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ARTICLE

Effects of solar heating on the moisture dynamics of forest floor litter in humid environments: composition, structure, and position matter

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Abstract: Much of fire behavior is driven by fine-scale patterns of fuel moisture; however, moisture predictions typically occur over large scales. The source of fine-scale variation in moisture results from a combination of fuelbed properties and overstory forest structure that influences water movement and distribution of solar radiation. Fine-scale moisture variation is of particular relevance in humid forests managed with frequent prescribed fire where fire behavior variation is tightly linked to differential fire effects. Results of a three-tiered experiment combining laboratory and field methods demonstrated that solar radiation exerted a strong influence on fuel moisture patterns in a temperate humid pine forest. Infrared radiation more rapidly dried *Quercus* and *Pinus* litter in laboratory experiments compared with controls. Litter exposed to sunlight during small-scale outdoor experiments was significantly drier than shaded litter. *Quercus* litter was wetter than *Pinus* on mornings, but dried more rapidly, becoming drier than *Pinus* litter by mid-day when exposed to sunlight. Field observations validated small-scale outdoor and laboratory results but also revealed the influence of fuel position: elevated litter was wetter than ground-level litter at peak burning time. Results provide insight into how overstory structure and composition may influence fine-scale heterogeneity of surface moisture dynamics and fire behavior.

Key words: forest structure, fuel moisture, *Pinus palustris*, prescribed fire, *Quercus*.

Résumé : Le comportement du feu est en grande partie déterminé par le profil à petite échelle de l'humidité des combustibles; cependant, les prévisions concernant l'humidité sont faites à grande échelle. La source de variation à petite échelle de l'humidité vient de la combinaison des propriétés des lits de combustibles et de la structure forestière de l'étage dominant qui influence le mouvement de l'eau et la distribution du rayonnement solaire. La variation de l'humidité à petite échelle est particulièrement pertinente dans les forêts humides aménagées en ayant recours à de fréquents brûlages dirigés où la variation du comportement du feu est étroitement reliée aux différents effets du feu. Les résultats d'une expérience à trois niveaux combinant des méthodes en laboratoire et sur le terrain ont démontré que le rayonnement solaire exerce une forte influence sur le profil de l'humidité dans les combustibles dans une forêt humide tempérée de pin. Le rayonnement infrarouge a asséché plus rapidement la litière de chêne et de pin en laboratoire comparativement aux témoins. La litière exposée au soleil dans le cadre des expériences à échelle réduite réalisées à l'extérieur était significativement plus sèche que la litière ombragée. La litière de chêne était plus humide que la litière de pin le matin, mais elle séchait plus rapidement et devenait plus sèche que la litière de pin en milieu de journée lorsqu'elle était exposée au soleil. Les observations sur le terrain ont validé les résultats des expériences à échelle réduite à l'extérieur et en laboratoire, mais elles ont également révélé l'influence de la position des combustibles : la litière surélevée étant plus humide que la litière située à ras du sol au plus fort de la saison des feux. Les résultats fournissent un aperçu de la façon dont la structure et la composition de l'étage dominant peuvent influencer l'hétérogénéité à petite échelle de la dynamique de l'humidité de surface et le comportement du feu. [Traduit par la Rédaction]

Mots-clés : structure forestière, humidité des combustibles, *Pinus palustris*, brûlage dirigé, *Quercus*.

Introduction

Among the many factors determining wildland fire behavior, processes that govern fuel moisture dynamics are of critical importance (Albini 1976; Nelson 2000). As water content increases, the energy required to heat fuels to ignition is substantially increased due to both the high specific heat and the high latent heat of vaporization of water. Moisture content is also the most dynamic fuel characteristic, capable of reacting to subtle environmental changes, especially in fine dead fuels (Viney 1991). For these reasons, fuel moisture content is key to fire behavior predictions for both wildfire and prescribed burning applications (Viney 1991; Matthews 2014). While stand- to landscape-scale fuel moisture predictions are typical for fire danger assessment (Deeming et al. 1977; Bradshaw et al. 1984; Van Wagner 1987; Chuvieco et al. 2002), fine-scale spatial and temporal moisture dynamics are critical for prescribed fire planning to meet specific ecological objectives (Kreye et al. 2014; O'Brien et al. 2016*a*). There remain many questions regarding how fine fuels react to environmental conditions at these scales.

Early wildland fire research established that fuel and environmental factors influence the moisture content of forest floor fuels

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(Gast and Stickel 1929; Gisborne 1933; Byram 1940). Relationships between air temperature, relative humidity, and fuel equilibrium moisture content were observed early on (Gray 1933) and further established for different types of wildland fuels (Blackmarr 1971; Nelson 1984). Strong impacts of solar radiation were also identified in early studies (Byram and Jemison 1943; Countryman (1977) reporting results from a 1936 study). Time-lag theory (Byram 1963) provided the framework to establish drying dynamics across different fuel types (e.g., grasses, leaves, woody sticks, and lichens), species, and sizes of fuels (Nelson 1969; Van Wagner 1969; Anderson et al. 1978; Anderson 1985). Time-lag classification and established relationships between temperature, humidity, and equilibrium moisture content of wood (Simard 1968) were used to make predictions of 1-h (<0.64 cm diameter) and 10-h (0.64–2.54 cm diameter) woody time-lag fuels (Fosberg and Deeming 1971) and were incorporated into the initial 1978 U.S. National Fire Danger Rating System (NFDRS) (Deeming et al. 1977; Bradshaw et al. 1984). Fuel response time (Viney and Catchpole 1991) and hysteresis in time-lag theory (Blackmarr 1971; Nelson 1984) complicates the interpretation of wetting and drying fuels in a dynamic environment.

