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Research Note

Temperatures below leaf litter during winter prescribed burns: implications for litter-roosting bats

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Abstract. Some bat species, including eastern red bats (*Lasiurus borealis*), roost for short periods beneath leaf litter on the forest floor during winter in the south-eastern USA, a region subjected to frequent fire. The variability in fuel consumption, the heterogeneous nature of burns, and the effects of litter and duff moisture on forest-floor temperatures during winter burning could influence potential survival for bats beneath the leaf litter if they are unable to escape on-coming flames. We measured temperatures below leaf litter in 64 south-slope plots during nine controlled burns in the Ouachita Mountains of Arkansas to determine the probability of survival. Maximum temperature recorded under leaf litter at each plot averaged 292°C (±20 s.e.) and ranged from 10 to 717°C. Only three (5%) of the plots experienced temperatures that were deemed survivable (<60°C sustained for 60 s) during burns on warmer winter days (air temperatures 15.0–26.1°C). Temperatures below the leaf litter measured just before the arrival of fire (average = 19.6°C) suggested that if bats were roosting in plots they would have been in shallow torpor, which would have enabled faster escape from approaching flames. Burning during the warmer periods of winter (e.g. ≥15°C) and during afternoons could potentially improve survival by bats roosting under leaf litter by reducing arousal and escape times.

Additional keywords: Arkansas, fire, hibernation, *Lasiurus borealis*, Ouachita Mountains, red bat.

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Introduction

Land managers use prescribed fire to meet many forest-management objectives, including hazardous fuel reduction, preparing sites for seeding, improving wildlife habitat, controlling insects and disease, and ecological restoration (e.g. Waldrop and Goodrick 2012). The indirect effect of these fires on wildlife is improved habitat for many species (e.g. Means and Campbell 1981; Kennedy and Fontaine 2009), but the burning process may also have direct effects on wildlife, including injury or death. The season of burning may determine which wildlife species are most at risk for direct effects. For example, spring burns may lead to nestling mortality of ground-nesting birds (Tucker 2002; Cox and Widener 2008), and growing season burns may cause direct mortality or injury of some herpetofaunal species such as box turtles (*Terrapene carolina*) (Platt *et al.* 2010; Howey and Roosenburg 2013). Throughout the eastern USA, land managers often conduct prescribed burns during winter, which reduces the chance of direct mortality to many wildlife species, including most herpetofauna and ground-nesting bird species.

During winter in southern portions of the USA, some bat species, including eastern red bats (*Lasiurus borealis*) and Seminole bats (*Lasiurus seminolus*), remain active during warmer periods of winter but roost for short periods (days or weeks) beneath leaf litter on the forest floor during cold periods (<10°C). Temperatures under litter typically remain warmer and more stable than air temperatures during these cold periods (Mormann and Robbins 2007; Hein *et al.* 2008; Flinn 2009; Perry 2013). Although mortality of bats under leaf litter during winter burning has not been documented, winter burning has the potential to cause injury or death to bats, especially during colder periods of winter. Studies suggest that fire cues, such as smoke, may cause these bats to arouse from torpor and escape, but the time between the fire-related stimuli until the arousal of bats in these studies was 5–60 min, with longer times associated with colder temperatures (Scesny 2006; Layne 2009). Nevertheless, red bats are commonly seen exiting the leaf litter during winter burns, suggesting that many bats escape (Saugey *et al.* 1989; Moorman *et al.* 1999; Rodrigue *et al.* 2001).

Bats use periodic torpor to reduce energy usage when food is not available, and long-term torpor (over days or weeks) is considered hibernation. Torpor is characterised by a state of inactive lethargy, making immediate escape from fire by torpid bats unlikely. The level of torpor is typically dictated by the surrounding temperature, with cold but above freezing (e.g. 5°C) temperatures resulting in the deepest torpor (Davis and Reite 1967). It may take 60–80 min for some species to become fully active from deep torpor at these cold temperatures (Davis and Reite 1967). At warmer temperatures (e.g. 20°C) bats arouse more quickly. Thus, a bat's level of torpor and its ability to escape oncoming flames is dictated, in part, by the temperature the bat experiences under the leaf litter just before flames reach that point.

