

A comparison of thermocouples and temperature paints to monitor spatial and temporal characteristics of landscape-scale prescribed fires*

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Abstract. A method to better monitor landscape-level fire characteristics is presented. Three study areas in southern Ohio oak-hickory (*Quercus-Carya*) forests were established with four treatment areas of ~20 ha each: control (C), burn only (B), thin only (T) or thin plus burn (TB). Two independent measures useful for qualitatively characterising fire intensity were established on a 50-m grid, resulting in over 120 sampling locations at each site, in the burned areas: aluminum tags painted with temperature-sensitive paints, and logger-probe units that logged probe temperature every 2 s during burns. Fires were conducted in spring 2001. The logger-probe units allowed five measures qualitatively related to fire intensity or timing to be calculated at each grid point: maximum probe temperature; duration of probe temperature above 30°C; a heat index, defined as the summed temperatures above 30°C; time of maximum temperature; and estimated rate of spread. Maximum temperatures recorded by the two measuring systems were highly correlated ($r^2 = 0.83$). Relative to painted tags, logger-probe units provide information useful for assessing some other components of fire behaviour. The temporal recording of temperatures allowed us to prepare a web-based simulation of the fires. Heat index and rate of spread estimates provided additional fire information. The TB units consistently burned cooler than the B units, perhaps because of uncured slash and a disrupted fuel bed in those units.

Additional keywords: animation of fire; fire intensity; oak forests; oak regeneration; Ohio.

Introduction

Prescribed fire is increasingly being recommended as a tool to reduce threats from wildfires as well as to promote many fire-dependent ecosystems of the United States (Allen *et al.* 2002). After more than a half century of fire suppression, there has been a general deterioration in ecosystem integrity of some forest types, especially in those with historically short-interval, low- to moderate-severity fire regimes (Agee 1993; Clark 1993; Yaussy and Sutherland 1993; Taylor and Skinner 1998; Brose *et al.* 2001). These conditions led to the development of the 2001 Federal Wildland Fire Management Policy that directs federal agencies to achieve a balance between suppression capability and the use of prescribed fire to regulate fuels and sustain healthy ecosystems (National Interagency Fire Center 2001).

Ohio is typical among many mid-west and eastern states in that it is undergoing a conversion of its oak-hickory (*Quercus-Carya*) forests to mesophytic species; the change is due at least in part to fire suppression (Brose *et al.* 2001). Dendroecological studies have shown that, from the time of

Euro-American settlement (ca. 1800) to the 1920s, surface fires were frequent in oak forests in the area (Sutherland 1997; Hutchinson *et al.* 2002). However, since the 1920s fire has been largely suppressed or eliminated and species composition gradually is shifting to dominance by maples (*Acer* spp. L.) and other mesophytic species.

As part of the national Fire and Fire Surrogates Study (FFS) and the National Fire Plan (NFP), we are studying prescribed fire and thinning as possible means to improve the oak regeneration in this region. We are examining the effects of fire and/or thinning on soils, forest plants, trees, forest pathogens and wildlife in order to identify ecological tradeoffs inherent in the application of such management activities.

The behaviour of fire across a landscape can vary markedly depending on conditions associated with fuel, weather, topography and vegetation structure and composition, conditions that vary considerably across North America. Anticipating potential prescribed fire behaviour is very important in subsequently anticipating fire effects on the vegetation and wildlife

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(Whelan 1995). It is difficult to safely obtain good data on fire behaviour (e.g. flame lengths, residence times) across large landscapes on prescribed surface fires, as interior locations cannot be easily monitored. However, temperatures related to ambient conditions at positions above the ground can be and have been measured in many fires; these measures are often valuable for understanding and interpreting fire effects. Most of these studies have used temperature-sensitive paints as a surrogate for fire intensity (e.g. Gibson *et al.* 1990; Cole *et al.* 1992; Abrahamson and Abrahamson 1996; Franklin *et al.* 1997), and to relate fire conditions to effects on vegetation (e.g. Glitzenstein *et al.* 1995; Ramsay and Oxley 1996; Drewa *et al.* 2002; Iverson *et al.* 2004). Electronic thermocouples have also been used for a long time to record temperatures associated with fires in forests. For example, Heyward (1938) and later Miller *et al.* (1955), then Sackett and Haase (1992) used electronic recording devices to measure soil temperatures under prescribed fires. We have also used these devices to assess soil temperatures beneath prescribed fires in Ohio deciduous forests (Iverson and Hutchinson 2002). In this paper, we present a method to measure temperatures recorded by thick thermocouples (probes) placed 25 cm above the forest floor surface. We also compare this information to data obtained via painted tags over numerous sample locations for three study areas in southern Ohio. Because we placed more than 120 sensors in a grid across the landscape at each of three sites, we believe this is one of the first reported uses of electronic sensors to record temperatures across large landscapes during prescribed fires.

It is well known that thick thermocouples such as those used here cannot accurately record the temperature of the flame or the air surrounding the probe because of the large lag time for heating and cooling, along with many other errors associated with conduction and radiation (Walker and Stocks 1968; Ballantyne and Moss 1977; Van Wagner and Methven 1978). Rather, any indication of temperature reported in the paper simply is the temperature of the probe, which we assume is at least qualitatively correlated with true fire intensity. The same can be said of the aluminum tags painted with temperature-sensitive paints used for comparison in this study. We also understand that the elevated temperatures recorded during the fires can be attributed to a combination of several sources: primarily the convective heat flux from the flames but also glowing combustion and radiant heat from a larger fuel source some distance from the sensor (Bova and Dickinson 2003). We concentrate in this paper on the methodology to derive new information from the logger-probe units, and to compare the temperatures to those acquired from temperature-sensitive paints.

