LINKING FIRE BEHAVIOR TO EFFECTS: USE OF PYROMETERS AND THERMOCOUPLES

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ABSTRACT

Linking fire behavior and heating to plant responses is needed to generalize fire effects. Temperature recording devices, such as thermocouples and pyrometers, have been deployed in several studies. Use of these relatively unsophisticated devices is likely to continue as spatiotemporally explicit methods for quantifying temperature variability become more accessible. We compared pyrometer and thermocouple device temperatures placed at ground level and 30 cm aboveground to determine pyrometer suitability as a rapid deployment device for capturing variability within and among four burns conducted in a frequently (every 3 years) burned upland oak-hickory (*Quercus-Carya*) forest of the Ozark Mountains, AR. Pyrometer temperatures better reflected thermocouple temperatures for burns with higher fire line intensities and heat per unit area. Placement of pyrometers 30 cm aboveground appeared to be more advantageous in recording fire temperatures in upland oak-hickory forests such as those in this study. However, metal (aluminum tag) pyrometer deployment in prescribed burns with an anticipated very low to low fire behavior may not be suitable.

INTRODUCTION

Despite a plethora of fire effect studies, generalizations of wildland fire effects on fuel and vegetation remain difficult to establish (Butler and Dickinson 2010, Pyne and others 1996). Inconsistencies among study methodologies continue to present challenges in providing a comprehensive understanding of fire effects (Brose and others 2013, Pyne and others 1996). Perhaps the most significant of limitations is our inability to directly link fire behavior and heat transfer to vegetation and fuel responses. Linking of fire behavior and heating patterns to individual plant and species responses at fine spatial scales is needed to generalize results from fire effect studies by addressing the inherent variability in fire behavior within and among studies (Bataineh and others 2022, Brose and others 2013, Butler and Dickinson 2010, Rothermel and Deeming 1980). This linkage is the foundation in first order fire effects models that use a mix of species and fire-related attributes to predict immediate impacts (Lutes and others 2012). Plant mortality, tissue injury, and postfire resprouting and regeneration are all localized, neighborhood-level processes that are influenced by variability in fuel accumulation and consumption along with heat transfer at fine spatial scales.

Operational use of prescribed burning to reduce hazardous fuel loads, restore disturbance regime and woodland structures, and promote oak reproduction requires a better understanding of fire effects at relevant scales, if meaningful burning guidelines are to be developed. Traditionally, fire behavior is described using standardized metrics estimated or measured at the flaming front, such as rate of spread and flame length (Byram 1959, Rothermel and Deeming 1980). Fireline intensity, which cannot be directly measured, is defined as energy release rate from a linear section of the fire front and is estimated by multiplying rate of spread by heat yield and

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available and consumed fuel (Byram 1959). Flame length, distance between average flame tip and base at midpoint of the active flaming front, correlates with fireline intensity and may be used in its estimation (Alexander and Cruz 2012, Rothermel and Deeming 1980). Although fireline intensity, rate of spread, and flame length are useful metrics, their operational use in reporting fire behavior is limited. Even when these metrics are reported, the values represent limited locations along the active flaming front of a burn unit. These metrics are also only suited for surface fires in uniform, porous fuelbeds and cannot be used to describe crowning or fire behavior in clumped fuelbeds (Rothermel and Deeming 1980).

