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Thermocouple Probe Orientation Affects Prescribed Fire Behavior Estimation

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Abstract

Understanding the relationship between fire intensity and fuel mass is essential information for scientists and forest managers seeking to manage forests using prescribed fires. Peak burning temperature, duration of heating, and area under the temperature profile are fire behavior metrics obtained from thermocouple-datalogger assemblies used to characterize prescribed burns. Despite their recurrent usage in prescribed burn studies, there is no simple protocol established to guide the orientation of thermocouple installation. Our results from dormant and growing season burns in coastal longleaf pine (*Pinus palustris* Mill.) forests in South Carolina suggest that thermocouples located horizontally at the litter-soil interface record significantly higher estimates of peak burning temperature, duration of heating, and area under the temperature profile than thermocouples extending 28 cm vertically above the litter-soil interface ($p < 0.01$). Surprisingly, vertical and horizontal estimates of these measures did not show strong correlation with one another ($r^2 \leq 0.14$). The horizontal duration of heating values were greater in growing season burns than in dormant season burns ($p < 0.01$), but the vertical values did not indicate this difference ($p = 0.52$). Field measures of fuel mass and depth before and after fire showed promise as significant predictive variables ($p \leq 0.05$) for the fire behavior metrics. However, all correlation coefficients were less than or equal to $r^2 = 0.41$. Given these findings, we encourage scientists, researchers, and managers to carefully consider thermocouple orientation when investigating fire behavior metrics, as orientation may affect estimates of fire intensity and the distinction of fire treatment effects, particularly in forests with litter-dominated surface fuels.

Core Ideas

- No simple protocol exists for thermocouple probe installation in fire research.
- We installed thermocouple probes horizontally and vertically for comparison.
- Horizontal and vertical thermocouple values differed within the same fires.
- Horizontal and vertical thermocouple values were poorly correlated.
- Determination of fire effects was affected by thermocouple probe orientation.

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PEAK burning temperature (PBT) is a common measure used to describe prescribed fires (Keeley, 2009; Wotton et al., 2012). Many methods and techniques have been developed and tested to measure PBT, including pyrometers and calorimeters (Iverson et al., 2004; Kennard et al., 2005; Wally et al., 2006). Another common method involves the use of thermocouple probes attached to datalogger units. These dataloggers can be programmed to record temperature throughout the duration of a burn. Because they log temperature over an interval of time, some researchers suggest that the total duration of heating (DOH), or the amount of time the datalogger records temperatures above ambient temperature, can be just as useful, if not more useful, as a descriptor of fire behavior (Keeley, 2009; Dayamba et al., 2010). Area under the temperature profile (AUTP) can be calculated with these units as well by multiplying the change in temperature as a result of heating by the DOH (Kennard et al., 2005; Wenk et al., 2011).

Some scientists question the usefulness of the data thermocouples record (Bova and Dickinson, 2008). Peak burning temperature, for example, is questioned because it is largely dependent on the metal used in creating the thermocouple (Kennard et al., 2005). The diameter, length, and orientation of the thermocouple are all important items to consider that may influence thermocouple readings (Dayamba et al., 2010). Thermocouple values have been shown to vary widely as a result of their metallurgical properties (Bailey and Anderson, 1980; Bova and Dickinson, 2008). It is also suggested that PBT is only a loose surrogate to describe fire intensity (Kennard et al., 2005), and thermocouple DOH values may be greatly affected by thermocouple diameter (Bova and Dickinson, 2008). Technological advancements greatly favor hyperspectral methods and other strategies to better estimate heat release, fire intensity, and other estimates of fire behavior that may be related to fire's effects on ecosystems and fire danger ratings (Hudak et al., 2016). Despite these criticisms, the inexpensive cost of thermocouple probes, along with their ability to determine DOH, make them a tool of choice for fire-related research,

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Abbreviations: AUTP, area under the temperature profile; DOH, duration of heating; PBT, peak burning temperature.

particularly in situations where fuel types are similar among treatments of interest (Bova and Dickinson, 2008).

Few studies using thermocouples to estimate these fire behavior metrics have investigated how differences in thermocouple orientation (vertically above the litter-soil interface or horizontally at the litter-soil interface) might affect value estimation. Dayamba et al. (2010) found that differences in orientation existed when burning was conducted at different times during the fire season in a Sudanese savanna-woodland. In early fires (December), PBT and DOH were highest and longest 20 cm above the soil surface, but that result was opposite in midseason (mid-January) and late-season (end of March) fires, as PBT and DOH were highest and longest at the ground surface. In contrast, Franklin et al. (1997) found that PBT was highest at the litter-soil interface, as opposed to some distance aboveground, in upland *Quercus* communities.