Study area

Three study areas were selected from the highly forested portion of south-eastern Ohio: the Raccoon Ecological

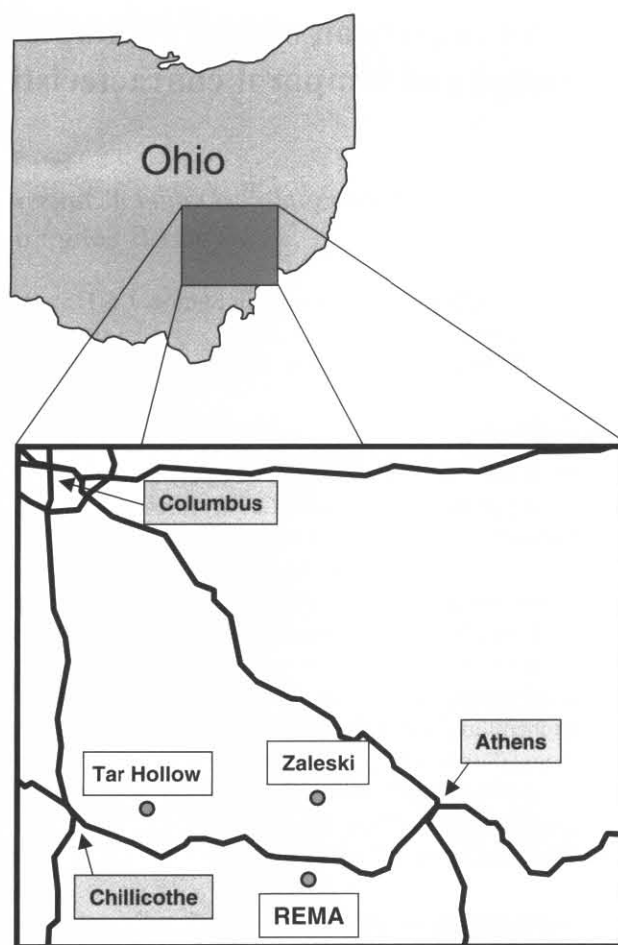


Fig. 1. Study areas of the project in southern Ohio, USA.

Management Area (REMA), the Tar Hollow State Forest (TAR) and the Zaleski State Forest (ZAL) (Fig. 1). REMA is a 6880-ha (17 000-acre) tract of land, owned by the MeadWestvaco Corporation and co-managed with the USDA Forest Service, Northeastern Research Station. The Zaleski State Forest and Tar Hollow State Forest are 10 860 ha (26 827 acres) and 6526 ha (16 120 acres) in size, respectively, and are managed by the Ohio Department of Natural Resources (ODNR), Division of Forestry.

The study areas are characterised by deeply dissected topography with ~100 m of total relief within each study area. The upland forests are mostly a complex mosaic of oak-hickory and mixed-oak communities, with some mesophytic communities in ravines and other mesic areas (Beatley and Bartley 1959). Much of the land was clearcut in the mid-to late-1800s to furnish charcoal for several iron furnaces in the region. Conditions for establishment in the late 1800s likely were influenced by frequent fires (Sutherland 1997; McCarthy *et al.* 2001), so that oaks were able to successfully compete across the landscape (Crow 1988).

The study consists of four treatments on the three study areas (REMA, TAR, ZAL), resulting in 12 experimental units

of ~20 ha each. The four treatments implemented at each study area were: untreated control (C); prescribed fire only (B); thinning from below (T); and thinning followed by prescribed fire (TB). Prior to treatment, each area had an average basal area of ~29 m² ha⁻¹. The T and TB treatment areas were commercially thinned from below (removals concentrated on the smaller size classes) during the autumn and winter of 2000–2001, resulting in a 30% reduction in basal area. For the study reported here, only the burned units (B and TB) were assessed, and only the REMA and ZAL study areas were fully analysed as equipment failure plagued the TAR study area on our first attempt.

Methods

Field instrumentation and pre-fire sampling

A 50 × 50 m grid of points was established on the ground with a Global Positioning System (GPS) to aid in navigation, placement of study plots and assessments of landscape-level changes resulting from the treatments. In total, 311 points were established across all four treatments at ZAL, 289 at REMA and 288 at TAR. Temperature probes and data loggers were placed at a total of 380 of these points among the three study areas within the B and TB treatment areas. Each probe consisted of a 304 stainless steel jacket packed with MgO, 30.5 cm long and 4.8 mm in diameter, with an isolated Type K thermocouple junction at the tip. These thick probes therefore have long lag, response and residence times so that recorded temperatures will be lower than flame temperatures, the time of maximum temperature will be slightly delayed and the recorded duration of elevated temperatures will be longer, respectively, just because of the thermal characteristics of the metals comprising the thermocouple and the probe. Nonetheless, preliminary evidence indicates that the recorded data can provide a qualitative index of fire intensity (Bova and Dickinson 2003). The probes were installed from the soil extending upward to a position 25 cm above the ground (Fig. 2). The 25 cm height was selected as the most appropriate height for correlating tag temperatures to sapling topkill, based on 6 years of using painted tags at various heights in these types of fires. The 2-m cable extending from the probe was buried to a depth of 3–6 cm in a slit of soil extending to a PVC chamber used to house the data logger. Extreme care was used to limit disturbance of the litter layer during the burial of the cable; a hatchet was used to cut a small slit in the ground to lay the cable and the litter layer was reconstructed over the closed slit. Hobo® (Onset Computer Corporation) data loggers were programmed to measure and record probe temperature every 2 s during the day of each burn. Two logger channels collected data, one with a maximum temperature of 500°C, the other with a maximum temperature (at a coarser resolution) of 1250°C; ~9 h of data could be collected at this rate. As it turns out, we needed only the 500°C data but, by collecting data from both channels, we are assured

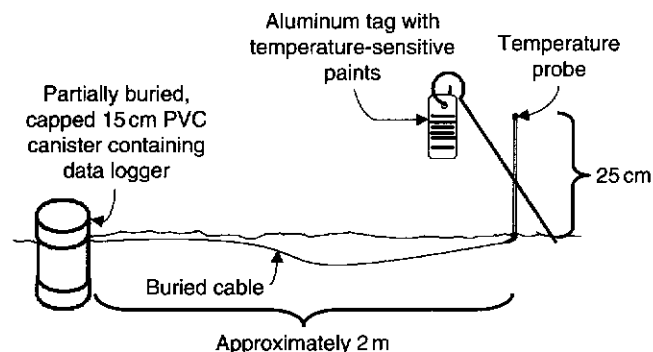


Fig. 2. Diagram displaying the logger-probe unit and the painted tag pair.

of a temperature estimate, even at very high temperatures. The data recorders were transported to the field and put into the closed, partially buried PVC chambers during the mornings of the burns. A removable cover on the PVC chamber allowed access to the data loggers. Some leaves were moved away from these chambers to reduce the probability of the chambers being burned.