The use of an elevated 10-h fuel stick (*Pinus ponderosa* dowel) to calculate NFDRS fuel moisture inputs was subsequently integrated into many remote automated weather stations for a national standard to monitor fuel moisture (Burgan 1988). The current method used to predict 1-h and 10-h fuel moisture inputs into the 2016 NFDRS when a fuel stick is unavailable is the Nelson (2000) 10-h fuel stick moisture model. The use of a 10-h fuel stick to predict forest floor moisture content will lag behind the rapid response of finer fuels (e.g., forest litter) to changing environmental conditions. Litter load and structure, however, may significantly influence drying rates, e.g., dense horizontal litterbeds (Nelson and Hiers 2008). Worst-case fire danger rating systems (e.g., NFDRS) may benefit from underestimating fine fuel moisture content and overestimating fire danger, ensuring that adequate preparedness levels are met. Moisture predictions in fire danger rating (NFDRS; Bradshaw et al. 1984) and fire behavior prediction (BEHAVE; Rothermel et al. 1986) were designed with the objective of providing a consistent tool for comparison of fire behavior potential. Such a large-scale focus and fire safety application have led to poor site-specific estimates of fuel moisture dynamics (Weise et al. 2005). As a result, use of landscape-scale moisture predictions in prescribed burning applications may make it difficult to predict prescribed fire behavior or develop prescriptions. Better understanding of moisture and fuel temperature dynamics at fine spatial and temporal scales may be important for more precise planning of ignition timing and firing operations to meet burning or suppression objectives. There exists a need for more mechanistic prediction of fine fuel moisture and fuel temperature, and their interaction, especially for prescribed fire applications.

The assumption of stable conditions has provided a useful laboratory-experimental context for assessing differences between fuel types (Anderson 1990; Kreye et al. 2013) and fuel position (Nelson and Hiers 2008), but few studies have validated laboratory results in dynamic field conditions (Gibos 2010). Gradients at the fuel–atmosphere interface (temperature, moisture, and vapor pressure) that drive evaporation and diffusion of water fluctuate and vary at fine scales where forest structure, clouds, and time of day influence microclimate and solar radiation. The influence of solar heating on the fuel–atmospheric boundary-layer conditions may be especially critical for understanding surface moisture dynamics in humid environments where atmospheric conditions are otherwise moist.

Prescribed fire is the dominant form of fire in the humid southeastern United States (US), with fire-maintained sites primarily occurring in *Pinus* and *Pinus–Quercus* ecosystems (Ryan et al. 2013; Melvin 2015). Fire applications in the region are typically driven by ecological objectives that require specific fire effects to restore, maintain, and enhance ecological community, structure, and process (Hiers et al. 2003). Accurate predictions of surface-fuel moisture content are of primary importance for ensuring that prescribed fire objectives are met. Given that fine surface fuels rapidly respond to environmental conditions, understanding impacts of factors that occur at fine spatial and temporal scales is important. For example, if solar heating influences are significant and occur rapidly, effects of canopy structure, clouds, and sun angle would all likely be important factors in predicting fine fuel moisture content for prescribed burning applications. These factors may be especially important in humid environments where boundary-layer conditions near the fuel surface may differ significantly from the above atmosphere and where most prescribed burning occurs in North America (Ryan et al. 2013; Melvin 2015). Radiative heating of litter would be expected to reduce near-surface humidity via temperature–humidity relationships. Altered boundary-layer conditions, i.e., lower near-surface humidity, would be most important in humid environments if atmospheric conditions are used to predict surface moisture. In arid environments, the atmosphere and surface fuels are typically dry so impacts of the sun on boundary-layer humidity would not be as drastic.

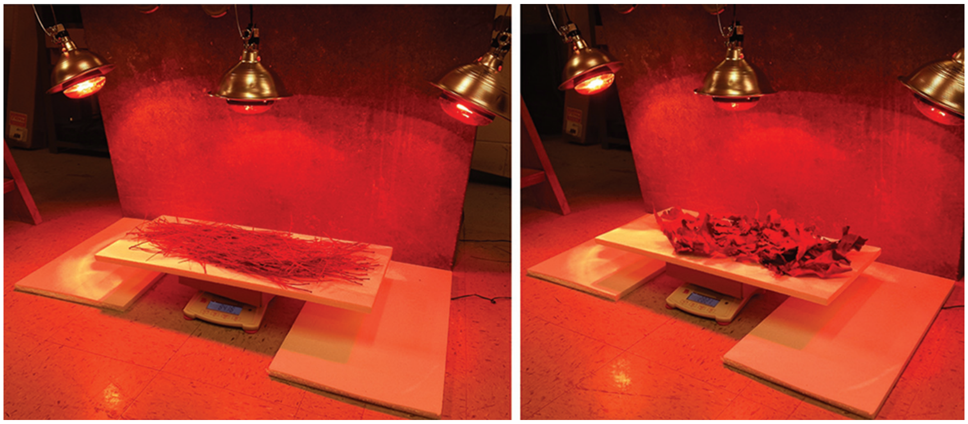
Because overstory trees cast both litter and shade to the forest floor, the role of forest structure and composition in moisture dynamics is important for prescribed fire applications. Moreover, this connection between the overstory and the forest floor provides insight into the ecological interactions of vegetation, fuels, and fire behavior in these pyrophytic fire regimes (Kane et al. 2008; Mitchell et al. 2009; Kreye et al. 2013). The spatial context in which fuels occur (e.g., beneath tree crowns vs. in the open, elevated vs. on the ground surface) is a function of vegetation structure. Vegetation structure (e.g., open vs. dense overstory) influences localized fuel inputs and fine-scale environmental conditions (e.g., shaded vs. unshaded). Effects of overstory structure on surface fuel moisture have varied across studies, with differences likely a result of differing climates, arid vs. wetter, and variation in the surface fuels being evaluated (Pook and Gill 1993; Tanskanen et al. 2006; Whitehead et al. 2006; Faiella and Bailey 2007). Composition is also key given that wide differences in moisture dynamics have been found across co-occurring species' litter in the region, where interspecific differences in leaf-scale (e.g., size, ratio of surface area to volume, density) and fuelbed-scale (e.g., bulk density) characteristics influence moisture response (Kreye et al. 2013). These linkages not only provide insight into the interdependence of vegetation, fuels, and fire behavior, but also should provide better predictive capability at scales that are important for meeting prescribed burning objectives (Mitchell et al. 2009).