Thermocouple orientation became an important item of consideration as we sought to investigate potential differences in fire behavior resulting from alterations in fire frequency and season in coastal longleaf pine (*Pinus palustris* Mill.) forests. We had difficulty determining which orientation might provide the most reliable and useful estimates of PBT, DOH, and AUTP. We decided to install thermocouples in both directions: vertically (extending 28 cm above the litter-soil interface) and horizontally (at the litter-soil interface) to see if thermocouple location and orientation affect fire behavior estimation and which orientation is most related to pre- and post-fire measures of fuel loading.

Our hypotheses were: (i) the parameters obtained from horizontal thermocouples are different than their vertical counterparts, but there should be correlation among the parameters; (ii) pre- and post-fire measures of fuel loading and depth will be significantly correlated with the fire behavior metrics with both orientations ($r^2 > 0.50$).

Materials and Methods

Study Design

This study was conducted at the Tom Yawkey Wildlife Center in Georgetown, SC (33.23° N, 79.22° W). Since 1978, the forest in the preserve has been managed mainly by prescribed fire, and the predominant tree species present on these sites were longleaf pine, loblolly pine (*Pinus taeda* L.), turkey oak (*Quercus laevis* Walter), and sweetgum (*Liquidambar styraciflua* L.). Six units 1 to 2 ha in size were selected for burning in 2015: three to be burned during the dormant season, and three to be burned during the growing season. Each of these areas was previously burned in 2014, 2013, and an additional five to eight times since 2004.

Fuel Sampling

In each burn unit, a 300-m transect was established. Every 25 m, thermocouples were installed (see next section). Every 50 m, a 1-m × 1-m sampling frame was used to destructively sample understory live vegetation mass. Down and dead woody debris mass was determined using Brown's Planar Intercept Method (Brown, 1974) as modified by Stottlemyer (2004). Using this technique, down and dead woody debris 0.00 to 0.64 cm (0–0.25 in.), 0.64 to 2.54 cm (0.25–1 in.), 2.54 to 7.62 cm (1–3 in.), and >7.62 cm (>3 in.) in diameter was tallied as 1-,10-, 100-, and 1000-h timelag size classes, respectively. Timelag refers to how each individual fuel-size class responds to changes in relative humidity (Brown, 1974). The 1000-h fuels were not altered due to burning at these sites and are not reported in the results or discussion.

Litter mass was determined at each plot within our burn units using one 0.30-m × 0.30-m (1-ft. × 1-ft.) destructive sample obtained 1 m opposite of the middle transect azimuth. The sum of understory vegetation mass, fine fuel mass (1-, 10-, and 100-h fuels), and litter mass was tallied as one combined measure for total fuel load (Table 1). Heights of down and dead woody material and litter depth were visually measured using a 0.30-m (1-ft.) ruler at three locations along each Brown's transect (Brown, 1974; Stottlemyer, 2004). Height of elevated down and dead woody debris was measured from the bottom of the litter layer to the highest intersecting woody particle occurring within 0.30-m segments of the sampling plane for each transect. Litter depth was measured from the mineral soil surface to the top of the litter layer. Because of the frequent burning present on these sites, duff was rarely present, but when it was present, it was included in the tally of litter. Post-burn down and dead woody fuels were tallied using Brown's Planar Intercept Method (Brown, 1974). Post-burn detrital mass was determined similarly to the pre-burn detrital mass at each plot using one 0.30-m × 0.30-m destructive sample obtained 2 m opposite of the middle transect azimuth. Detrital samples were collected within 48 h after prescribed fires were implemented. Fuel consumption was calculated as pre-fire fuel mass minus post-fire fuel mass.

Thermocouple Probe Installation

The thermocouple probes employed in this study were insulated, high-temperature, stainless steel, Type-K thermocouples (Onset model TCP6-K12). They determine instantaneous heating temperatures. The probes are 4.8 mm in diameter and 30 cm long. They can measure up to 900°C when connected to an appropriate datalogger (Onset Computer Corporation). There is no published information regarding response time for these thermocouples, but we determined that the mean thermocouple response time when exposed to flames was 9.35 s ($n = 32$). The mean time for these 32 thermocouples to cool after exposure to a flame was calculated as 406.32 s.