Given the potential variability in fuel consumption, the frequent heterogeneous nature of winter controlled burns, and the effects of duff and leaf litter moisture on forest-floor temperatures during burning, survival of bats beneath the leaf litter that are unable to escape on-coming flames is uncertain (e.g. Layne 2009). Litter consumption during low-intensity burns may only range from 30 to 80% with little consumption of the duff layer (Boerner 1983; Cole *et al.* 1992; Blankenship and Arthur 1999; Boerner *et al.* 2000). Furthermore, moisture levels of duff and litter may also have a direct effect on potential survival of bats roosting below litter because these parameters influence forest-floor and soil temperatures during fires.

Although substantial research has been conducted on temperatures associated with controlled burning, these studies have focussed mostly on temperatures of soil during fires or temperatures immediately above the forest-floor (e.g. Heyward 1938; Frandsen and Ryan 1986; Bradstock *et al.* 1992; Swift *et al.* 1993; Iverson and Hutchinson 2002). We are unaware of studies that have examined temperature profiles below the leaf litter but above the duff during fires, the position roosting red bats occupy during winter. Therefore, we initiated this study to determine temperature profiles under the leaf litter during winter prescribed burns to determine the probability of survival of bats roosting under the leaf litter if they are unable to escape on-coming flames. We compared the characteristics of sites, including fuel loads and litter moisture, to determine if survivability under leaf litter could be predicted based on these parameters.

Methods

The study was conducted throughout the Ouachita National Forest (ONF) of western Arkansas. The Ouachita Mountains consist of east–west oriented ridges and valleys that extend from central Arkansas into east–central Oklahoma. Elevations in this region range from 152 to 853 m, and mean annual precipitation ranges from 112 to 137 cm. The climate of the region is humid subtropical. Based on weather stations near the study areas, mean (max/min) winter temperatures (for the years 1971 to 2000) were 15.4/3.5°C for November, 10.3/−0.9°C for December, 8.8/−2.8°C for January, 11.9/−0.9°C for February and 16.6/3.7°C for March (NCDC 2004). The dominant forest type in the region is mixed shortleaf pine (*Pinus echinata*)-hardwood forests, but also includes pure pine and pure hardwood forest stands. The hardwood component in forest stands throughout the region is diverse (>32 species), but is dominated mostly by oak (*Quercus* spp.) and hickory (*Carya* spp.).

Plots were established within nine prescribed burn areas; burns were conducted between 1 January and 15 March 2012–2013. Stands selected for sampling within burn areas were similar to those selected by eastern red bats for litter roosts (Mormann and Robbins 2007). These stands were located on southerly aspects (S, SE or SW), had a hardwood component in the overstorey (pine-hardwood, hardwood-pine or hardwood stands), and had visible hardwood litter on the forest floor; deciduous leaf litter comprised 41–79% (mean = 62.2 ± 4.1% s.e.) of litter samples among the nine stands. Although anecdotal accounts of red bats being flushed from leaf litter during winter burns suggested that north slopes may be used as winter roost sites in the Ouachita Mountains (Saugey *et al.* 1989), quantitative studies using radio-telemetry that evaluated roost selection by red bats during winter indicated that the majority of roosts were located on south slopes (Mormann and Robbins 2007; Flinn 2009). Therefore we selected only south-slope stands for study.

In each stand, two transects were established that ran perpendicular to the slope and ≥30 m apart. Transects were a minimum of 50 m from roads. Along each transect, four plots were established. Because fire intensity may be affected by slope position (e.g. Rothermel 1983), we located one plot each at the lower, middle and upper slope positions and one plot on the ridge top of each transect. Thus, eight plots were sampled (two at each slope position) in each stand during each burn, for a total of 72 plots. Because of differences in the length of slope among stands, plots averaged 48.9 m (±3.1 s.e.; range 12.0–133 m) apart in upslope distance. At each plot, litter and duff moisture, along with fuel load (litter and twigs <2.5 cm; $\mathrm{kg\,m^{-2}}$) was estimated by removing litter and duff from a 0.3 × 0.3-m area adjacent to each plot and drying at 60°C to constant mass. Overstorey pine and hardwood basal area and midstorey basal area (>2.5 cm dbh) were estimated at each plot using a 10-factor English prism.