The TAR study area, the first one instrumented, had a high proportion of loggers fail (71%) due to the build-up of static electricity within the loggers while being transported to the field in small plastic boxes. For subsequent fires at REMA and ZAL, transporting the loggers in individually wrapped anti-static bags rectified this problem, with less than a 2% failure rate on the loggers.

Aluminum tags (2.5 × 7 cm) were painted with six Tempilaq® paints that melt at the following temperatures: 79°, 121°, 163°, 204°, 315° and 427°C (175°, 250°, 325°, 400°, 600° and 800°F). The painted tags were covered with a blank tag and fastened with paper clips to reduce char or soot deposits that impede the accurate assessment of melting temperature; all painted tags were readable. These painted tags were hung from an aluminum pin at the same height and location as the probes (Fig. 2), so that a comparison of maximum temperature could be made. The thermal characteristics mentioned above for the thick probes, i.e. longer lag, response and residence times also apply, in a similar but not identical way, to the aluminum plates containing temperature-sensitive paints. The visual interpretation of whether a paint has melted introduced variability to the estimated maximum temperature as does the large interval between melting temperatures. One person read all tags to minimise inconsistencies in determining if paint had melted. The paint was categorised as melted even if it was only partially melted. Only tag–probe pairs that had a detectable rise of at least 5°C in logged ambient temperature (there was fire nearby) were used in the calculations. The paint tag temperatures should be considered a 'minimum' maximum temperature because, if the paint was melted, it could indicate a temperature up to the next paint-melting temperature.

Table 1. Summary of local meteorological data at the time of the fires
First number indicates condition at start, second is condition at end of fires. For TAR and ZAL, the TB and B units were burned together as one block

Attribute	TAR, TB&B	ZAL, TB&B	REMA, TB	REMA, B
Date	28 Mar 2001	04 Apr 2001	05 Apr 2001	05 Apr 2001
Time (EST)	1230, 1630	1300, 1553	1153, 1439	1520, 1750
Ambient temp. (°C)	11, 13	15, 18	18, 23	23, 24
Rel. humidity (%)	41, 44	35, 23	39, 25	26, 22
Windspeed (km h ⁻¹)	3, 3	6, 6	5, 5	6, 8
Wind direction	S, S	S, E	ESE, ESE	SSW, W
Fuelstick moisture ^A	n/a	6.5, 6.3	6.9, 5.9	5.9, 5.7

^AFuelstick may not have fully equilibrated with environment.

A portable meteorological station (Forest Technology Services, Inc.) was set up close to the burn units before each of the fires. It collected hourly measurements of air temperature, relative humidity, wind speed, wind direction and fuelstick moisture (Nelson 2000).

Fuels were sampled within 20 m of a subset of the points (Riccardi and McCarthy 2002, 2003) before and after the fires. Fuels consisted of surface litter composed entirely of newly fallen leaves (very little grass or understory vegetation), along with deeper humus layer litter and 1, 10, 100 and 1000 h fuels (Brown 1974). In both quantity and moisture, the data were highly heterogeneous but generally similar among treatments within each study area before the prescribed fires. Average site fuel loads before the fires ranged from 3.2 to 7.4 Mg/ha for surface litter, and were 3.6–7.2 Mg/ha for the humus layer, 0.3–0.4 Mg/ha for 1 h fuels and 1.3–2.0 Mg/ha for 10 h fuels. Moisture levels for the surface litter were quite dry (<2.5% moisture by volume), and the 1 h fuels had 2.4–8.6% moisture, but the humus and larger pieces (>1 h) were mostly more than 12% moisture. Consequently, most all of the surface litter (intact leaves fallen previous fall) was consumed in these spring fires, a small portion of the 1 h fuels was consumed, but very little other fuel was consumed because of high moisture and only moderate intensity fires.

Fires

Fires were conducted before leaf-out on 28 March, 4 April and 5 April 2001, at the TAR, ZAL and REMA respectively. Times and meteorological conditions during fires are presented in Table 1. The B and TB units were adjacent to each other for TAR and ZAL, so were burned as one block, while they were burned in two fires at REMA.

The TAR study area had received several mm of rain 2 days earlier, followed by cool temperatures between rainfall and ignition. The two units were burned as one block, which was ring-ignited from the fire lines. The observed fire behaviour ranged from smouldering on the north slopes to flame lengths exceeding 2 m in slash piles on south-facing slopes. Based on percentage burn estimates within a 5-m radius of the grid points, 70% of TB burned, while 81% of B burned.

The ZAL study area was fired using three firing teams, two working along the north and south edges of the unit and one firing through the centre of the unit. Each firing team used two or three drip torches allowing them to light several lines of fire parallel to the control lines. The area had received a light dusting (13 mm) of snow on 1 April and less than 3 mm of rain on 3 April, the day before the burn. The warm temperatures and dry air mass that moved in on that day allowed the fuels to dry quickly. The use of interior ignition aided in building heat in the unit and increased the intensity of the fire across the unit. Fires generally burned completely but not with extreme intensity. Based on percentage burn estimates across the grid points at ZAL, 86% of TB and 99% of the B unit burned.

The REMA study area consisted of two units that were sequentially burned (TB unit followed by B unit) on 5 April. The TB unit was fired using three firing teams, two working along the north and south edges of the unit and one firing through the centre of the unit. The B unit was fired primarily from the exterior lines, with some interior ignition via flare gun. The TB unit burned nearly completely on south-west-facing slopes but incompletely on the north-facing slopes. The B unit had a relatively hotter fire; a few spot fires occurred along the north and east lines. For REMA, percentage burn estimates across the grid points (5-m radius) were 68% for the TB unit and 96% for the B only unit.