Two Type-K thermocouple probes were connected to HOBO dataloggers (Onset Computer Corporation) and were installed at 12 locations ~25 m apart, yielding 24 thermocouples per burning replication. These locations coincided with the tally and sampling of fuels, as described in the previous section, providing an opportunity to evaluate thermocouple-derived metrics in locations with known pre- and post-fire fuel masses and depths. At each location, a hole was dug and the dataloggers were individually placed in bags and buried, leaving the thermocouple probes outside the hole. The HOBO dataloggers were programmed to detect temperature on a 5-s interval before and throughout the duration of burning using HOBO BoxCar Pro 4.3 (Onset Computer Corporation, 2002) as the programming software. We chose this time interval, as opposed to a shorter one, due to the limited storage capacity and battery life of the datalogger, and to account for potential delays in ignition. Once the fires were extinguished, thermocouples and dataloggers were collected and removed from the field. Peak burning temperature was noted and recorded for each unit. Duration of heating was calculated for each individual dataset by determining the ambient temperature before burning and subsequent escalation above

Table 1. Fuel loads, soil moisture contents, fuel moisture contents, and fire weather data associated with annual dormant and annual growing season burns in 2015 at the Tom Yawkey Wildlife Center, Georgetown, SC, USA.

Season	Fire date	Fuel load	Soil moisture (0–10 cm)	Fuel moisture			Fire weather		
				Litter	Down and dead woody	Live fuels	Ambient temperature	Relative humidity	Wind speed
		Mg ha^{-1}	%				°C	%	km h^{-1}
Annual Dormant	9 Mar.	12.2 ± 2.1	24.6	45.8	38.4	181.4	18	74	6.9
	10 Mar.	20.8 ± 1.6	43.5	11.4	18.3	94.3	27	60	4.8
	11 Mar.	21.6 ± 2.5	8.9	35.9	36.5	148.4	26	70	8.2
Annual Growing	5 May	10.1 ± 0.2	9.7	2.6	17.7	72.1	24	55	3.2
	5 May	10.0 ± 0.4	17.6	2.6	3.8	40.3	30	48	5.4
	6 May	19.0 ± 1.4	11.1	4.2	10.1	92.7	28	52	5.3

and return to that ambient temperature. Area under the temperature profile was then calculated as the difference in heating temperature and ambient temperature multiplied by the number of seconds from DOH.

Fire Implementation

Burning took place in the dormant season blocks on 9 to 11 Mar. 2015 and in the growing season blocks on 5 to 6 May 2015. On the day of the burns, down and dead woody debris, soils (0–10 cm), and live understory vegetation were sampled in three locations in each of the burn units to determine the pre-fire moisture content of each parameter. Wet mass (*g*) was obtained in the field using a portable, battery-operated scale. The woody fuels, soils, and live vegetation were then taken back to the laboratory and were oven dried at 70°C for no less than 48 h. Moisture content of fuel was equal to [(wet mass – dry mass)/dry mass] × 100%. Relative humidity and wind speed were measured before and during the burns using a Kestrel 3000 Pocket Wind Meter (KestrelMeter) (Table 1). These burns were headfires, and flame lengths in all fires averaged 0.3 to 1 m (personal observation).

Statistical Analyses

Matched pair *t* tests were used to determine differences in mean PBT, DOH, and AUTP due to thermocouple orientation. Simple linear regression analysis was used to determine relationships among the thermocouple orientations. Differences in mean PBT, DOH, and AUTP as a result of burning season were additionally determined using *t* tests. Correlations among the fuel measurements and the fire behavior metrics were evaluated using simple linear regression. Results shown in the text below