To illuminate the effects of solar heating on litter moisture dynamics, we designed a suite of complimentary field and laboratory experiments in *Pinus palustris* – *Quercus* spp. fuels. The goal of these experiments was to observe the effects of variation in fine-scale environmental conditions on moisture dynamics. Specifically, we sought to understand the effects of solar radiation, fuel position (ground vs. elevated), and species differences. We hypothesized that (*i*) solar radiation would increase drying rates of *Pinus palustris* and *Quercus* spp. litter, (*ii*) moisture content of *Pinus palustris* and *Quercus* spp. litter would differ during experimentation, and (*iii*) drying response of elevated *Pinus palustris* litter would differ from the litter on the ground surface. These experiments will inform future work on the mechanistic understanding of fire behavior and fire effects in litter-dominated surface fuels.

Materials and methods

All experiments were conducted between September 2016 and July 2017 at Tall Timbers Research Station in Tallahassee, Florida,

Fig. 1. Indoor laboratory drying experiments with *Pinus palustris* (left) and *Quercus stellata* (right) litter beneath infrared radiation lamps producing 600 W·m^{-2} at the fuelbed surface.



USA (–84.225°W, 30.657°N). We performed a series of related experiments at the laboratory, field mesocosm, and in situ natural fuel conditions to understand how exposure to solar radiation in the surface fuelbed affected drying rates of common fuels. This suite of experiments added increasing realistic variation to the complex environmental context of fuel drying to document the effects of solar radiation on moisture content, as well as the interaction with common fuel types and fuel positions.

Indoor laboratory drying experiments

We conducted controlled laboratory experiments under constant ambient temperature and humidity to quantify the effects of radiant energy on the drying of fine dead fuels. From forested stands at Tall Timbers Research Station, we collected longleaf pine (*Pinus palustris* Mill.), southern red oak (*Quercus falcata* Michx.), and post oak (*Quercus stellata* Wangenh.) leaf litter. Recently cast litter (Oi horizon; no visible signs of decomposition) was collected in fall 2016, sorted by hand to remove litter of other species, and used for subsequent experiments within two weeks. Litter was sorted separately by species (*P. palustris*, *Q. falcata*, and *Q. stellata*) and all experimentation, as described below, was conducted without mixed fuelbeds.

Pine and oak litter were each exposed to moderately warm and humid conditions (23–24 °C and 84%–91% relative humidity) within an enclosed environmental chamber for 48 h. In the high-humidity chamber, litter was positioned on a wire rack approximately 10 cm above standing water. Litter was then removed from the chamber and placed on one of two drying platforms: one exposed to three 250 W infrared heat lamps emitting 600 W·m^{-2} at the litter surface (Fig. 1) and the other exposed to stable ambient laboratory conditions (22 °C, 55% relative humidity). The radiant heat flux of the lamps was calculated by Stephan–Boltzman equations from infrared thermography (FLIR A655sc, FLIR Systems, Inc., Wilsonville, Oregon, USA) using a block of oak wood of known emissivity (0.90) exposed to the lamps. When the wood block is in equilibrium (temperature has plateaued), it is assumed that incoming and outgoing radiation is in balance and radiant heat flux can thus be calculated using the block's thermodynamic temperature. Infrared radiation flux approximated median noon solar irradiance (572 W·m^{-2}) recorded at the Tall Timbers Research Station Remote Automated Weather Station (TTRAWS) between January 2013 and January 2017; maximum irradiance recorded over that time period was 935 W·m^{-2}. The drying platforms consisted of 36 × 74 × 1.5 cm white Styrofoam placed atop a 0.01 g precision bench scale (Ohaus Corp., Parsippany, New Jersey, USA) tared prior to litter placement. We placed similar amounts of litter, by mass, per species onto each of the two platforms (Table 1).

We performed drying experiments with three replications of *P. palustris* needles and one each of *Q. stellata* and *Q. falcata.* The heated litterbeds were exposed to infrared heat lamps for 1 to 3 h (see Table 1), and then the lamps were turned off and the fuel was allowed to continue to react to laboratory conditions. Both heated and unheated litterbeds were periodically weighed throughout the drying experiments for >20 h. After the drying experiments concluded, all litter was oven-dried at 70 °C for 48 h. Gravimetric moisture content was then back-calculated for each litterbed for each weighing over the duration of the drying experiments.