Data analysis

Logger-probe units and painted tags

Data captured by the logger-probes consisted of a temperature profile with time for the point 25 cm above the surface (Fig. 3). With the data captured by these logger-probes, four qualitative indicators of fire intensity or timing could be derived at each grid point: maximum temperature; duration of temperature above 30°C (an arbitrary temperature slightly warmer than ambient so that we know that fire contributed to the elevated temperatures); a heat index, defined as the cumulative temperatures above 30°C, as measured every 2 s (an integral under the temperature curve as shown in Fig. 3); and time of maximum temperature. The data from each logger-probe were downloaded into separate files and

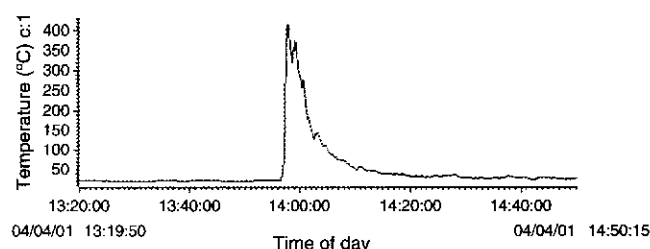


Fig. 3. Temperature profile for grid point 559 from ZAL TB.

then processed in spreadsheets for indicator calculations, summary analysis and animation pre-processing. The maximum temperatures recorded by the heat-sensitive painted tags were statistically compared to the maximum temperature from the logger-probes via linear regression analysis and a paired *t*-test.

Estimates of rate of spread

An effort was made to use the time-stamping aspect of the data loggers to devise a scheme for estimating rates of fire spread within the landscape. To be sure, a 50-m spacing is too large in dissected terrain (i.e. 100 m relief but with multiple ridgelines and valleys within a 20 ha area) to get an accurate spatial estimate of rate of spread. However, for this methodology paper, we demonstrate a possible technique that could be modified (e.g. increase the density of the grid, controlled ignition points, etc.) to suit the location being tested. For such estimates, we focused on a spatial analysis of the time of maximum temperature recorded for each point. For each grid point, an 80-m radius was searched for the time of maximum temperature closest below and closest above the time at the grid point. Thus, for internal points on a 50-m grid, eight surrounding points were evaluated. The time difference between the grid point in question and the grid point with the nearest time *before* is an estimate of the time (in minutes) for the fire to spread *to* the point. Conversely, the time difference between the grid point in question and the one with the nearest time *after* is an estimate of the time for the fire to spread *away from* the point. The sum of these two estimates is an estimate of the time for the fire to move *across* the point. In the event that either the *before* or *after* times could not be calculated (because the grid point had either the lowest or highest time of maximum temperature within the 80-m radius circle), the other number was multiplied by two to reach an estimate of rate across the point. The distance between three grid points could range between 100 m (three points in an east–west or north–south line) and 140 m (three points diagonally). In calculating estimated rate of spread, we used a conservative estimate of 100 m of flame travel in the time calculated from the logger-probe units (e.g. 100 m of fire travel per minute is a slower rate of spread than 140 m of travel per minute). The rate of spread estimates, calculated in m/min, are only approximate and should be considered

relative values because theoretically the fire front could be passing across two or more grid points nearly simultaneously. To minimise this source of error, only those adjacent points with at least 2 min of time difference from the point in question were considered in the above calculations. This screening process meant that the maximum rate of spread allowed by the calculation was 50 m/2 min = 25 m/min.

Animations

Maximum temperature, duration of elevated temperature and time of the maximum temperature were used to animate the prescribed fires across the landscape. At ZAL, 126 grid points were used for the animation; at REMA, 121. For each point, the time of the maximum temperature and duration of elevated temperature (continuous time above 30°C) were identified. Half the duration was then used to approximate the beginning and ending times of elevated temperatures. Even though exact beginning and ending times were available in the data, the extra effort and precision were not needed for a visual animation. Linear spreadsheet functions were used to raise the temperature to the maximum and then lower the temperatures from the maximum, with each time slice as a column in the spreadsheet. The time step for ZAL was 30 s for each of 248 ‘slices’ of time, animating 2 h 4 min of fire across 41.9 contiguous hectares. Both the ZAL B and TB units were burned during this period. With REMA, the two units were distinct, but they were burned sequentially on 5 April so that the TB unit had not completely burned before initiating fire on the B unit. Consequently, we chose to animate these two units together as well, but over a longer period. As such, the time slice was 1 min for each of 343 slices for a total of 5 h 43 min of animation.

The time-slice temperatures were next linked to the grid points via ArcView 3.2a (Environmental Systems Research Institute 1996), and each slice was interpolated to a separate layer using the inverse weighted distance function in Spatial Analyst, via an Avenue script. As an area is burned (i.e. ‘affected’ by the burn because the area burned is dependent on the accuracy of the interpolation), the colour changes from light brown to grey. Temperatures above 30°C are represented by colours grading from yellow to orange to red, with red representing temperatures above 250°C. The resulting slices were stitched together into a movie, using the software Platypus Animator Version 5.4 (C Point Pty Ltd, Australia).

Results and discussion

Maximum temperature recording technology

Maximum fire temperatures recorded by paired logger-probes and paint tags were highly correlated ($r^2 = 0.83$, $n = 278$, Fig. 4). Using a paired *t*-test, the logger-probes registered an average temperature 26.1°C higher than the paint tags. This difference was expected as discussed earlier because the paint tag temperatures reflected the ‘minimum’

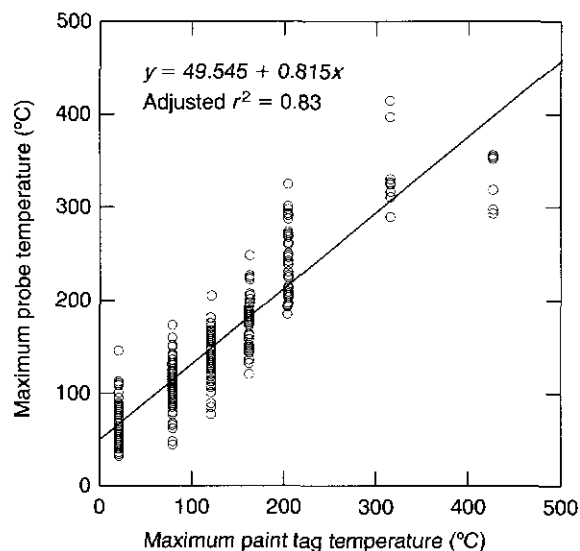


Fig. 4. Relationship between maximum temperatures recorded via logger-probe units v. painted tags.

maximum temperature. This difference could also be partially attributable to the difference in thermal properties between the probe unit and the painted aluminum plates. There were no differences among treatments or study areas in this relationship. At higher temperatures ($>315^{\circ}\text{C}$), there was more variability between the two recording systems. The disagreement occurring at the higher recorded temperatures may be attributable to human error in interpretation of melted paint on these few tags; this possibility could not be checked because the tags were recycled before the discrepancy was discovered. The higher temperature fires blackened the tags making the observations more difficult. Alternatively, it could be that the relationship is not linear at the higher temperatures.