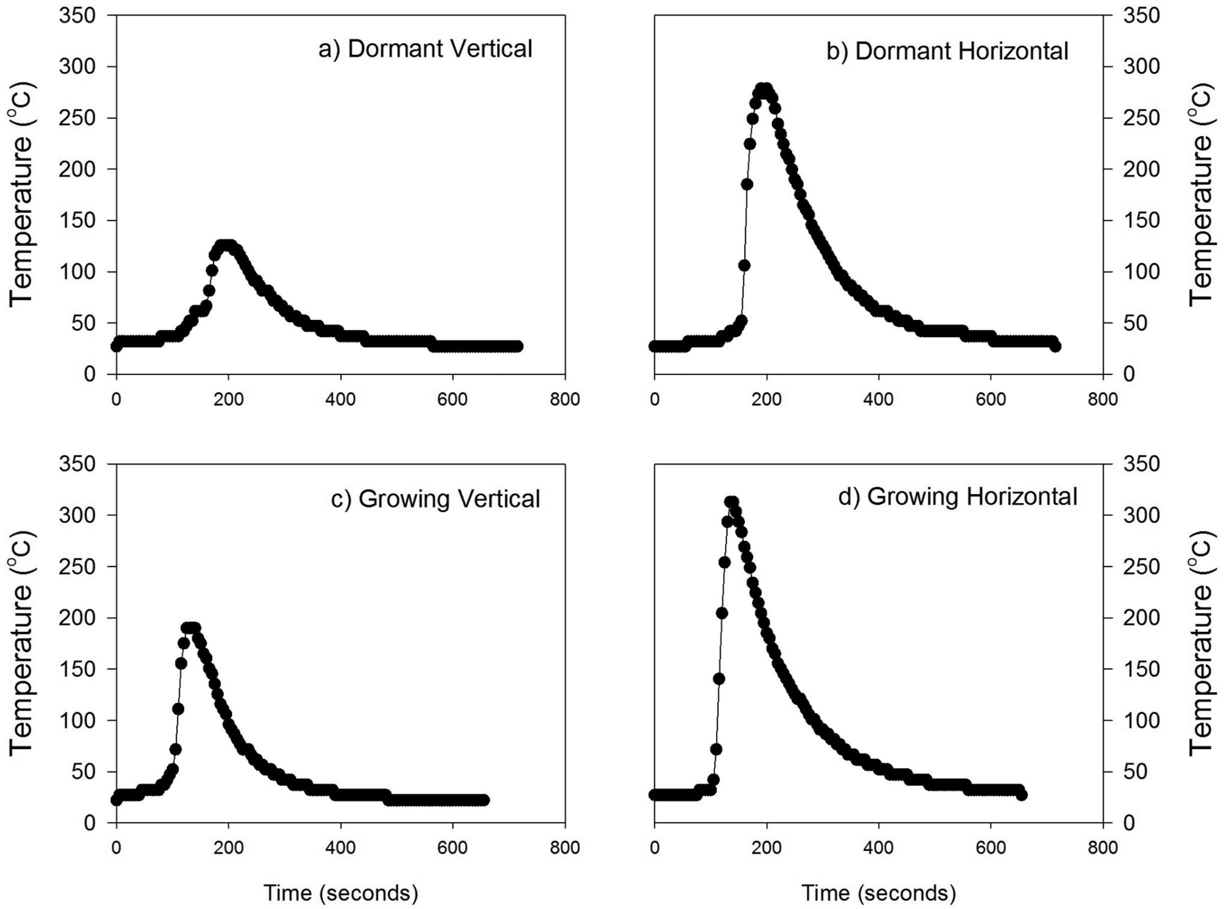

Fig. 1. Individual examples of thermocouple output and temperature data recorded every 5 s during prescribed burns in the (a, b) dormant and (c, d) growing seasons using (a, c) vertical and (b, d) horizontal thermocouples at the Tom Yawkey Wildlife Center in Georgetown, SC.

are based on original scale variables, *t* tests, and simple linear regression (as no complex regression models improved our correlations). All statistical calculations were conducted using JMP 12 (SAS Institute, 2015).

Results

Thermocouple Probe Orientation

A typical time-temperature heating curve generated from the thermocouple-datalogger assemblies at each of the burning locations is shown in Fig. 1. Visually, it appears that the horizontal thermocouples heated to a higher temperature more quickly and remained above ambient temperature for a longer period of time. Statistically, this was confirmed using data obtained from all of the thermocouple-datalogger assemblies, as shown in Fig. 2. Values for PBT, DOH, and AUTP were all significantly greater using the horizontal thermocouples ($p < 0.01$) (Supplemental Table S1). Using simple linear regression analysis, we observed that vertical values of PBT and AUTP displayed significance with their horizontal counterparts, as indicated by $p = 0.00$. The DOH p-value = 0.26. Despite the significant p-values for PBT and AUTP, the r^2 value for these correlations indicated little significance of a predictive relationship between the two orientations (PBT $r^2 \leq 0.13$, DOH $r^2 = 0.03$, AUTP $r^2 \leq 0.14$).

Burning Season

Figure 2 additionally displays the ranges and means of PBT, DOH, and AUTP as a result of burning season. These data are provided in Supplemental Table S2. Peak burning temperature did not differ significantly as a result of burning season with either the horizontal or vertical thermocouples ($p = 0.97$ horizontal, $p = 0.32$ vertical). Horizontal DOH was estimated to be significantly greater in the growing season burns than in the dormant season burns ($p < 0.01$), but vertical DOH did not differ between the growing and dormant season burns ($p = 0.52$). The AUTP was significantly greater in the growing season both vertically and horizontally ($p \leq 0.03$ for all values).