Outdoor small-scale (mesocosm) drying experiments

To observe the influence of solar radiation on fine dead fuel surface temperatures and moisture dynamics, we conducted outdoor experiments that, while partially controlled through constructed fuelbeds, relied on fuel reactions to in situ environmental changes from sunrise through peak burning conditions (approximately 1300 local time). For these completely randomized experiments, a 4 × 4 m litterbed, approximately 5 cm deep, was constructed in an open grassy area using freshly cast *P. palustris* needles collected from an adjacent longleaf pine forest at Tall Timbers Research Station (Fig. 2). Litter was sorted to eliminate other fuels as in experiment 1 above. We housed a thermal infrared camera (FLIR A655sc, FLIR Systems, Inc.) 4.75 m above the center of the fuelbed using a 5 m tripod (see O'Brien et al. 2016*b*) to observe surface-fuel temperatures throughout the experiments. *Quercus falcata* and *Q. stellata* leaves were placed on top of the *P. palustris* litter fuelbed in six groups. These litter groups were evenly spaced within the perimeter of the litterbed (Fig. 2), and *Quercus* leaves within each pile were placed without overlap. A nearly continuous fuelbed of *P. palustris* needles with scattered *Quercus* leaves typifies forest floor fuels in *P. palustris* forests that have scattered codominant and midstory *Q. falcata* and *Q. stellata*. Individual *Quercus* leaves were randomly assigned to each group, with equal numbers for each species per treatment. Leaves were randomly oriented with the upper or lower leaf surface facing upwards (i.e., exposed to the sun). For each leaf, the surface exposed to the sun was then labeled with a marker to keep track of individual leaves and to keep leaves oriented in their original position throughout the experiments. We positioned all litter (*Pinus* and *Quercus*) on the night prior to experiments to allow fuels to react to overnight temperature and relative humidity changes, as well for dew formation.

On the morning of each experiment, beginning within an hour of sunrise local time, each pile of *Quercus* leaves, separately by species, was weighed and returned to their original location. Three grab samples of *P. palustris* needles, of similar mass as each *Quercus* sample, were also weighed but not returned to the fuel-

Table 1. Longleaf pine (*Pinus palustris*) and oak (*Quercus stellata* and *Q. falcata*) litterbeds used in indoor laboratory experiments conducted to observe the influence of radiative energy input, simulating solar heating, on litter drying.

			Exposed				Unexposed			Laboratory conditions	
Litter species	Initial mass (g)	Drying time (h)	Dry mass (g)	Initial FMC (%)	End FMC (%)	Fuel temp. (°C)	Dry mass (g)	Initial FMC (%)	End FMC (%)	Air temp. (°C)	RH (%)
P. palustris	131	1	103	27.0	13.6	44	101	29.8	25.7	24	50
P. palustris	107	3	85.5	25.2	7.3	52	84.0	27.9	21.3	24	45
P. palustris	88	3	69.1	27.0	7.3	48	68.5	27.7	19.6	26	43
Q. stellata	37	3	27.3	35.8	1.6	47	26.5	37.3	13.6	24	41
Q. falcata	42	3	31.1	33.7	2.5	45	31.4	34.0	14.3	23	39

Note: End FMC (fuel moisture content) was determined after 1 or 3 h of drying under laboratory conditions of litter unexposed or exposed to infrared lamps producing 600 W·m^{-2}. Initial mass of litterbeds (exposed and unexposed) was determined after incubation for 24 h in a moisture chamber. Fuel temperatures (temp.) are given for litterbeds that were exposed to infrared radiation, quantified from thermal infrared imagery. RH, relative humidity.

Fig. 2. Outdoor drying experiments conducted with a 4 × 4 m bed of *Pinus palustris* needles and six groups of *Quercus stellata* and *Q. falcata* leaves. Surface-fuel temperatures were monitored with a fixed thermal infrared camera (FLIR A655sc, FLIR Systems, Inc.) located on tripod 4.75 m above fuelbeds (left). Shade cloths were fixed above three of the *Quercus* samples (right) to examine effects of in situ solar radiation.

bed; they were bagged to be oven-dried. Tracking individual *Pinus* needles would have been difficult given the needle fuelbed (Fig. 2). Three of the six *Quercus* samples were then covered with shade cloth on a PVC frame that reduced solar radiation by 60%, quantified by a pyranometer (Fig. 2), which falls within the range of shading reported for *P. palustris* forests in the region (Battaglia et al. 2002). The shading box was large enough to cover the *Quercus* samples as well as *P. palustris* needles adjacent to them. During the sun's low angle early in the morning, two sides of the shade boxes were temporarily covered to limit horizontal solar radiation exposure, while the other two sides remained open. To ensure that wind passed across shaded fuels unobstructed, these temporary sides were removed as soon as sun angles allowed. Shade cloths were located such that they would not cast shade on unshaded *Quercus* samples or adjacent *Pinus* needles. *Quercus* leaves were re-weighed every hour and replaced, while grab samples of *P. palustris* needles nearby *Quercus* samples (three shaded and three unshaded) were weighed and bagged to be oven-dried. At the end of each experiment, the *Quercus* leaves were bagged and all of the collected fuel samples were oven-dried and weighed and gravimetric moisture content was back-calculated throughout the prior experiments. *Quercus* leaves were repeatedly sampled, given the ease of tracking, while *P. palustris* needles were destructively sampled because pine needles would be difficult to resample. Removal of the small masses of pine litter during each sampling period did not alter the fuelbed depth or dimensions. We were careful to take pine needles from the surface of the fuelbed in each sampling period to ensure that needles were exposed to intended solar treatment conditions.

Surface litter temperatures were quantified through post-processing infrared imaging. Temperatures were extracted from infrared images by isolating pixels of *Quercus* leaves, within litter groups, and the nearby area of *Pinus* needles from which destructive sampling occurred for moisture content. Litter emissivity was assumed consistent (0.95) between species. Shading devices were removed at litter collection times for just long enough to capture an infrared image and then were immediately replaced before sampling. This ensured minimal response of shaded litter to any solar radiation. Temperature data were averaged within litter groups for analysis. Litter temperatures were not differentiated between *Q. stellata* and *Q. falcata* for the 22 October 2016 experiment, where both *Quercus* species were evaluated for moisture content because they were grouped together and difficult to discern in infrared images.