The minimum threshold for detecting temperature rise in the paints we used was 79°C , whereas any rise above ambient can be detected with the logger-probe units. This could be important if it is desired to capture minor temperature changes due to small or interrupted fires.

These results show that if maximum temperature is the only variable of interest, then temperature-sensitive paints provide an easy, inexpensive and reasonably reliable method of providing that information. The cost for materials using painted tags is about \$US0.05 each, compared to about \$US110 per logger-probe unit. Even though the logger-probe units can be used multiple times and with more confidence than paints, this differential in costs should be carefully considered before embarking on use of a logger-probe system.

Analysis of individual fires

The logger-probes were first used at the TAR study area, where 71% of the recorders failed and only 31 units successfully captured data. From that experience, we learned that the data recorders must be moved and stored separately

in anti-static bags. Subsequently, the data recorders successfully captured temperature data for 244 points for the ZAL and REMA study areas; only a few of those sensors failed. Though data also are presented for the TAR study area, using the 31 successful logger-probes, subsequent discussion on fire temperatures is based primarily on data from the ZAL and REMA study areas. Because the painted tag temperatures were correlated with logger-probe temperatures, no specific discussion is provided on those temperatures.

Tar Hollow

Even though most of the logger-probes failed, we can confidently say that the TAR study area had the coolest burn. The absolute maximum and average maximum probe temperatures were only 293°C and 129°C for the B unit and 226°C and 116°C for the TB unit (Table 2). Only 22–29% of the sensors recorded temperatures above 150°C . The heat index and heat duration values were also low as compared to the ZAL and REMA study areas. This site also had the lowest percent burn overall, $\sim 75\%$, as compared to 93% for ZAL and 82% for REMA.

Zaleski

The most intense fire was recorded on the ZAL B unit, with maximum and average probe temperatures of 397°C and 171°C respectively. On this unit, 68% of the sensors recorded maximum temperatures of at least 150°C , the highest of all units (Table 2; Fig. 5). Average duration of elevated temperatures was ~ 9.5 min on the B unit but, in one case, elevated temperatures were recorded for more than 1 h. The average heat index for the B unit was 10 069. Finally, the average rate of spread for this unit was 11.3 m/min, the highest of all units. In contrast on the TB unit, all indicators of fire intensity were lower relative to the B unit; maximum temperature and rate of spread significantly so (Table 2). Only 40% of the sensors recorded maximum temperatures of at least 150°C ; the maximum and average probe temperatures were 324°C and 140°C respectively, the average duration of elevated temperatures was 8.9 min, the average heat index was 9633 (lowest of all ZAL and REMA units; Table 2), and average rate of spread was 8.7 m/min.

Spatially, the most intense fire, based on rate of spread and maximum temperature, was located in the interior regions of both units where the fire spread away from the firelines (Fig. 5a). The south-facing slope on the TB unit burned relatively intensely, as did the south-west-facing section on the west side and a higher elevation, north-facing nose of the B unit.

REMA

The REMA fires had maximum and average probe temperatures of 356°C and 144°C for the TB unit and 354°C and 155°C for the B unit. Of these logger-probes, 38–42%

Table 2. Summary of fire behaviour data at grid points of three study areasTreatments: B = Burn only, TB = thin and burn. Standard deviations are also given. TB and B treatments within study areas differed significantly if marked with * ($P < 0.05$) or ** ($P < 0.01$)

Study area	Treatment	Probes (<i>n</i>)	Tags (<i>n</i>)	Paint max. temp. (°C)		Probe max. temp. (°C)		Heat index ^A		Heat duration (s)		Sensors > 150°C		Spread (m/min ⁻¹)
				Abs. max.	Ave. max.	Abs. max.	Ave. max.	Abs. max.	Ave. max.	Abs. max.	Ave. max.	<i>n</i>	%	
REMA	TB	55	66	427	105.4 ± 94.5	356	144 ± 85	49880	11433 ± 9349	1007	561 ± 246**	21	38.1	6.7 ± 4.0
REMA	B	65	65	427	128.9 ± 83.4	354	155 ± 71	42491	12201 ± 6984	1918	971 ± 402**	27	41.5	6.2 ± 5.0
ZAL	TB	64	67	427	114.9 ± 96.3*	324	140 ± 75**	45696	9633 ± 7750	2956	532 ± 450	23	40.0	8.7 ± 5.5*
ZAL	B	60	62	316	141.4 ± 61.8*	397	171 ± 60**	44029	10069 ± 6297	4472	568 ± 546	41	68.3	11.3 ± 5.0*
Both	TB	119	133	427	110.2 ± 95.2*	356	141 ± 79*	49880	10408 ± 8551	2956	597 ± 371*	44	37.0	7.8 ± 4.9
Both	B	125	127	427	135.2 ± 72.6*	397	163 ± 67*	44029	11197 ± 6729	4472	779 ± 515*	68	54.4	8.6 ± 5.6
Total/ average		244	260	427	117.7	381	152	45524	10809	2588	691	28	46.0	8.2
TAR ^B	TB	16	72	427	110.0 ± 99.9	226	116 ± 51	22138	6467 ± 5671	1214	409 ± 265	5	29.4	n/a
TAR	B	15	48	316	92.5 ± 66.8	293	129 ± 71	15364	5899 ± 3853	796	359 ± 197	4	22.2	n/a

^AIndex = temperature over 30°C summed over duration (integral under curve).^BBecause TAR had few successful sensors, it was not included in the statistical analysis for treatment effects or totals.