Prior to burning, thermocouples (CASS-18G-12-NHX, Omega Engineering, Stamford, CT) were placed under the leaf litter but above the duff. Thermocouples were connected to Hobo data loggers (U12-014, Onset Computer Corp., Cape Cod, MA), which were placed just below the soil surface to protect them from heat. Data loggers recorded the thermocouple temperature every 10 s during the burn. During each burn, ambient air temperature, wind speed and relative humidity were obtained from the nearest remote automated weather station located on the district in which the burn was conducted. In addition, the Keetch–Byram Drought Index (KBDI) was calculated from local weather stations. KBDI is a soil/duff drought index that ranges from 0 (no drought) to 800 (extreme drought).

The nine burns conducted by ONF District personnel were typical of burns conducted during winter, with KBDI values of 16–43. Four of these burns were hand-ignited strip-head fires (49–904 ha) and five were aerial ignitions (391–1256 ha) (Waldrop and Goodrick 2012). Flame heights were visually estimated during burning. Red bats are expected to roost in leaf litter when nightly temperatures fall below 10°C (e.g. Mormann and Robbins 2007). Minimum temperatures the night before each burn ranged from −6.1 to 0°C; thus, all burns were conducted when red bats were expected to be roosting in leaf litter. Fires occurred with air temperatures ranging from 15.0 to 26.1°C at the time of ignition. Compared with a sample of 372 burns conducted from 2007 to 2010 by the Ozark and Ouachita National Forests during winter (6 November to 31 March), burns in this study fell in the top 38% in air temperatures at the time of ignition.

Maximum lethal temperature and duration are unknown for bats. Some bats may use summer roosts with temperatures that reach 50–60°C and may exceed 40°C for 6 h or more daily (Bronner *et al.* 1999). Temperatures over 62.8°C are considered lethal to most small mammals (Howard *et al.* 1959), with maximum survival temperatures for animals being time-dependent and subject to conditioning (Willmer *et al.* 2000).

Similarly, 60°C is considered the lethal threshold for tree roots and plant cells (e.g. Zeleznik and Dickmann 2004; Busse *et al.* 2005) and heating soil to 55°C may cause tissue mortality in plants (Levitt 1980). Therefore, we used 60°C, sustained for 1 min, as the critical maximum temperature threshold for bat survival. Likewise, Dickinson *et al.* (2010) used 60°C as the temperature at which bats roosting in trees may receive injury when exposed to fires.

We compared means of plot-level variables measured at survivable plots with those of non-survivable plots using *t*-tests. Initially, we believed that a sizable number of plots would provide survivable temperatures. However, the low number of survivable plots did not allow most statistical analyses. Using Pearson correlation coefficients we related fuel load, litter moisture, duff moisture and KDBI to temperatures recorded below leaf litter just before fire reached the plots, the maximum temperatures encountered below the leaf litter during the burn, and the duration of temperatures above 60°C. We compared maximum temperatures attained and duration of temperatures above 60°C among the four slope positions using mixed-model analysis of variance with stand (burn unit) as a random effect. Using information from Layne (2009) and the regression formula presented by Dickinson *et al.* (2010), we estimated the time (in minutes) it would take a bat in torpor to obtain flight based on the temperature beneath leaf litter just before the arrival of fire in each plot. All analyses were conducted using SAS (SAS Institute Inc. 2014) at $\alpha = 0.05$.

Results

Fire intensities were generally low during most controlled burns, with flame heights averaging 56 cm (±4.4 s.e., range 18–122 cm). Plots were burned with head fires (47%), back fires (49%) and flanking fires (4%). Of the 72 plots we sampled, eight had malfunctioning data recorders, resulting in 64 total plots with usable data.