Relationship to Other Field Measurements

Figure 3 shows examples of PBT, DOH, AUTP, pre-fire fuel (1–10–100 h fuels + litter) mass (Mg ha^{-1}), pre-fire fuel depth (cm), and post-fire detrital mass (Mg ha^{-1}) from one of our burn areas along one 300-m transect. Using simple linear regression analysis, we observed that some of the fire behavior metrics displayed a significant relationship with some of the fuel variables (Table 2). However, the r^2 values for all of the linear regression models assessed were ≤ 0.29, with the exception of horizontal PBT and pre-fire total fuel mass ($r^2 = 0.41$). The low r^2 values suggest poor correlation due to the heterogeneity these variables displayed in the field.

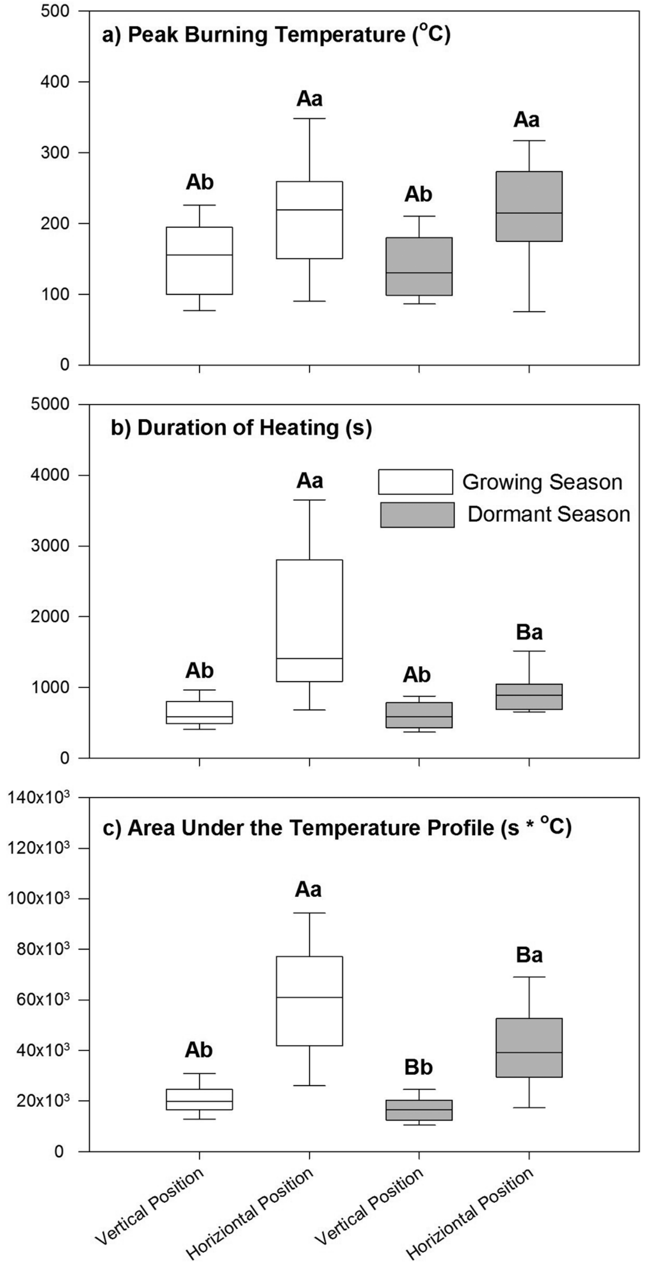

Fig. 2. Ranges and means for (a) peak burning temperature, (b) duration of heating, and (c) area under the temperature profile. Large letters indicate differences due to burning season; small letters indicate differences due to thermocouple orientation.

Discussion

Thermocouple Orientation Affects Value Estimates of Fire Behavior Metrics

We found that horizontal estimates of our fire behavior metrics were significantly greater than their vertical counterparts. Few studies have investigated these metrics as they fluctuate with height above the litter-soil interface within the same burn. The results from these studies are not uniform and seem to vary with both fuel type and structure. Using pyrometers, Gibson et al. (1990) found that PBT in areas burned every 5 yr yielded higher temperatures at the ground surface than some degree above the ground surface in the Florida sandhills, but differences in PBT as a result of measurement location were not present in annually burned forests and forests that were burned every 3 yr. In contrast, Kennard et al. (2005) found that PBT was less at the litter-soil interface than at 30 cm above the litter-soil interface in a longleaf pine ecosystem containing a significant shrub and grass understory. In a study of grassland fires in Canada, Bailey and Anderson (1980) found that PBT was highest some distance aboveground, as opposed to at ground level.