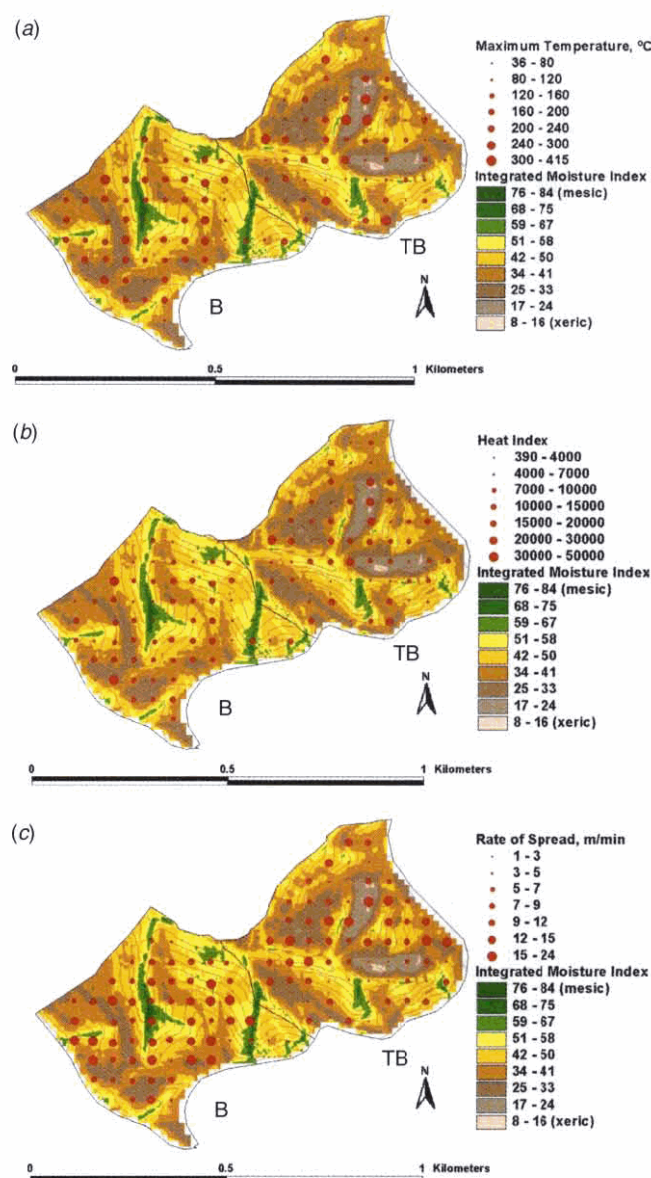


Fig. 5. Maximum fire temperatures (a), heat index (b) and estimated rate of spread (c) recorded at ZAL. The Integrated Moisture Index is mapped in the background, which shows long-term soil moisture regimes based on topographic and soil characteristics (see text).

recorded temperatures of at least 150°C (Table 2). The duration of the elevated temperatures lasted 9.4 min on the TB unit and more than 16 min on the B unit. These statistically longer durations at REMA also caused the average heat index to be higher at REMA than at ZAL, ranging from 11 433 on the TB unit to 12 201 on the B unit (Table 2; Fig. 6). The longer durations of elevated temperatures and consequent higher heat indexes at REMA can be attributed mostly to the additional day of drying time over ZAL, as well as the warmer and drier conditions during the burns (Table 1). Within REMA, the B unit had relatively higher elevation (thus exposure) and lower water-holding capacity of soils as compared to the TB unit.

The rate of spread of the fire was about equal for the two units at REMA (6.2–6.7 m/min) (Table 2; Fig. 6).

Spatially, the TB unit had more intense fire on the south- and west-facing slopes at mid-positions. The fire intensified as it moved from the ignition lines. On the north-facing slope this unit burned at a much lower intensity, due to moist soils and a different overstory tree species composition. On the north-facing slope, the relative basal area of oak and maple/yellow-poplar were 57% and 21% respectively (D. Yaussy, unpublished data). By contrast, oak was more dominant on the SW-facing slope; here the relative basal area for oak and maple/yellow-poplar were 74% and 13%, respectively. This predominance of oak likely created fuelbeds that were dominated by slowly decomposing and more flammable oak litter on the south-west-facing slope. The B unit had its hottest intensity at the mid-positions on south- and south-east-facing slopes (Fig. 6).

General fire characteristics

Effect of thinning on temperatures

The TB units had cooler recorded probe temperatures (an average of 22°C cooler), for both areas, than the B units ($P < 0.05$, $n = 260$; Table 2). On average, the percentage of area burned was also lower on TB (75%) v. B (92%) units across all sites ($P < 0.01$). This pattern can be attributed to three factors. First, there is a significantly higher score of the Integrated Moisture Index (IMI) (Iverson *et al.* 1997) on the TB units ($P < 0.05$) as compared to B units (see also IMI background on Figs 5–6). The IMI is an index based on topographic shading, flow accumulation of water downslope, curvature and soil water-holding capacity, and has been related to fertility, productivity and species composition spatially (Iverson *et al.* 1996, 1997). Second, the extra slash resulting from the thinning had not dried sufficiently to increase fire intensity on the study areas, and at times downed debris inhibited the movement of flames across the units. Third, the skid roads and other logging activity also disrupted the fuel layer, and thus fire movement, in some portions of the TB units. From a management standpoint, these last two points indicate that, in order to achieve the desired greater fire intensity, there should be a time lag of several years after thinning before the prescribed fire is implemented.

Relationship to fire intensity

Even though we measured probe temperatures as detected by the relatively thick thermocouples (e.g. relatively slow temperature response times), early work by Bova and Dickinson (2003) suggests a positive relationship between these probe data and Byram's Intensity, defined as the product of available fuel energy and the fire's rate of advance (Byram 1959; Alexander 1982). If this relationship can be proven and verified across studies, it provides a valuable tool to use