For each experiment, main effects of species and shading treatment, and their interaction, were tested for both moisture content and fuel temperatures using general linear modeling analysis of variance (ANOVA) in NCSS version 9 (NCSS, Kaysville, Utah). Comparisons were made separately for the start of the experiments (i.e., the initial moisture content) and then subsequently at 1030 (approximating typical prescribed fire ignition start time) and at 1430 (the end of the experiment). Where the *F* statistic was significant (α = 0.05) and three levels of species were tested (22 October experiment only), post hoc analyses were conducted using the Fisher's LSD test. For the initial moisture contents, prior to shading, comparisons were also made across species and then between the *Quercus* leaves to be shaded vs. those to be exposed; this ensured similar initial moisture content prior to solar heating. Comparisons of surface litter temperatures were made across species and shaded vs. unshaded using GLM ANOVA. Assumptions of GLM modeling were met using the Shapiro–Wilk test and modified Levene test.

Within-forest field drying experiments

To examine solar impacts in the field, we conducted in situ moisture experiments within a mature, frequently burned (biennially, most recently February 2017) longleaf pine forest at Tall Timbers Research Station. Recently fallen *P. palustris* needles were collected from a nearby longleaf pine stand in late May 2017 and sorted to remove other species and any highly weathered needles from the samples. To make the needles identifiable in the field when relocated into the mature forest (ensuring no loss or accidental additions from falling needles), each experimental needle had 2–5 mm of its fascicle tip painted using high-visibility acrylic paint. Painted needles were separated into 16 bunches of ~100 g each at ambient humidity. Bundles were then separated and moved to a drying rack so that initial dry mass could be measured. Needles were dried for 121 h, reweighed immediately, and transferred to a high-humidity chamber with 93% relative humidity for 5 days before field experimentation began. Initial weights were used to ensure no loss or addition of needles in the field, but each set was dried as an experimental fuelbed.

Pine needle bunches were then relocated in the field for the in situ measurement study. Experimentation involved four locations, two levels of canopy exposure (within gap vs. beneath canopy) and two positions within the surface fuelbed (elevated and on the ground). While the position of the fuelbeds was stratified within the forest by proximity to individual crowns, analysis of hemispherical images using WinSCANOPY 2014a (Regent Instruments, Inc., Quebec, Canada) revealed no difference in total openness (*P* = 0.20) between the gaps (mean = 47.1%, standard deviation (SD) 5.2%) and closed canopy positions (mean = 41.3%, SD 6.1%), highlighting the relative openness of these regularly burned pine forests at scales larger than our fuelbeds (Battaglia et al. 2002; McGuire et al. 2001). To reduce variation in the shade environment beneath tree canopies and more directly influence shading, we added shade covers (40% reduction in solar flux) during peak sun (0800–1800). Covers were constructed from PVC pipe and a single mesh shade cloth 0.75 m above the ground; covers were removed each night or during rain events to allow for dew formation characteristic of treatment location. Thus gap vs. canopy positions could be examined for differences in litter moisture content in the morning following evening effects. For fuelbed position, elevated fuels were placed atop a PVC frame with a 2.5 cm mesh galvanized metal grating positioned 30 cm above the soil surface. This grate allowed airflow and represents a common perched needle position in understory vegetation dominated by the surrounding bunchgrasses *Aristida stricta* (recently burned in February 2017). Ground positions were adjacent (within 1 m) to elevated plots within a 30 × 30 cm area of removed understory vegetation. To prevent splash of soil particles by rainfall, a single section of shade cloth was placed on the ground beneath the litterbeds. For all samples, we placed needles on a 30 × 45 cm bed of galvanized 2.5 cm mesh enabling weighing and reducing the chance of losing needles. Thus, plots were arranged in four blocks, each consisting of four scenarios: shaded elevated, shaded ground, exposed elevated, and exposed ground.

All litter was positioned for drying on 31 July 2017. Shade cloths were removed during nighttime or rain events until cloud cover dissipated. Sampling of litterbed mass was then conducted every 3 h from 0800 to 1700 for three subsequent days. Following the sampling period, we subtracted the known mass of each metal bed from our samples and calculated gravimetric moisture content of litter samples.

The within-forest drying data were statistically analyzed for treatment differences in moisture content at different times: initial morning conditions (0800) and afternoon conditions (1400) on day 1, as well as morning and afternoon conditions on days 2 and 3 of experiments. Treatment effects on fuel moisture content was analyzed as a randomized block design using mixed linear model with block (location) as a random effect using NCSS version 9 (NCSS, Kaysville, Utah, USA). The initial (0800) measurement on day 1 was compared to ensure no bias in initial fuel moisture content. The afternoon conditions (1400) corresponded to time frames used in the mesocosm experiment. We provide data for all collection times for the 3 days to show the consistent diurnal moisture patterns observed.

We plotted measured litter moisture content throughout the experiment along with estimated fuel moisture data from the TTRAWS, located approximately 100 m from the study site. The TTRAWS records hourly weather metrics using National Fire Danger Rating System (NFDRS) standards for analysis. For reference fuel moisture, 10 h fuel stick sensor (Campbell Scientific, Logan, Utah, USA) data were plotted.

Results

Indoor laboratory drying experiments

Litterbeds generally dried in a negative exponential pattern under laboratory conditions (22 °C, 55% ambient relative humidity), but heated litterbeds dried more rapidly and to lower moisture content than unheated litterbeds under infrared exposure of 600 W·m^{-2} (Table 1; Fig. 3). FLIR cameras recorded peak surface temperatures of 53, 47, and 59 °C in the heated *Pinus* litter, while heated *Quercus* litter reached 52 and 55 °C (average temperatures for the heated litterbeds are found in Table 1). Unheated litterbeds continued to dry throughout the experiments at ambient temperatures, while the heated litterbeds appeared to re-adsorb moisture immediately following removal of infrared heating (Fig. 3). After approximately 20 h, the previously heated litterbeds approached similar moisture content to that of the unheated litterbeds but were still slightly lower, indicative of hysteresis (Blackmarr 1971).