Maximum temperatures recorded under leaf litter averaged 292°C (±20°C) and ranged from 10 to 717°C (Fig. 1). Average duration of temperature above 60°C was 417 s (±33 s) and ranged from 0 to 1290 s. There was no significant difference in maximum temperatures attained ($F_{3,52.7} = 0.86$, $P = 0.4701$) or duration of temperatures above 60°C ($F_{3,52.5} = 1.47$, $P = 0.2341$) among the four slope positions. Only 3 of 64 (5%) plots experienced temperatures that would have been below lethal limits to bats (≤60°C for 1 min), and this included a single plot that did not burn. Plot-level variables compared between survivable and non-survivable plots indicated no significant differences except for temperatures under litter before the arrival of fire. However, sample sizes for survivable plots were small and these results should be interpreted with caution (Table 1).

Mean temperature below leaf litter just before arrival of fire in our study was 19.6°C (±0.9°C) and ranged from 10.1 to 41.9°C; 25 plots (39%) had temperatures >20°C before fire arrival. The mean time it would take a bat in torpor to obtain flight was 13.2 ± 0.5 min (range 6.9–19 min) based on these litter temperatures (Fig. 1). We found a significant correlation (-0.71, $P < 0.001$) between air ambient temperatures during burning and estimated time for a bat to fly based on temperatures under the leaf litter. The mean litter moisture ranged from 11 to 44%, and litter fuel loadings ranged from 0.41 to 1.54 kg m^{-2} for each burn unit. The temperature under leaves just before arrival of fire, the maximum temperature under litter during burning, and the duration of temperatures above 60°C were negatively related to litter moisture, duff moisture and litter mass (Table 2).

Discussion

We found that burns of low to moderate intensity, conducted on south slopes during relatively warm winter days, resulted in temperatures that were mostly not survivable by bats under leaf litter if they were unable to escape on-coming flames. Only 5% of plots would have resulted in survival by bats if they were unable to escape. However, it should be noted that this 5% survival estimate is based solely on litter temperatures during burning and would only affect bats that could not escape before the arrival of fire. Actual survival by bats was likely greater due to the shallow torpor (and relatively quick escape times) that we expected based on litter temperatures before the arrival of fire.

Temperature under litter before fire arrival has implications for a bat's level of torpor and their ability to escape on-coming flames. Layne (2009) found that red bats exposed to smoke during winter were able to fly in ~31 min when air temperatures were 10–15°C, but were able to fly in ~15 min when air temperatures were 15–20°C. However, these response times are biased towards high response times because fires in that study took place in the early morning, the period of lowest below-leaf temperatures (Perry 2013). Layne (2009) suggested igniting fires when temperatures are ≥10°C and on clear days so that leaf litter is warm enough to allow quick response by red bats. During our study, the average time of day (CST) that plots burned was ~1510, which coincides with the warmest period below leaf litter during winter days (Perry 2013). Below-litter temperatures just before the arrival of flames at plots in our study (10.0–41.9°C, mean 19.6°C) suggested that most bats would likely have only been in shallow torpor during most of these afternoon winter burns, allowing relatively quick escape. Because burn parameters (e.g. higher temperatures and lower humidity) are often more favourable during late morning to early afternoon, the average time of ignition for winter prescribed fires in the Interior Highlands was ~1100 (CST) (Perry 2012). During burns in our study, fire personnel observed instances of red bats escaping from the leaf litter, indicating that temperatures were warm enough for bats to escape before flame arrival.

Historical data suggests that fire frequency in Arkansas peaked in March–April and again in September–November (USDA 1999), leading others to suggest that bats may not have adapted to winter burning in the past (Carter *et al.* 2002). However, burning during the warmer periods of winter (e.g. ≥15°C) and during afternoons could potentially improve survival by bats roosting under leaf litter. Nevertheless, additional study is needed to determine bat thermoregulation under leaf litter and their response and potential survival during winter fires.