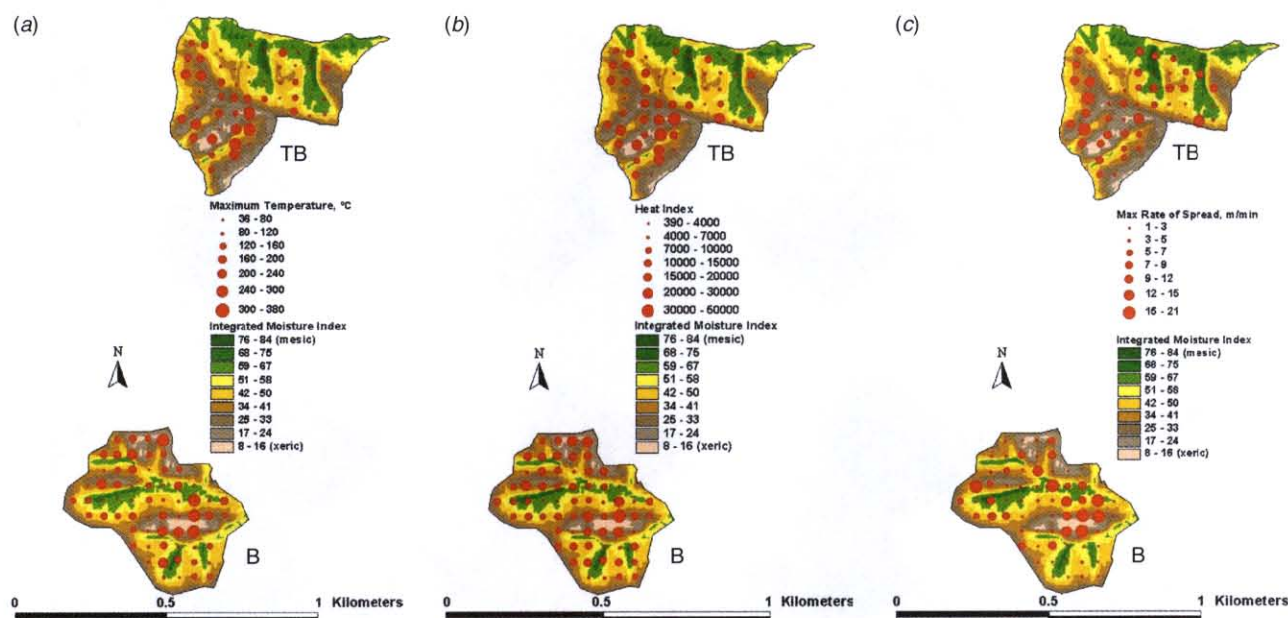


Fig. 6. Maximum fire temperatures (a), heat index (b) and estimated rate of spread (c) recorded at REMA. The Integrated Moisture Index is mapped in the background which shows long-term soil moisture regimes based on topographic and soil characteristics (see text).

thermocouple data to remotely capture a more quantitative indicator of fire intensity.

Meanwhile, it is useful to compare the temperatures recorded here to those reported in other studies (as ascertained by paints). Because the melting temperature of the paints is standard (though the method of applying them in the field may not be), and because the maximum temperatures recorded by thermocouples and paints are highly correlated, we can make these rough comparisons. Mean temperatures in our study (140–155°C) were similar to those recorded by Franklin *et al.* (1997) in Kentucky oak forests (150°C). Cole *et al.* (1992) documented higher temperatures in Indiana oak forests, with means ranging from 150 to 225°C.

Rate of spread

The mean rates of spread estimated in our study (6.2–11.3 m/min) were higher than the 1.5–6.0 m/min estimated previously in prescribed fires in oak-dominated forests (Reich *et al.* 1990; Franklin *et al.* 1997; Barnes and Van Lear 1998; Brose and Van Lear 1998). As mentioned earlier, our estimates are very rough because of the large spacing between sensors in a highly dissected terrain and because the fire front may have crossed sensors in a nearly parallel line. The requirement that there had to be at least 2 min for fire to travel between points helped eliminate the probable false responses due to methodology, but we cannot be sure that our estimates are higher than other studies because of this methodological reason. However, another contributing factor may be that we were able to estimate rates of spread in the interior of the burn units, where rates of spread can accelerate with distance from the boundaries or points of ignition (Figs 5–7). In many

studies, rates of spread have only been monitored safely by observing fires near unit boundaries. In several Missouri oak savannas, rate-of-spread clocks recorded mean rates of spread in unit interiors ranging from 2 to 8 m/min (Grabner *et al.* 2001). The logger-probes demonstrated here can be used on a smaller scale and with more controlled ignition to obtain more accurate estimates of rate of spread. This was done in West Virginia in spring 2002, using similar equipment, and the estimated average rate of spread was 8.9 m/min (range: 4.6–15.7 m/min) (Tom Schuler, personal communication).

Fire animations

The temporal assessment of the maximum temperatures allowed us to evaluate and visualise some aspects of the fire behaviour, including a web-based simulation of the fire at the ZAL study area: http://www.fs.fed.us/ne/delaware/4153/ffs/zaleski_burn.html and the REMA study area: http://www.fs.fed.us/ne/delaware/4153/ffs/rema_burn.html. The ZAL fire animation is represented by 20 of the 248 slices of the fire temperatures (Fig. 7). The animation shows the fire being set on the north and south lines in parallel, with fire progressing rapidly across interior regions. It took 173 min to burn (ignition to safe finish) the combined B and TB units (41.9 ha) at ZAL, while REMA B took 120 min and REMA TB took 166 min for 19.0 and 21.6 ha respectively. The simulations also show that fires generally were cooler with a slower rate of spread in the valleys, with hotter, faster fires on upland slopes.

The animation of the fires from the logger-probe data provided a dynamic visual representation of the progress of the prescribed fires. Because these animations correlate well with