Outdoor mesocosm drying experiments

Diurnal ambient weather during the three outdoor experiments was variable but generally more similar on the two September days (Table 2). Morning solar radiation, however, reached a greater peak on 12 September 2016 compared with 13 September 2016, averaged hourly, but was less during the afternoon compared with the second day (Fig. 4), a result of differences in intermittent cloud cover. It was cooler during the late October experiment and much less humid, with relative humidity reach-

Fig. 3. Gravimetric moisture content of *Pinus palustris* (left), *Quercus stellata* (center), and *Q. falcata* (right) litterbeds that were either heated (with infrared lamps) or unheated throughout laboratory drying experiments. The horizontal axis (duration) is log-transformed in the lower graphs to better illustrate differences between heated and unheated litterbeds. Note: Heated litterbeds were exposed to 600 W·m⁻² infrared lamps for the first 3 h.

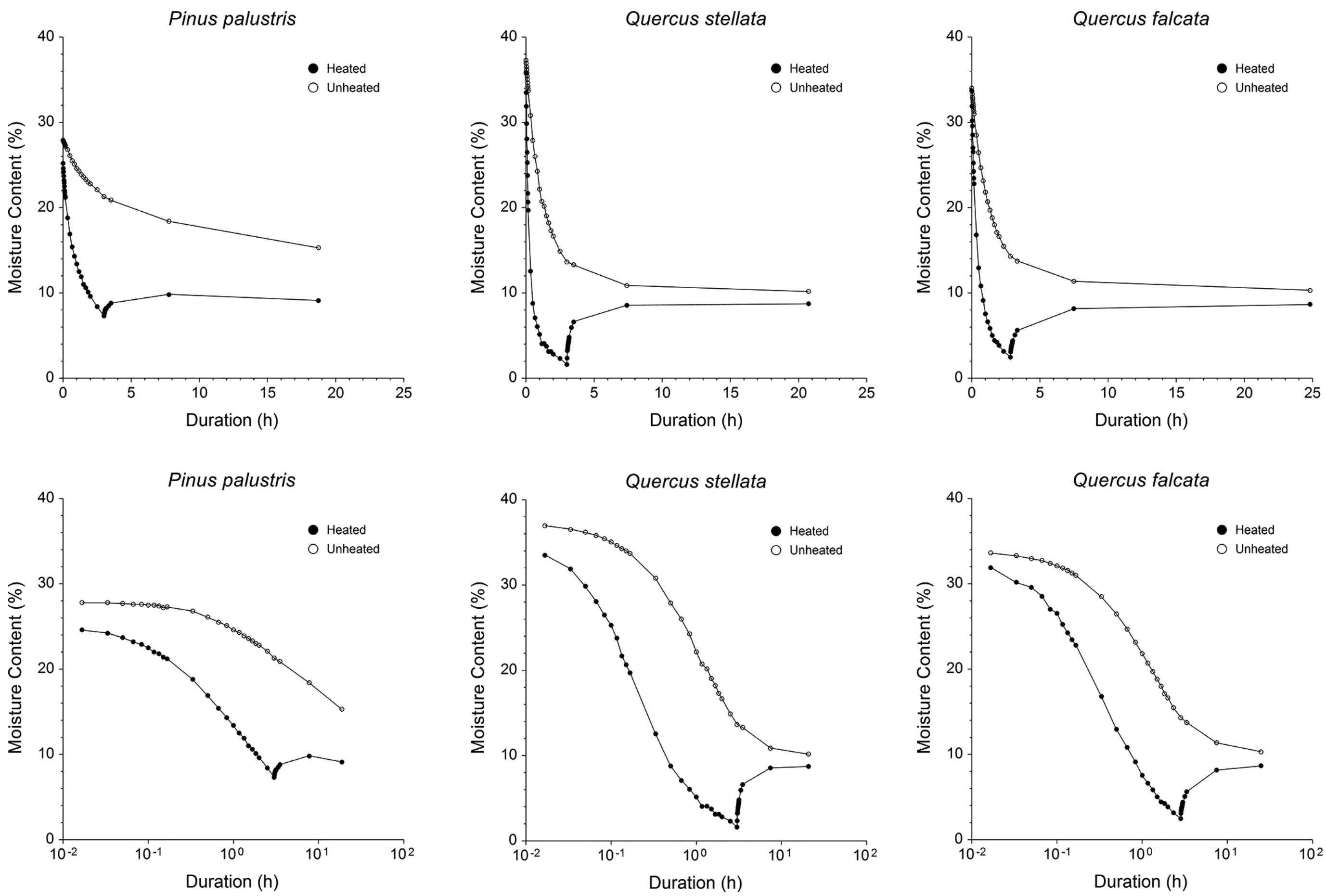


Table 2. Observed weather during outdoor mesocosm and within-forest fuel drying experiments at Tall Timbers Research Station, Florida, U.S.A.

Date	Temperature (°C)	RH (%)	Wind (m·s⁻¹)	Solar radiation (W·m⁻²)
Mesocosm experiment				
12 September 2016	21–31	76–100	0.0–1.4	0–526
13 September 2016	23–32	67–100	0.0–3.0	0–779
22 October 2016	10–22	26–80	0.5–4.0	0–744
Within-forest experiment				
31 July 2017	23–29	61–93	0.9–1.8	74–810
1 August 2017	19–30	51–91	0.6–1.7	80–879
2 August 2017	23–31	66–97	1.0–2.2	22–615

Note: Data are from 0800–1400 local time. Relative humidity (RH) and wind data are based on 10 min average.

ing as low as 26% compared with 67% and 76% minima during the 12 and 13 September experiments, respectively. Surface temperatures of litter, measured by thermal imagery, increased from morning to afternoon, but litter exposed directly to solar radiation was significantly hotter, i.e., as much as 10–15 °C, on average, during peak solar heating compared with shaded litter for both *Pinus* and *Quercus* species (Table 3; Figs. 5 and 6).