Our differences are particularly noteworthy given the frequency of fire used at our study site. The blocks included in this portion of our study were previously burned in 2014, 2013, and

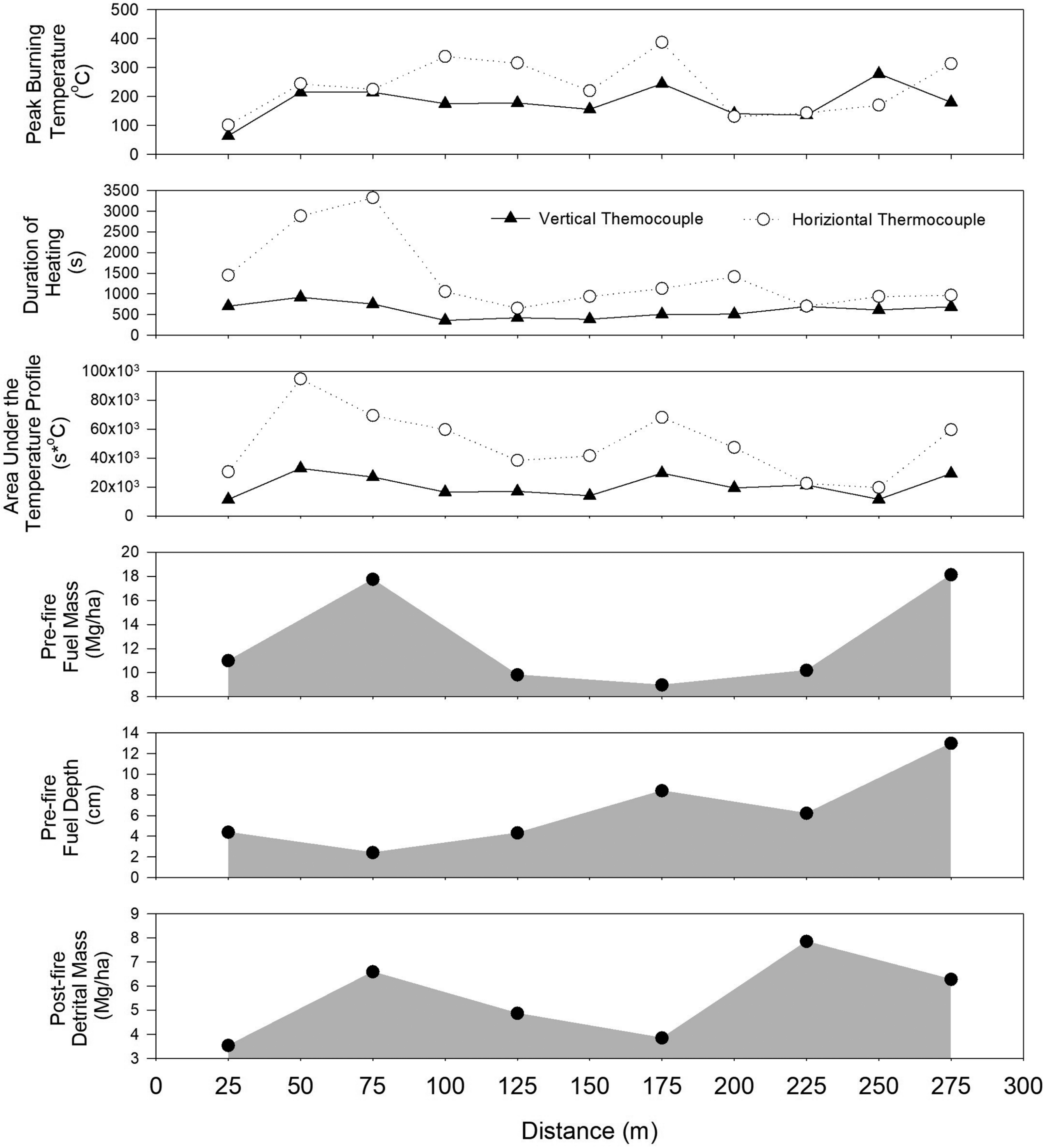

Fig. 3. Depiction of peak burning temperature, duration of heating, and area under the temperature profile as related to pre-fire fuel mass (Mg ha^{-1}), pre-fire fuel depth (cm), and post-fire detrital mass (Mg ha^{-1}) along one 300-m sampling transect at one of the dormant season burning sites at the Tom Yawkey Wildlife Center, Georgetown, SC.

at least five additional times since 2004 and did not contain large amounts of fuel before burning in 2015 (10.0–21.6 Mg ha^{-1}). Given the low fuel masses, fuel depths, and observed flame lengths, these fires were considered low-intensity, low-severity surface fires. We suspect that the tips of the thermocouples installed horizontally were influenced by their contact with the actively burning detrital layer. The vertically oriented thermocouples would not have been exposed to direct contact with the fuel bed. According to our findings and those mentioned above, it appears horizontally oriented thermocouples provide unique insight when fuel beds are largely dominated by litter and surface fuels, as opposed to grasses and vertically oriented fuels.