Although anecdotal information suggested most bats flushed from leaf litter during burning were on north slopes (Saugey *et al.* 1989), quantitative studies using radio-telemetry found

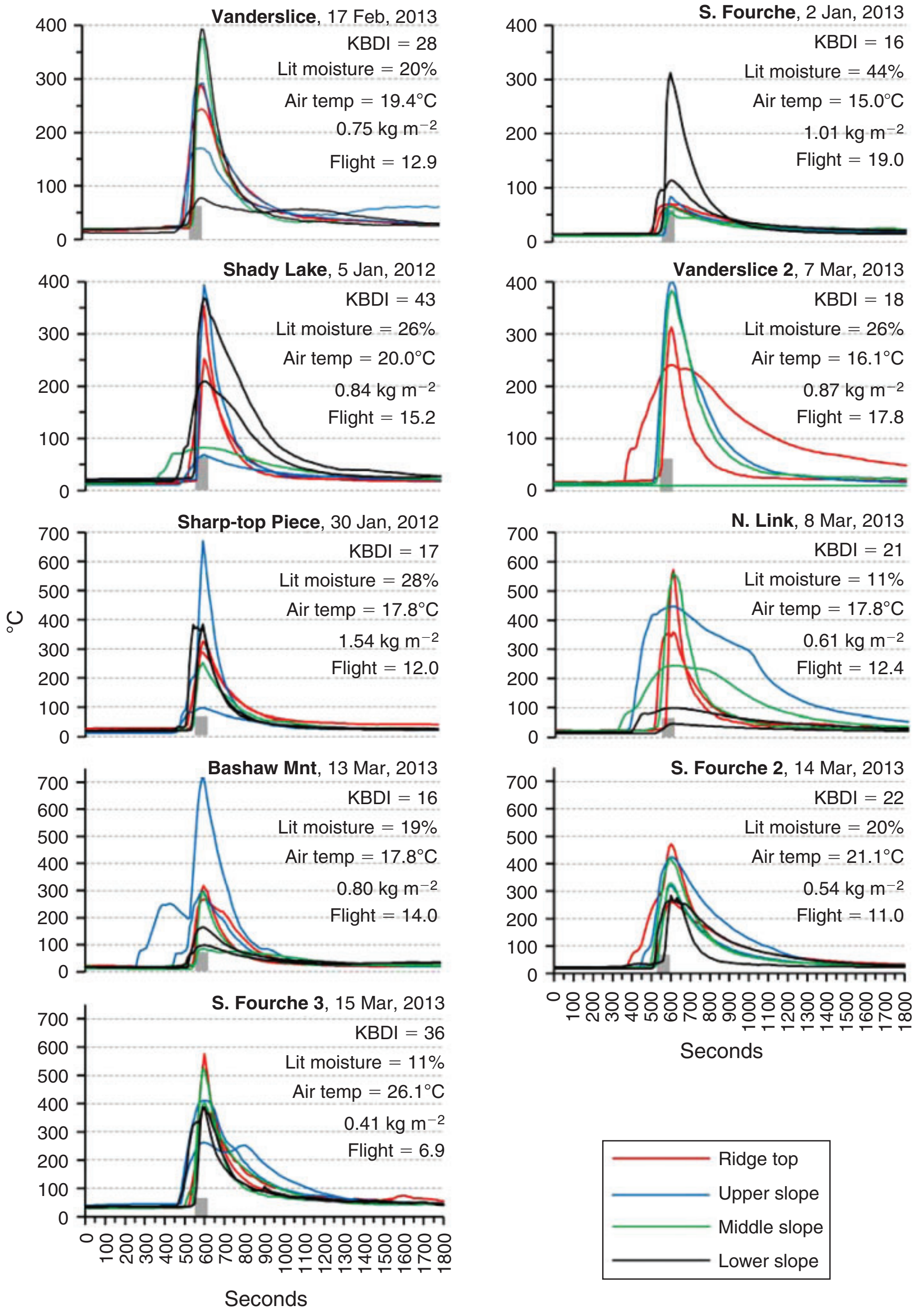

Fig. 1. Temperature profiles below leaf litter for 64 plots measured during nine winter controlled burns in the Ouachita Mountains of Arkansas, 2012–2013. Each burn is identified by the burn name, and includes the date of burn (day/month), Keetch–Byram Drought Index (KBDI) for that day, mean percentage moisture content of the leaf litter, the ambient air temperature (°C) during the burn, mean fuel loads (kg m^{-2} of litter including twigs <2.5 cm), and estimated time (min) it would take a red bat to arouse and fly. Estimated flight time was modelled from Layne 2009 and Dickinson *et al.* 2010, and was based on temperatures below leaf litter just before arrival of fire. The grey box in each graph represents the area of expected survival for an organism below the leaf litter (<60°C sustained for 1 min).