At the beginning of each experiment, *Quercus* samples that were randomly assigned for shading did not differ in moisture content from those to be exposed to solar radiation ($P = 0.362$, 12 September; $P = 0.947$, 13 September; $P = 0.687$, 22 October). Moisture content of *Quercus* litter was much higher than that of *Pinus* litter on the mornings of all experiments (Table 3; Fig. 7), likely a result of substantial surface moisture from dew on the large *Quercus* leaf litter. *Quercus* litter was approximately three times greater in moisture content as a percentage of dry mass compared with *Pinus* litter on both September mornings (0900) and almost twice as high as *Pinus* at 0930 on the drier day in October. Post hoc differences between *Q. stellata* and *Q. falcata* were not detected at 0930 on 22 October. By late morning on all experimental days (1100 in September, 1130 in October), considerable drying had occurred across all species, with evidence of increased drying in the sun vs. shade treatments (Table 3). Across all species, unshaded litter was drier than its shaded counterpart on all days, but sun-exposed *Quercus* litter dried exceptionally fast. On 12 September, shaded *Q. stellata* had dried from 112% down to 23% moisture content and unshaded *Q. stellata* had dried from 113% to only 12% moisture content by 1100. Although all *Quercus* litter dried rapidly, on 13 September at 1100, an interaction between species and shading treatment was detected, with shaded *Q. falcata* litter still being wetter than all other litter (unshaded *Q. falcata*, unshaded or shaded *P. palustris*). On the drier October day, shaded litter was wetter than unshaded litter, but post hoc differences between species revealed that *P. palustris* and *Q. stellata* were drier than *Q. falcata*. By midday, when peak prescribed burning conditions

Fig. 4. Air temperature and solar radiation during outdoor small-scale drying experiments. Weather data are from a remote automated weather station located at Tall Timbers Research Station, Florida, USA.

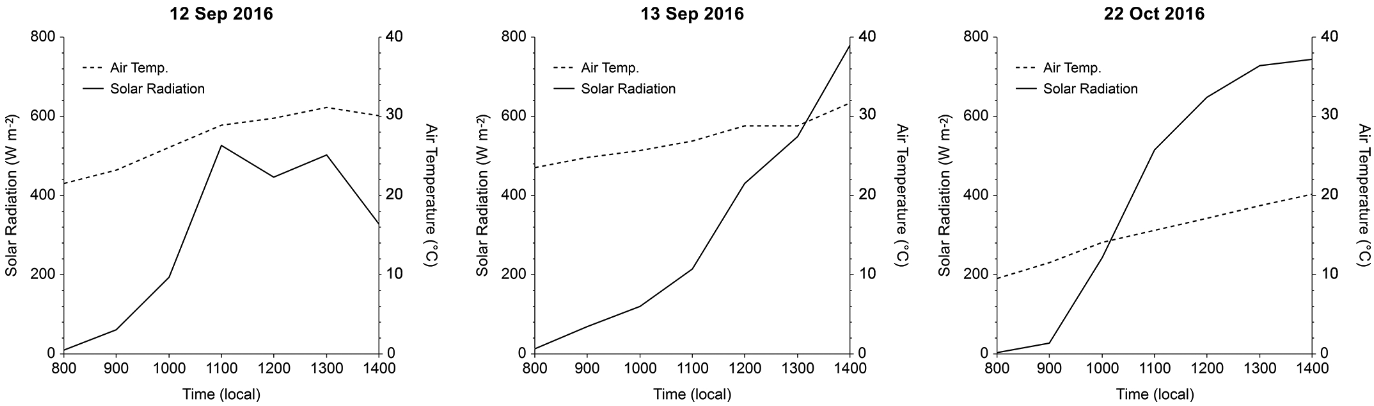


Table 3. Gravimetric moisture content of shaded and unshaded longleaf pine (*Pinus palustris*) and oak (*Quercus falcata* and (or) *Q. stellata*) litter during three small-scale (mesocosm) outdoor solar-heating experiments (at 0900, 1100, and 1300 on 12 and 13 September 2016 and at 0930, 1130, and 1330 on 22 October 2016).