Fire temperature has been commonly used to provide a linkage between fire behavior and effects, albeit not without limitations (Breuer 1965, Fons 1946, Van Wagner and Methven 1978, Walker and Stocks 1968). Use of temperature to characterize fire behavior has been criticized as a coarse resolution metric requiring fast-reacting sensors that integrate data across the whole energy field of view (Van Wagner and Methven 1978). Fire temperature alone cannot be mechanistically linked to effects, nor is it an adequate descriptor of fire intensity (McGranahan 2020, Smith and others 2016). However, temperature is needed in the calculations of fire's radiative heat flux density and convective heat transfer (Bova and Dickinson 2008). Fire temperature recording devices such as metal or ceramic pyrometers with temperature-sensitive paint, calorimeters, and thermocouples have been deployed or tested in several studies (Bataineh and others 2022, Iverson and others 2004, Kennard and others 2005). Although temperature from these devices reflects device temperature (Bova and Dickinson 2008, Kennard and others 2005), use of these relatively unsophisticated devices is likely to continue in the near future as spatiotemporally explicit methods for quantifying temperature variability, such as thermal imagers, become more accessible and affordable (Dickinson and others 2016). It is also unrealistic to expect abandonment of relatively simple to use, low labor, and low-cost devices when accurate direct measurements or predictions of fire heat flux remain out of reach (Bova and Dickinson 2008, Kremens and others 2010). Furthermore, device temperature correlates highly with the fire's heat flux, reflecting an integration of fire-induced heating magnitude and duration, and allowing for accurate estimation of fuel consumption and flame residence times (Bova and Dickinson 2008, Kennard and others 2005). Pyrometer and thermocouple deployment in prescribed burns is far better than mere qualitative characterization of fires (e.g., season or severity-of-burn comparisons). Thermocouple deployment with data loggers allows for time-temperature integration and consequently the calculation of various fire behavior metrics reflecting the magnitude and duration of heating effects such as residence time above a specific threshold or the arithmetic product of degree times seconds (Bova and Dickinson 2008, Kennard and others 2005, McGranahan 2020). While acknowledging the limitations of fire temperature measuring devices and use of temperature in characterizing fire behavior, here we compare pyrometer and thermocouple device temperatures to determine the suitability of pyrometers as rapid deployment devices for capturing variability within and among four prescribed burns conducted in a frequently burned (every 3 years) upland oak-hickory forest of the Ozark Mountains, AR. Temperature devices were compared for ground level and 30 cm aboveground placement of pyrometers and thermocouples.

MATERIALS AND METHODS

Study Area

The study was located within the University of Arkansas Savoy Experimental Forest in Washington County, AR (Bataineh and others 2022). Located within the Ozark Highlands ecoregion, the area is an upland oak-hickory forest with a gently rolling topography. Elevation range is 300–400 m above sea level. Annually, the region receives 117 cm of rainfall and 16 cm of snowfall. Annual frost-free period is 180–194 days. Mean annual temperature is 14 °C; mean minimum and mean maximum temperatures are 8 °C and 20 °C, respectively. Soils consist mostly of the Clarksville-Nixa-Baxter and Captina-Nixa-Pickwick associations which are well-drained, level to gently sloping soils formed mainly under hardwoods (Harper and others 1969). Predominant soil series of the area are the Nixa (loamy-skeletal, siliceous, active, mesic Glossic Fragiudults) with 3 to 8 percent slopes and the less prevalent Clarksville (loamy-skeletal, siliceous, semiactive, mesic Typic Paleudults) with 12 to 60 percent slopes (Harper and others 1969). The area of 142 ha was high graded in 1996–1998 removing all merchantable trees >31 cm in diameter at breast height (Bataineh and others 2022). The preharvest stand originated following exploitative cuts in the early 1900s. Postharvest residual overstory ranged from 324 to 348 trees per ha and was composed of low commercial quality white (*Quercus alba*), black *(Q. velutina*), and post (*Q. stellata*) oaks as well as blackgum (*Nyssa sylvatica*), hickory (*Carya* spp.), and low proportions of other red oaks and red maple (*Acer rubrum*). Stand-level basal area was around 14 m^2ha^{-1} with a quadratic mean diameter of 23.4 cm, representing understocked conditions, below the B-line, based on Gingrich's stocking charts for upland hardwoods (Gingrich 1967). Site index was around 18 m for white oak using a base age of 50 years. Advance reproduction of red maple, blackgum, black cherry (*Prunus serotina*), and flowering dogwood (*Cornus florida*) represented 50–60 percent of total number of stems, whereas oaks represented roughly 25 percent (Bataineh and Pelkki 2018).

