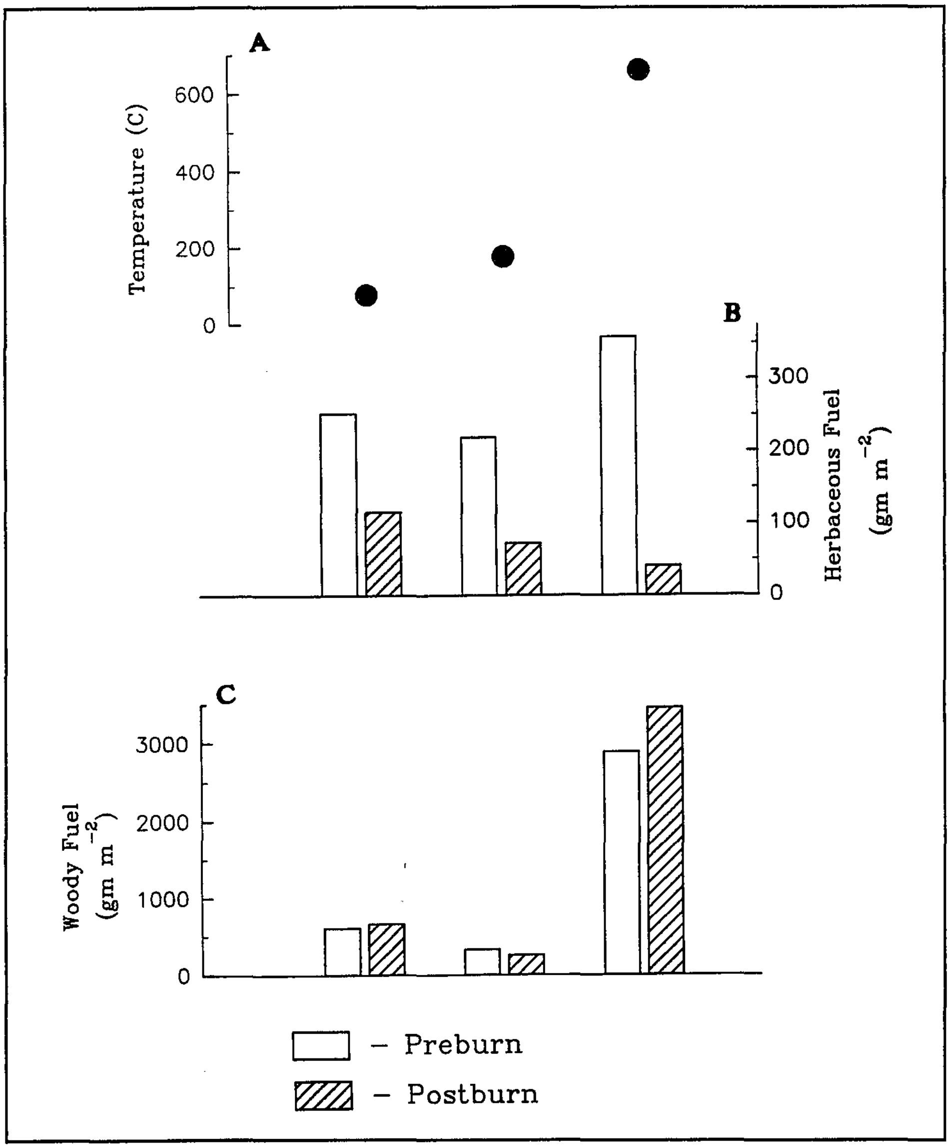

Figure 5. (A) Average temperatures recorded at 46-cm height for three plots in the mesic woods are compared to (B and C) fuel load measurements taken before and after the fire from stations nearby the three plots. Values for herbaceous fuel (B) are mostly leaf litter.

Our failure to detect differences between plots having one versus two years of fuel load may be attributable to the low productivity of these plant communities on sand, where there is a minimal buildup of fuel loads in only two years. The high variability between plots may be caused by differences in community type (fuel load type), slope, aspect, wind speed, wind direction, and location within the fire.

The monitors described herein are only a first effort at developing a standardized temperature monitor. Further research comparing other designs and different methods such as fuel load sampling would be advisable. For the assessment of large fires in diverse habitats, the rapid positioning of many monitors may be more important than the accuracy of individual monitors. In this study we found that the variability encountered within each 100-m^2 plot necessitated the use of at least three arrays of several monitors each. The monitors described in this article are inexpensive and several hundred can be placed within a burn area by two persons with only a single day's notice. Use of these monitors was easier than other methods such as fuel load sampling, and they do not disturb the vegetation of a permanent plot.

The biggest drawbacks to the use of aluminum tags may be the melting of the tags at high temperatures and charring of the paint from smoke (Wright and Bailey 1982). Charring can be minimized by orienting the tags with the paint on the upper surface. A thin cover of mica may prevent charring (Stott 1986), or the paint may be placed on mica sheets to prevent melting. However the temperature monitors are constructed, they must be inexpensive and easy to deploy to ensure adequate coverage in a fire.

Creation and Perpetuation of Vegetation Mosaics

Many of the vegetation patterns in natural communities are the result of differential fire disturbance in the past. A particularly severe fire in a natural community that rarely burns is likely to leave its mark on the resultant vegetation for more than a century (Rowe and Scotter 1973). Persistent mosaic patterns in chaparral have been attributed to past fires (Bradbury, 1977). As a result, variable fire intensities may give rise to subsequent patterns in the vegetation that may defy understanding without data on past fire temperature.