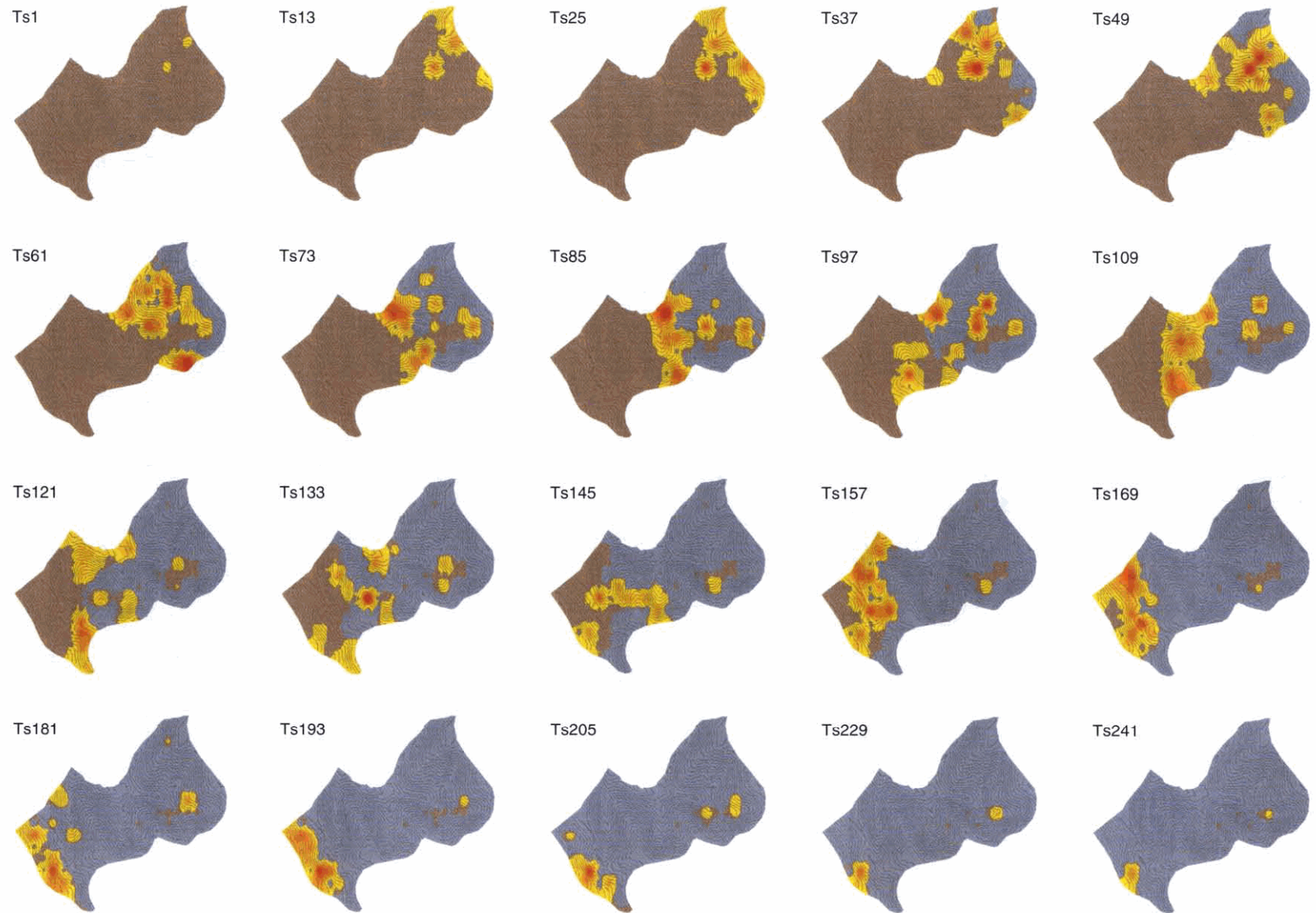


Fig. 7. Fire temperature 'slices', representing fire temperature at 25 cm for ZAL. Each of the 20 slices (out of a total of 248 slices) is separated by 6 min in this spatial representation. Figures are labelled Ts1 to Ts241, representing time slice 1 at 30 s after the first sensor detected elevated temperatures to time slice 241, 2 h later. The brown colour indicates unburned area while grey indicates burned; the remaining warm colours indicate relative temperatures, grading from yellow to red.

observations of fire behaviour by the fire crews, they could be used as a teaching tool for prescribed fire training courses, both to analyse strategies for igniting prescribed fires and the subsequent fire behaviour across a complex landscape.

Conclusions

We have demonstrated that stainless steel thermocouple probes and data recorders provide valuable information on maximum temperature, duration, heat index and rate of spread of prescribed fires in dormant season deciduous leaf-dominated ground fires. Though relatively expensive, the logger-probe units can provide continuous data on probe temperature in soil or air both during and after the fires. As such, the data recorded from these devices provide objective information on fire characteristics, at the landscape scale, which was not easily obtained previously. Though thermocouples have a long history of use in fire research, our study is among the first to use this technology to estimate landscape-scale patterns of fire behaviour/intensity.

Maximum temperature recorded from painted tags was highly correlated with maximum temperature recorded by the logger-probe units. The more common practice of acquiring maximum temperatures using tags painted with temperature-sensitive paint is still much more cost-effective if a crude measurement of maximum temperature is satisfactory. Initial costs are ~2000 times greater for the logger-probe units compared to the painted tags. However, the logger-probes provide additional information that can help understand more features of the fire, as well as enable visualisation of the fire's behaviour. The heat index is a measure that factors in both maximum temperature and the duration of elevated temperatures. Presumably, it may better relate to the biological effects resulting from the fires, but these studies are still under way. Better yet, early indications show that Byram's Intensity can be determined from the thick thermocouples (Bova and Dickinson 2003). This relationship, however, is not fully tested and requires further study and review before it can be verified. Byram's Intensity has been well correlated with depth of tissue necrosis and possible tree mortality (Dickinson and Johnson 2001). Rough estimates of rate of spread were also made possible with the logger-probe units. Better estimates would be possible if the density of probes was higher than one every 50 m. At 50 m spacing, the fires can move at numerous speeds and angles between points, especially on highly dissected terrain as in southern Ohio. Because of the complex terrain, the 'front' of the fires can shift frequently.

The logger-probes also can be used in multiple fires (provided adequate care is taken to buffer the equipment from flames). We lost only a few loggers due to excessive heat. The logger-probes also can be used to record data after the fires to assess the longer-term seasonal trends in soil or air temperatures (Iverson *et al.* 2004). Since the K-probe is rated to measure and record temperatures up to 1250°C, it could

be used in much hotter fires than reported here (maximum absolute temperature was 415°C).

The REMA and ZAL study areas were successfully monitored for several aspects of fire behaviour. Ongoing studies are evaluating the relationship between recorded fire temperatures and topographic, soil, and fuel characteristics, as well as the effects of these fires (and thinning) on several ecosystem characteristics, including forest structure and tree regeneration, understory vegetation, tree health, wildlife populations, soil nutrient dynamics and fuel characteristics. The fire behaviour information is being used to analyse the subsequent spatial patterns of fire effects on ecosystem attributes.

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