Study Design and Measurements

As part of a long-term study initiated in 2004, this study used repeated burning applications to compare device temperatures. The long-term study aimed to evaluate prescribed burning, herbicide application, and combinations of burning and herbicide for improving the composition and structure of high-graded oak-hickory stands (Bataineh and Pelkki 2018, Morris 2007). With initial burning occurring in 2005, repeat burns were conducted in 2008, 2011–2012, 2014–2015, and 2017. Repeat burns scheduled as part of the long-term study in 2017, and four treatment units, each 0.8 ha, were used in this study.

Within each burn unit, 10 to 15 wildland fuel cells (each 9.3 m^2) with uniform fuel abundance and distribution were established (Hiers and others 2009). Fuel cells were selected randomly from a sampling frame of 720 grid cells systematically dividing each burn unit, excluding a 5-m buffer around each unit. Over a 3-day period in April 2017, burns were conducted within each unit. Ignition pattern for all but one unit was circular (ring) ignition (burn units 6, 13, and 17) without spot fires in the center of the unit. Due to higher wind speeds and air temperature, burn unit 19 ignition pattern was strip heading with an average strip width of 20–25 m. Fire behavior parameters were recorded during each burn, and weather conditions were recorded prior to and during burning (table 1). Air temperature, relative humidity, eye-level wind speed, and wind direction from origin were recorded using a handheld Kestrel® 3000 weather meter. Ranging wooden poles coated with fire resistant paint with alternate gradations at 30 cm intervals were used as sighting reference within each burn unit. Poles were spaced in a 10- by 10-m grid across each burn unit. Timing of flame front passage from one pole to another was recorded and rate of spread calculated. Flame height and average flame angle were estimated using ranging pole gradations as reference. Flame length was calculated from flame height and average angle. Heading, backing, and flanking fires flame length and rate of spread were estimated separately, and recorded in the field as an average across each burn unit. Fireline intensity was calculated from flame length estimates for each burn unit (Byram 1959, Rothermel and Deeming 1980). Heat per unit area was calculated from fireline intensity and rate of spread estimates (Byram 1959, Rothermel and Deeming 1980).

As part of an accompanying study examining first-order fire effects on oak and maple reproduction (Bataineh and others 2022), two relatively thick (4.8 mm diameter) HOBO® (HOBO®, Bourne, MA) type-K thermocouple probes and two pyrometers, Tempilaq® (Tempilaq®, Holdahl, Minneapolis, MN) painted aluminum tags, were used within each wildland fuel cell. Thermocouple probes and pyrometers were placed in proximity prior to ignition at ground level and 30 cm aboveground. Ground-level probes were placed horizontally directly under the litter layer. Aboveground probes were placed vertically, perpendicular to ground surface. Thermocouple data loggers were buried outside each fuel cell to reduce disturbance and

Table 1—Weather, mean fuel moisture, mean soil moisture, and fire behavior characteristics for four dormant season prescribed burns conducted as part of a frequent burning regime at 3-year intervals in upland oak-hickory forests of the Arkansas Ozarks

	Burn unit			
Variable	6	13	17	19
Burn date (M/D/Y)	4/7/2017	4/7/2017	4/8/2017	4/9/2017
Start time (H:M)	12:46	18:40	13:53	14:21
Days since last rain	4	5	6	6
Soil moisture (percent)	21 (4)	19 (2)	18 (2)	19 (2)
Litter moisture (percent)	46 (14)	17 (14)	9 (9)	24 (13)
Duff moisture (percent)	71 (18)	36 (20)	37 (31)	33 (14)
Air temperature (°C)	20	21	28	27
Relative humidity (percent)	30	37	36	50
Wind speed (kph)	2.1	1.9	1.6	5.6
Wind direction from origin	E	NW	SE	SW
Flame lengths (m)	0.6	0.3	0.9	1.0
Rate of spread (m/min)	1.2	0.6	2.4	1.8
Fireline intensity (kW/m)	88	20	217	252
Heat per unit area (kJ/m^2)	4,402	1,956	5,430	8,414

Soil, litter, and duff moisture are means followed by standard deviation in parentheses. Relative humidity was measured around time of ignition.
Source: Bataineh and others (2022).