Results from our regression analyses suggest that the horizontal and vertical estimates show no strong correlation with one another. The vertical and horizontal thermocouples were placed in the same geographic location (dataloggers buried in the same

Table 2. p-values and correlation coefficients (r^2) of linear regressions where pre- and post-fire fuel measures were used as predictors of peak burning temperature (PBT), duration of heating (DOH), and area under the temperature profile (AUTP).

Fuel variables		Vertical PBT			Horizontal PBT			Vertical DOH			Horizontal DOH			Vertical AUTP			Horizontal AUTP		
		p	r^2	*n*	*p*	r^2	*n*	*p*	r^2	*n*	*p*	r^2	*n*	*p*	r^2	*n*	*p*	r^2	*n*
Pre-fire mass (Mg ha^{-1})	Understory vegetative mass	0.81	0.00	21	0.09	0.20	16	0.21	0.09	19	0.22	0.10	16	0.20	0.01	21	0.67	0.01	16
	1-h fuel mass	0.43	0.02	34	0.61	0.01	29	0.08	0.10	31	0.06	0.12	29	0.33	0.03	33	0.81	0.00	29
	10-h fuel mass	0.92	0.00	34	0.44	0.02	29	0.10	0.09	31	0.02	0.18	29	0.39	0.02	33	0.41	0.03	29
	100-h fuel mass	0.20	0.05	34	0.14	0.08	29	0.04	0.14	31	0.42	0.02	29	0.56	0.01	33	0.39	0.03	29
	Woody mass	0.14	0.07	33	0.08	0.11	28	0.07	0.11	30	0.00	0.01	28	0.10	0.01	32	0.07	0.03	29
	Detrital mass	0.99	0.00	32	0.30	0.04	27	0.58	0.01	29	0.41	0.03	27	0.54	0.01	31	0.41	0.03	27
	Total fuel mass	0.09	0.15	20	0.01	0.41	15	0.18	0.11	18	0.09	0.20	15	0.53	0.02	20	0.32	0.07	16
Depths (cm)	Woody fuel depth	0.99	0.00	30	0.83	0.00	25	0.36	0.00	27	0.02	0.23	25	0.90	0.00	29	0.00	0.29	26
	Detrital depth	0.24	0.04	33	0.45	0.02	28	0.75	0.00	30	0.48	0.02	28	0.33	0.03	32	0.79	0.00	28
Post-fire mass	Woody mass	0.27	0.03	34	0.12	0.09	29	0.97	0.00	31	0.58	0.01	29	0.48	0.02	33	0.86	0.00	29
	Detrital mass	0.10	0.08	34	0.59	0.01	29	0.63	0.01	31	0.01	0.23	29	0.01	0.22	33	0.00	0.27	29
Fuel consumption (Mg ha^{-1})		0.96	0.00	34	0.18	0.06	29	0.77	0.00	31	0.08	0.11	29	0.50	0.01	33	0.18	0.07	29

hole), yet their values did not seem to be related. Given the matched pair and regression results, one can conclude that PBT, DOH, and AUTP at the litter-soil interface are different measures than PBT, DOH, and AUTP 28 cm above the litter-soil interface. Thus, vertical and horizontal thermocouple estimates can be considered independent measurements.

Seasonal Burning Effects May Not Be Reflected by Peak Burning Temperature Alone

Of the fire behavior metrics we investigated, PBT is the metric most used in studies of prescribed fire (Franklin et al., 1997). When all other variables affecting fire behavior are held constant, it is assumed that higher ambient temperatures in the growing season contribute to higher PBT values in growing season fires (Whelan, 1997). Our results did not reflect this notion, as PBT did not differ between the growing and dormant season burns. Our burns were conducted 8 wk apart in the late-dormant and early-growing seasons. Ambient temperature was not drastically different on the dates of our burns, which suggests that there was no difference in the amount of heat needed to reach ignition between the dormant and growing season burns. Given the similarity in PBT values between the dormant and growing season burns, it would seem plausible that lower relative humidity values during the dormant season burns would have resulted in higher PBT values. Nevertheless, this was not observed.