In a region where some vegetation types are fire-adapted, fire mosaics have a possibility of becoming self-perpetuating. A severe burn may open up a portion of non-fire-tolerant vegetation and allow invasion of a fire-tolerant type. This fire-tolerant vegetation may then encourage future burns in a self-perpetuating cycle if fire is not excluded from the area. For example, the prairie on the western sides of rivers in the great plains (Gleason 1913) could have resulted from severe burns long ago. Once the forest was eliminated, the flammable prairie would retard reinvasion of the forest by producing high-temperature fires.

The characteristic temperature profile produced during the burning of a community often serves to perpetuate that community. For example, the low soil temperatures and high aboveground temperatures seen in the prairie communities in this study are ideal for the perpetuation of herbaceous species of those communities. Even though these fires may occur annually, they cause little harm to herbaceous plants with apical meristems and a seed bank just below the ground surface in moist litter. However, this type of frequent, intense fire is harmful to woody plants with much biomass invested above the soil layer.

The future vegetation on small remnant natural areas will ultimately be the best testament to the effectiveness of our management techniques. Although time may be limited in the present for research on fire effects, a record of fire history, including an indication of temperature, could be extremely valuable in the future for understanding resultant vegetation patterns.

CONCLUSIONS

Inexpensive fire temperature monitors can be constructed from aluminum tags and temperature-sensitive paint. The use of these monitors on prescribed burns at the Indiana Dunes documented high variabilities in fire temperature, which can be correlated to weather before and during the fire, community type, fuel loads, and the dynamics of individual fire events. Fire effects such as tree mortality can be shown to correlate with fire temperature and tree diameter.

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LITERATURE CITED

Bentley, J.R. and R.L. Fenner. 1958. Soil temperatures during burning related to postfire seedbeds on woodland range. Journal of Forestry 56:737-740.

Bradbury, D.E. 1977. The evolution and persistence of a local sage/chamise community pattern in southern California. Yearbook of the Association of Pacific Coast Geographers 40:39-56.

Brown, J.K. 1974. Handbook for inventorying downed woody material. USDA Forest Service, General Technical Report INT-16. Intermountain Forest and Range Experiment Station, Ogden, Utah.

Brown, J.K., R.D. Oberheu, and C.M. Johnston. 1982. Handbook for inventorying surface fuels and biomass in the interior west. USDA Forest Service, General Technical Report INT-129. Intermountain Forest and Range Experiment Station, Ogden, Utah.

Burgan, R. and R. Rothermel. 1984. BEHAVE — fire behavior prediction and fuel modeling system. USDA Forest Service, General Technical Report INT-167. Intermountain Forest and Range Experiment Station, Ogden, Utah.

Cole, K.L. 1986. Fire intensity and rate of spread for the April 18, 1986 research burn at Howes Prairie. Unpublished report to Indiana Dunes National Lakeshore.

Cole, K.L., P.K. Benjamin, and K.F. Klick. 1990. The effects of prescribed burning on oak woods and prairies in the Indiana Dunes (Indiana). Restoration and Management Notes 8:37-38.

Fonteyn, P.J., M.W. Stone, M.A Yancy, and J.T. Baccus. 1984. Interspecific and intraspecific microhabitat temperature variations during a fire. American Midland Naturalist 112:246-250.

Gleason, H.A. 1913. The relation of forest distribution and prairie fires in the middle west. Torreya 13:173-181.

Hobbs, R.J., J.E.P. Currall, and C.H. Gimingham. 1984. The use of 'thermocolour' pyrometers in the study of heath fire behavior. Journal of Ecology 72:241-250.

Howard, W.E., R.L. Fenner, and H.E. Childs. 1960. Wildlife survival in brush burns. Journal of Range Management 13:230-234.

Klick, K. 1988. A report of the April 9, 1988 fire at Howes Prairie. Unpublished report to Indiana Dunes National Lakeshore.

Konz, L. and D. Stanley. 1988. Inventorying herbaceous vegetation at Howes Prairie. Unpublished report to Indiana Dunes National Lakeshore. 4 p.

Moreno, J.M. and W.C. Oechel. 1988. Population dynamics of mature plants and resprouts of *Adenostoma fasciculatum* following hand clearing, fires of different intensities and fertilization with ash in southern California chaparral. Bulletin of the Ecological Society of America 69:238.

Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. USDA Forest Service, Research Paper INT-115. Intermountain Forest and Range Experiment Station, Ogden, Utah.

Rowe, J.S. and G.W. Scotter. 1973. Fire in the boreal forest. Quaternary Research 3:444-464.

Silen, R.R. 1956. Use of temperature pellets in regeneration research. Journal of Forestry 54:311-312.

Sokal, R.R. and F.J. Rohlf. 1981. Biometry. W.H. Freeman and Co., New York. 859 p.

Stanley, D. 1988a. Results of fuel load sampling, 1987–1988, Howes Prairie and Beverly Shores sampling areas, Indiana Dunes National Lakeshore. Unpublished report to Indiana Dunes National Lakeshore. 8 p.

Stanley, D. 1988b. Downed woody fuel load sampling guidelines. Unpublished report to Indiana Dunes National Lakeshore. 31 p.

Stinson, K.J. and H.A. Wright. 1969. Temperature of headfires in the southern mixed prairie of Texas. Journal of Range Management 22:169-173.

Stott, P. 1986. The spatial pattern of dry season fires in the savanna forests of Thailand. Journal of Biogeography 13:345-358.

Swink, F. and G. Wilhelm. 1979. Plants of the Chicago Region. Morton Arboretum, Lisle, Illinois. 922 p.

Taylor, R.S. 1990. Reconstruction of Twentieth Century fire histories in black oak savannas of the Indiana Dunes National Lakeshore. M.S. thesis, University of Wisconsin, Madison.

Wright, H.A. and A.W. Bailey. 1982. Fire ecology: United States and Southern Canada. Wiley-Interscience, New York.