were set to record at 1-second intervals starting 30 to 60 minutes before ignition. Pyrometers had 22 strips of temperature-indicating paint ranging from 79 °C to 427 °C, in increments of 14 °C for 79 °C to 316 °C and 28 °C increments for 343 °C to 427 °C. Pre and postburn fuel loadings were estimated using two transects (4.3 m each) following the procedure outlined in Brown (1974). Fuel loading transects intersected at the center of each fuel cell. Dead and downed woody debris was tallied in four timelag-size classes, namely: woody 1-hour (0.1–0.6 cm diameter at intersection), 10-hour (0.6–2.5 cm), 100-hour (2.5–7.6 cm), and 1,000-hour (>7.6 cm). Woody 1-hour and 10-hour classes were tallied along the first 0.9 m of each transect, whereas the 100-hour class was tallied along the first 1.8 m of each transect. Larger fuel sources in the 1,000-hour class were tallied along the entire length of each transect and were classified as sound or rotten. Litter (including freshly fallen leaves, dead herbs, dead shrubs, and acorns) and duff (organic soil horizons including fermentation and humus layers) were collected separately from 30 cm^2 quadrats, placed near but outside each wildland fuel cell and reflected fuel conditions of these cells. Litter and duff samples were weighed fresh before burning, oven dried to a constant weight at 60 °C for 3 days, and reweighed dry to estimate fuel moisture.

Analytical Approach

To compare device temperatures between pyrometers and thermocouples, peak or instantaneous maximum temperature from thermocouples was correlated to maximum temperature reached for pyrometers as indicated by the melting of paint strips. Simple linear regression was also used to attain proportion of variability in thermocouple temperature that is explained by pyrometers. Fuel consumption was calculated by subtracting post from preburn fuel loads for each fuel cell. Fuel loads for downed wood were calculated using the formulas presented in Brown (1974). Downed wood, litter, and duff loads were converted to unit area estimates. Subsequently, fuel consumption was calculated for the four downed wood timelag-size classes, litter, and duff. Fuel consumption estimates by component were correlated to temperatures of each thermocouple and pyrometer. Preburn litter and duff moisture content estimates were calculated as the difference between fresh and dry weight in proportion to oven dry weight. All analyses were performed using the R base package version 3.0.2 (R Development Core Team 2013).

RESULTS AND DISCUSSION

Four burns were conducted in April 2017 that varied in fireline intensities, flame length, and rate of spread (table 1). Burns for units 17 and 19 had higher fireline intensities and heat per unit area compared to fires in units 6 and 13. Rates of spread and flame lengths were also higher for units 17 and 19 compared to 6 and 13. Fire behavior ranged from very low to low for units 6 and 13 and low-moderate for units 17 and 19 based on flame lengths and rate of spread (Scott and Burgan 2005). Variation in fire behavior was a reflection of differences in weather and fuel moisture conditions among the four burns (table 1), rather than fuel loads (Bataineh and others 2022). Unit 17 burn was conducted during a period of relatively higher air temperature, lower relative humidity, lower southerly wind speeds, and lower litter moisture relative to the remaining burns. Compared to unit 17, similar air temperatures but higher southerly wind speeds, higher relative humidity, and higher litter moisture content resulted in lower rate of spread but higher fireline intensity, heat per unit area, and flame length for unit 19. Ignition pattern in unit 19 with strip heading fire of 20–25 m in width had a substantial impact on fire behavior that modulated rate of spread. Duff and litter moisture contents were highest for unit 6, which had the second lowest fireline intensity and flame length, with moisture levels at 71 ± 18 (standard deviation) and 46 ± 14 percent, respectively (table 1). Moisture content for duff and litter was obtained from samples collected before burning and was likely higher than that at ignition time, early afternoon for unit 6.