Even though PBT did not differ as a result of burning season, we did note significantly higher values for AUTP and horizontal DOH in the growing season. With this in mind, it appears that PBT may not fully encapsulate fire dynamics within a given fire, thus making it difficult to establish differences in fire behavior metrics between fire events. Other researchers have noted the potential shortcomings of PBT for these purposes as well (Byram, 1958; Bova & Dickinson, 2008; Keeley, 2009).

Prediction of Fire Behavior Metrics Using Pre-Fire Fuel Characteristics (and Post-Fire Detrital Mass) May Be Difficult Using Thermocouples Alone

Given the variables we assessed pre-fire and post-fire, we could not establish any significant predictive relationships for PBT, DOH, and AUTP, with the exception of horizontal PBT and pre-fire total fuel mass. Kennard et al. (2005) found a lack of correlation between these variables as well. This is not surprising, given the heterogeneity of fire events, both vertically and laterally.

Future Considerations when Using Thermocouples during Prescribed Fires

The use of thermocouples has been questioned in previous studies, particularly when PBT is the only metric considered (Bova and Dickinson, 2008). Thermocouples do not measure actual flame temperatures (Kennard et al., 2005) but instead give an estimate of the ability of a given fire in a given area to transfer heat (Bova and Dickinson, 2008). This is dependent on the diameter and composition of the thermocouple itself (Kennard et al., 2005) and any contact made between the fuelbed and thermocouple tips. Nonetheless, when fuel type is consistent, choosing one thermocouple type to assess these metrics may be beneficial (Bova and Dickinson, 2008).

One unique advantage of using thermocouples as opposed to other methods of obtaining PBT, such as calorimeters and pyrometers (Iverson et al., 2004; Kennard et al., 2005), is that thermocouple-datalogger assemblies can be programmed to record temperature throughout the duration of a given fire event. In light of the differences we noted in burning season with DOH and AUTP, we strongly recommend the use of thermocouple-datalogger assemblies because they afford the opportunity to obtain these metrics. This benefit must be noted with the caution that metallurgical properties and thermocouple diameter do influence the rate at which thermocouple probes heat and cool. This may greatly influence values for DOH and AUTP (Kennard et al., 2005).

In their work, Bova and Dickinson (2008) determined that thermocouple-generated data might be more useful when raw data are calibrated with additional data, such as flame height and mean rate of spread. Fireline intensity and fuel consumption can be generated from these calibrations. We did not attempt to use these calibrations and instead compared the raw data generated by the thermocouples. We chose this method because our fires were conducted in the same fuel type and because we were interested in the utility of the uncalibrated values in longleaf pine-dominated systems. As stated by Bova and Dickinson (2008), uncalibrated values obtained from thermocouples vary greatly spatially along the landscape but may serve as point estimates of fire and fuelbed characteristics in a given location. As such, the orientation comparison we conducted may provide needed insight for the deployment of thermocouple probes in prescribed fires occurring in longleaf pine-dominated forests and between differing fire treatments (i.e., dormant versus growing season fires) within the longleaf pine fuel type.

From our findings, it appears that thermocouple orientation may influence our determination of differences in PBT, DOH, and AUTP as a result of burning season. These results also suggest that fire behavior metrics generated at the litter-soil interface are different metrics than those obtained some distance vertically above the litter-soil interface. Many managers and foresters are interested in quantifying the metrics that thermocouples provide. In light of this study, we highly encourage scientists and managers to carefully consider thermocouple orientation when designing studies evaluating fire behavior metrics. Thermocouple orientation may affect the values generated and the ability to determine differences in burning regimes.

Conclusions

In this study, we investigated the orientation of thermocouples in six prescribed fires in southeastern coastal forests. We found that thermocouples located horizontally at the litter-soil interface obtained greater values of PBT, DOH, and AUTP than did thermocouples extending 28 cm vertically above the litter-soil interface. Estimates of these metrics from vertical thermocouples did not serve as significant predictors of horizontal metrics at any resolution. These results countered our first hypothesis and suggest that thermocouples oriented horizontally and vertically may capture inherently different estimates of these fire behavior metrics. The utility of both orientations to distinguish differences between dormant and growing season burns was consistent for PBT and AUTP. Duration of heating was only significantly greater in the growing season burns when measured with the horizontal thermocouples. We found that peak burning temperature obtained using the horizontal thermocouples was the only fire behavior metric that displayed a marginally significant correlation coefficient with one of the pre- or post-fire fuel loading and depth measurements ($r^2 = 0.41$). These results did not align with our second hypothesis. Given these findings and those from other studies, we recommend careful consideration of the implications posed by the placement of thermocouple-datalogger assemblies across the landscape when evaluating prescribed burns, as such details may affect the evaluation of treatment effects.

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