most litter roosts of red bats located on south slopes (Mormann and Robbins 2007; Flinn 2009). Therefore, we located all plots on southerly slopes. However, southerly slopes typically burned more consistently and thoroughly than other aspects across the landscape due to lower fuel moisture content and higher fuel and air temperatures (e.g. Taylor and Skinner 2003). Although our study did not include north slopes, these areas are thermally suitable for hibernation by red bats (Perry 2013) and may be less

Table 1. Comparison of variables (mean ± s.e.) from plots deemed survivable and not survivable by bats under leaf litter during nine winter prescribed burns in the Ouachita Mountains of Arkansas, 2011–2013

Non-survivable plots had temperatures ≥60°C sustained for >1 min

	Survivable ($n = 3$ plots)	Non-survivable ($n = 61$ plots)	P-value
Litter mass (g)	101.7 ± 11.2	74.6 ± 4.5	0.193
Litter moisture (%)	30.9 ± 10.7	21.9 ± 1.4[A]	0.170
Duff moisture (%)	45.1 ± 7.3	40.3 ± 1.7	0.541
Slope (%)	5.3 ± 1.9	9.9 ± 0.6	0.106
Hardwood basal area ($m^2 ha^{-2}$)	10.7 ± 2.8	9.7 ± 0.7	0.742
Pine basal area ($m^2 ha^{-2}$)	10.0 ± 1.5	12.2 ± 0.8	0.534
Fuel load ($kg\ m^{-2}$)	1.09 ± 0.12	0.83 ± 0.05	0.193
Temperature before arrival of fire (°C)	11.7 ± 0.9	20.9 ± 0.9	0.041

[A] $n = 60$ non-survivable plots due to missing data.

Table 2. Significant correlation coefficients ($P < 0.05$) for litter mass, litter moisture, duff moisture and Keetch–Byram Drought Index (KBDI) correlated with temperatures recorded below leaf litter just before fire reaching plots, maximum temperatures encountered below the leaf litter during the burn, and duration of temperatures above 60°C recorded in 64 plots subjected to nine prescribed burns in the Ouachita Mountains, Arkansas 2011–2013

Variable	Temperature below leaf litter at fire arrival (C°)	Maximum temperature during burn (C°)	Duration above 60°C during burn
Litter mass (g)	−0.421		−0.369
Litter moisture (%)[A]	−0.585	−0.334	−0.517
Duff moisture (%)	−0.588	−0.389	−0.487
KDBI	0.385		

[A] $n = 60$ non-survivable plots due to missing data.

prone to burning, which could potentially provide refuge to eastern red bats during winter burning at southerly latitudes. Studies suggest that red bats occasionally roost under litter on north slopes during winter (Saugey *et al.* 1989; Mormann and Robbins 2007; Flinn 2009). However, potential increased survival to bats roosting on north slopes during burning is conjectural.

Our data suggest that, during prescribed burning on warmer days of winter, few bats would have survived if they were unable to escape before flames reached their location. However, the warmer air temperatures associated with burn days in this study likely reduced the potential for mortality to red bats under leaf litter by reducing torpor depth and escape times. It is unknown how temperatures under leaf litter (and potential escape times by red bats) would be affected by burning on colder days. Although greater litter mass, litter moisture and duff moisture were associated with reduced temperatures both before and during the burning, these lower temperatures would have resulted in deeper torpor and potentially longer arousal times. Data are lacking on torpor use by red bats during winter under leaf litter, and how attributes such as aspect and litter depth affect torpor patterns. In addition, more information is needed on how efficient red bats are in escaping winter fires.

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