Device temperature correlation depended on burn characteristics and device placement at ground level or 30 cm aboveground (figs. 1 and 2). For 30 cm aboveground placement, burns with higher fireline intensities and heat per unit area (units 17 and 19) had high and statistically significant correlation coefficients compared to those with lower fireline intensities and heat per unit area (fig. 1). Regardless of burn, pyrometers at 30 cm aboveground explained 54 percent of the variability (P <0.01) in thermocouple instantaneous maximum temperature similar to results elsewhere (Kennard and others 2005). Poor performance of temperature-indicating paint (Kennard and others 2005) was also noted in this study. Low fireline intensity burns (units 6 and 13) had fewer pyrometers with melted paints that could be reliably recorded. Poor melting required that at least two observers score each pyrometer (Wally and others 2006), with only distinct melting recorded. For ground-level placement, device temperature correlation coefficients were low and statistically nonsignificant, showing greater discord between thermocouple instantaneous maximum temperature and maximum temperature reached for pyrometers (fig. 2). Regardless of burn, no significant linear relationship was found between thermocouples and pyrometers at ground level (P = 0.87). Placement of pyrometers 30 cm aboveground appears to be more advantageous in recording fire temperatures in upland oak-hickory forest of this study and elsewhere (Kennard and others 2005). Metal (aluminum tag) pyrometer deployment in prescribed burns with an anticipated very low to low fire behavior (Scott and Burgan 2005) may not be suitable for recording fire temperature and fire characterization, however.

Device temperatures did not correlate strongly with fuel components consumption (table 2). The general lack of linear relationships between device maximum temperatures and fuel consumption highlights the limitation of using temperature as a descriptor of fire intensity (McGranahan 2020, Smith and others 2016) and indicates that estimates of fuel consumption based on device maximum temperatures alone may not be adequate. A larger margin of error is expected when thermocouple instantaneous maximum temperature is used, rather than time-temperature integration, to predict fuel consumption (Bova and Dickinson 2008). Fuel consumption for the 1-hour and 10-hour components, however, showed statistically

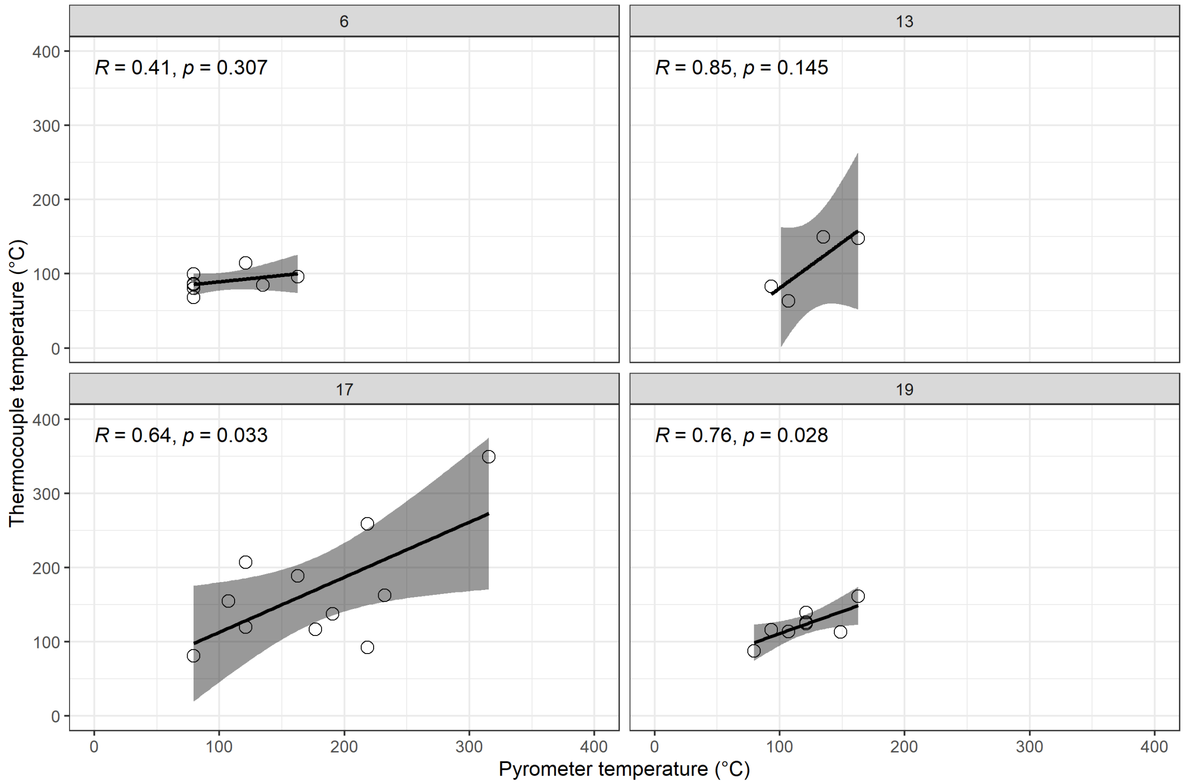

Figure 1—Scatter plots, with Pearson correlation coefficients and *P*-values, depicting the relationship between device temperatures, thermocouples and metal pyrometers, placed 30 cm aboveground for each of four burns conducted as part of a frequent burning regime (every 3 years) in upland oak-hickory forest of the Ozark Mountains, AR.

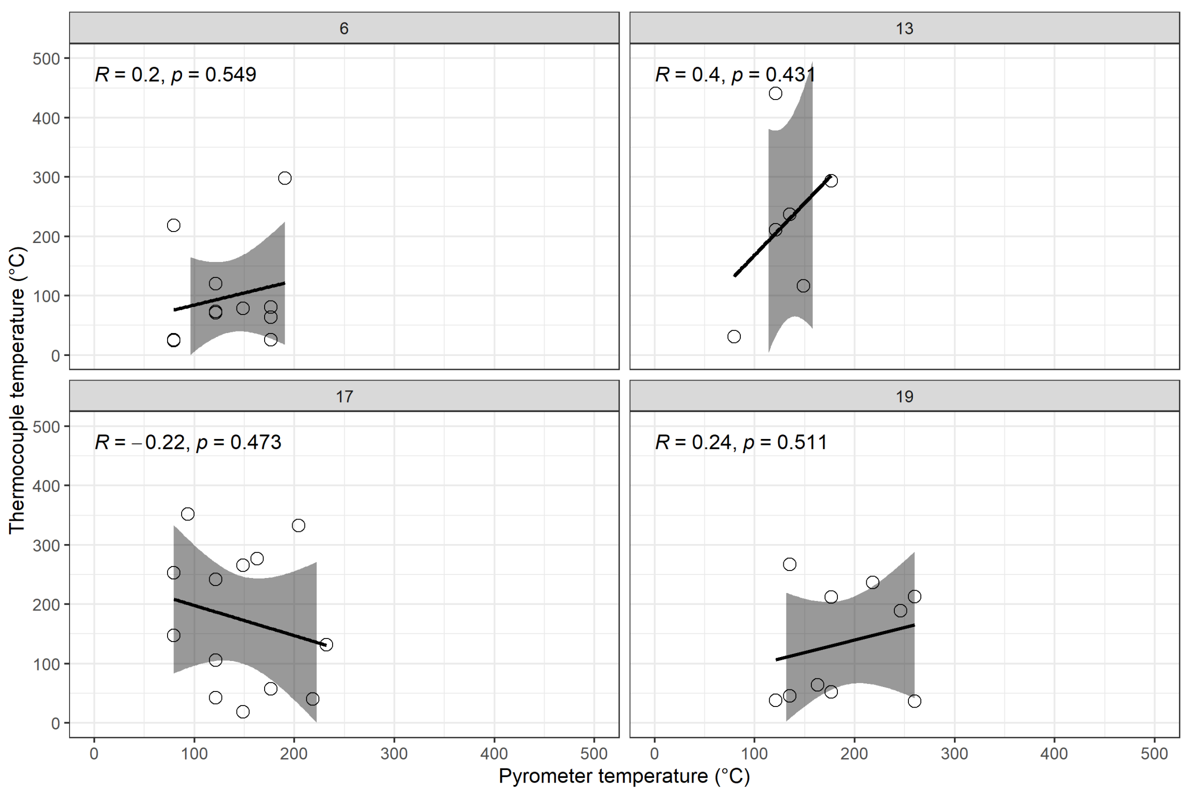

Figure 2—Scatter plots, with Pearson correlation coefficients and *P*-values, depicting the relationship between device temperatures, thermocouples and metal pyrometers, placed at ground level for each of four burns conducted as part of a frequent burning regime (every 3 years) in upland oak-hickory forest of the Ozark Mountains, AR.

Table 2—Pearson correlation coefficients (*P*-values in parenthesis) for temperatures recorded by pyrometers and thermocouples in relation to fuel components consumption during four prescribed burns conducted in a frequently (every 3 years) burned upland oak-hickory forest of the Ozark Mountains, AR

Temperature	Distance from ground	Burn unit	Litter	Duff	1-hour fuel	10-hour fuel	100-hour fuel
Thermocouple (°C)	30 cm aboveground	6	0.19 (0.51)	-0.24 (0.42)	0.05 (0.88)	-0.03 (0.92)	-0.11 (0.67)
		13	0.27 (0.34)	-0.14 (0.63)	0.04 (0.89)	-0.10 (0.74)	-0.32 (0.23)
		17	0.24 (0.42)	0.29 (0.31)	-0.10 (0.72)	-0.15 (0.62)	-0.06 (0.83)
		19	-0.12 (0.75)	-0.10 (0.79)	-0.45 (0.19)	***-0.83 (<0.01)***	-0.19 (0.61)
	At ground level	6	0.02 (0.95)	0.10 (0.73)	-0.09 (0.76)	-0.37 (0.19)	-0.06 (0.84)
		13	0.17 (0.56)	0.09 (0.78)	-0.30 (0.30)	-0.25 (0.39)	0.29 (0.32)
		17	-0.12 (0.67)	0.39 (0.15)	-0.21 (0.45)	0.16 (0.57)	-0.15 (0.59)
		19	-0.49 (0.15)	0.01 (0.99)	-0.38 (0.28)	-0.30 (0.40)	0.29 (0.42)
Pyrometer (°C)	30 cm aboveground	6	-0.06 (0.90)	-0.45 (0.26)	-0.19 (0.65)	-0.45 (0.27)	-0.30 (0.48)
		13	0.64 (0.36)	-0.71 (0.29)	***0.98 (0.02)***	0.23 (0.78)	-0.38 (0.62)
		17	-0.15 (0.66)	-0.19 (0.57)	-0.41 (0.21)	***-0.67 (0.02)***	-0.23 (0.49)
		19	0.25 (0.56)	0.51 (0.20)	-0.56 (0.15)	***-0.86 (<0.01)***	0.03 (0.95)
	At ground level	6	0.25 (0.46)	0.10 (0.77)	0.36 (0.28)	***-0.71 (0.02)***	0.24 (0.48)
		13	-0.21 (0.70)	-0.30 (0.57)	0.36 (0.48)	0.26 (0.62)	0.78 (0.07)
		17	0.26 (0.39)	0.13 (0.67)	0.34 (0.25)	-0.38 (0.20)	0.15 (0.63)
		19	0.39 (0.26)	-0.06 (0.86)	***-0.79 (<0.01)***	-0.62 (0.06)	-0.54 (0.10)

Statistically significant values are in bold italics.

significant negative relationships with device temperatures associated with burns of low-moderate fire behavior, namely units 17 and 19 (Scott and Burgan 2005).

CONCLUSIONS

Fire temperatures from thermocouples and pyrometers placed at ground level and 30 cm aboveground were compared to determine the suitability of pyrometers in characterizing fires, and thus providing an empirical linkage between fire behavior and effects. Metal (aluminum tag) pyrometers placed 30 cm aboveground correlated better and explained about half of the variability in thermocouple instantaneous maximum temperature compared to placement of pyrometers at ground level. Pyrometer temperatures better reflected thermocouple temperatures for burns with higher fireline intensities and heat per unit area, which may have reflected better performance of paint at higher temperatures or easier scoring of pyrometers by observers. Placement of pyrometers 30 cm aboveground appears to be more advantageous in recording fire temperatures in upland oak-hickory forests like those in this study. However, using metal (aluminum tag) pyrometers in prescribed burns with an anticipated very low to low fire behavior may not be suitable.

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