12 September 2016						
	0900		1100		1300	
Species (treatment)	Moisture content (%)	Fuel temperature (°C)	Moisture content (%)	Fuel temperature (°C)	Moisture content (%)	Fuel temperature (°C)
P. palustris (shaded)	36 (2)	24.1 (0.1)	20 (1)	28.6 (2.5)	16 (0)	34.0 (0.2)
P. palustris (unshaded)	36 (4)	25.6 (0.1)	15 (1)	41.6 (0.9)	11 (1)	39.4 (0.6)
Q. stellata (shaded)	112 (10)	23.3 (0.1)	23 (2)	30.7 (0.2)	16 (1)	37.8 (0.9)
Q. stellata (unshaded)	113 (10)	23.9 (0.2)	12 (2)	46.3 (1.3)	10 (0)	41.5 (0.5)
Species	$P < 0.001$	$P < 0.001$	$P = 0.695$	$P = 0.048$	$P = 0.376$	$P < 0.001$
Treatment	$P = 0.903$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$
Species × treatment	$P = 0.933$	$P = 0.006$	$P = 0.074$	$P = 0.402$	$P = 0.268$	$P = 0.199$
13 September 2016						
	0900		1100		1300	
Species (treatment)	Moisture content (%)	Fuel temperature (°C)	Moisture content (%)	Fuel temperature (°C)	Moisture content (%)	Fuel temperature (°C)
P. palustris (shaded)	51 (6)	25.5 (0.1)	27 (1)	32.4 (0.3)	17 (1)	32.8 (0.3)
P. palustris (unshaded)	42 (1)	26.5 (0.3)	24 (1)	37.8 (0.3)	13 (1)	40.7 (0.4)
Q. falcata (shaded)	148 (6)	24.9 (0.1)	51 (3)	32.8 (0.6)	23 (1)	34.4 (1.0)
Q. falcata (unshaded)	128 (4)	25.6 (0.1)	31 (2)	45.0 (1.0)	10 (1)	45.0 (1.4)
Species	$P < 0.001$	$P = 0.005$	$P < 0.001$	$P < 0.001$	$P = 0.177$	$P = 0.012$
Treatment	$P = 0.017$	$P = 0.002$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$
Species × treatment	$P = 0.303$	$P = 0.444$	$P = 0.006$	$P < 0.001$	$P < 0.001$	$P = 0.168$
22 October 2016						
	0930		1130		1330	
Species (treatment)	Moisture content (%)	Fuel temperature (°C)	Moisture content (%)	Fuel temperature (°C)	Moisture content (%)	Fuel temperature (°C)
P. palustris (shaded)	17 (1)	12.2 (0.1)	15 (1)	16.3 (0.2)	12 (1)	19.9 (0.2)
P. palustris (unshaded)	19 (2)	14.2 (0.5)	12 (0)	26.8 (0.5)	9 (0)	31.2 (0.4)
Q. stellata (shaded)	35 (4)	11.5 (0.0)[a]	16 (1)	17.4 (0.3)[a]	11 (2)	21.6 (0.5)[a]
Q. stellata (unshaded)	34 (3)	13.3 (0.4)[a]	12 (0)	22.9 (1.6)[a]	7 (1)	32.3 (0.1)[a]
Q. falcata (shaded)	29 (1)		20 (1)		14 (1)	
Q. falcata (unshaded)	30 (1)		16 (1)		9 (1)	
Species	$P < 0.001$	$P = 0.044$	$P < 0.001$	$P = 0.125$	$P = 0.062$	$P = 0.002$
Treatment	$P = 0.817$	$P = 0.023$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$
Species × treatment	$P = 0.797$	$P = 0.841$	$P = 0.461$	$P = 0.019$	$P = 0.671$	$P = 0.389$

Note: Experiments were started (shade devices installed) at 0800 on 12 and 13 September 2016 and at 0830 on 22 October 2016.
[a]Temperatures were not differentiated between *Quercus* species.

typically occur, differences in moisture content between species were no longer evident; however, sun-exposed litter was still drier than all shaded counterparts. By 1300 on 12 and 13 September, shaded litter ranged from 16% to 23% moisture content, while unshaded litter ranged from only 10% to 13% moisture content. On the drier October day, shaded litter ranged from 11% to 14% moisture content, while litter exposed to the sun was only 7% to 9% moisture content.

Fig. 5. Fuel temperatures of shaded and unshaded *Pinus* and *Quercus* litter during outdoor small-scale (mesocosm) drying experiments. Three separate experiments were conducted on 12 September 2016 (left), 13 September 2016 (center), and 22 October 2016 (right).

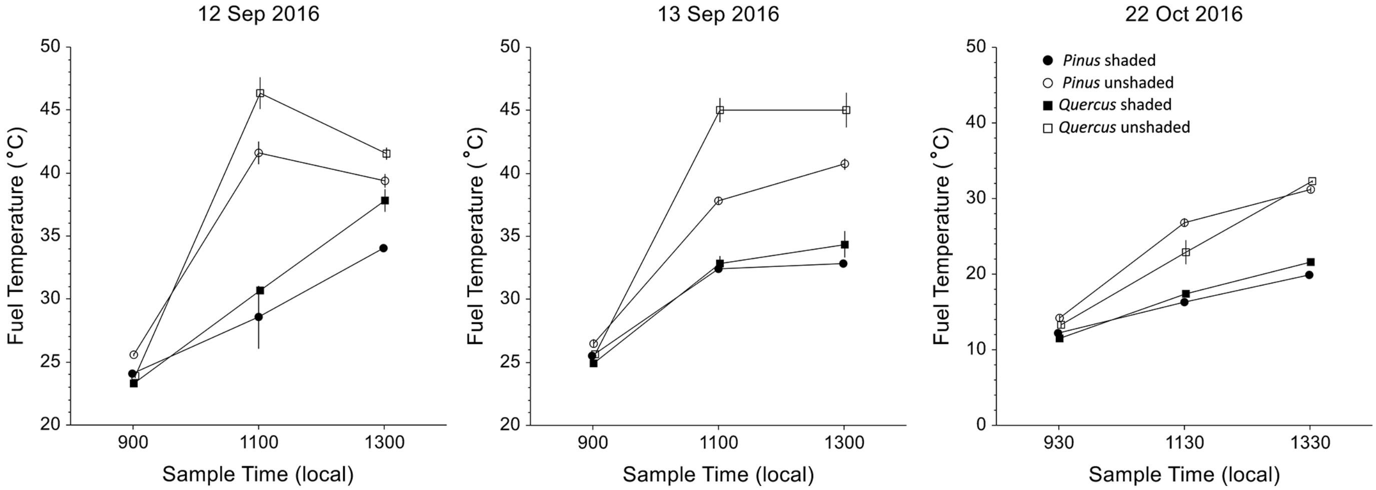
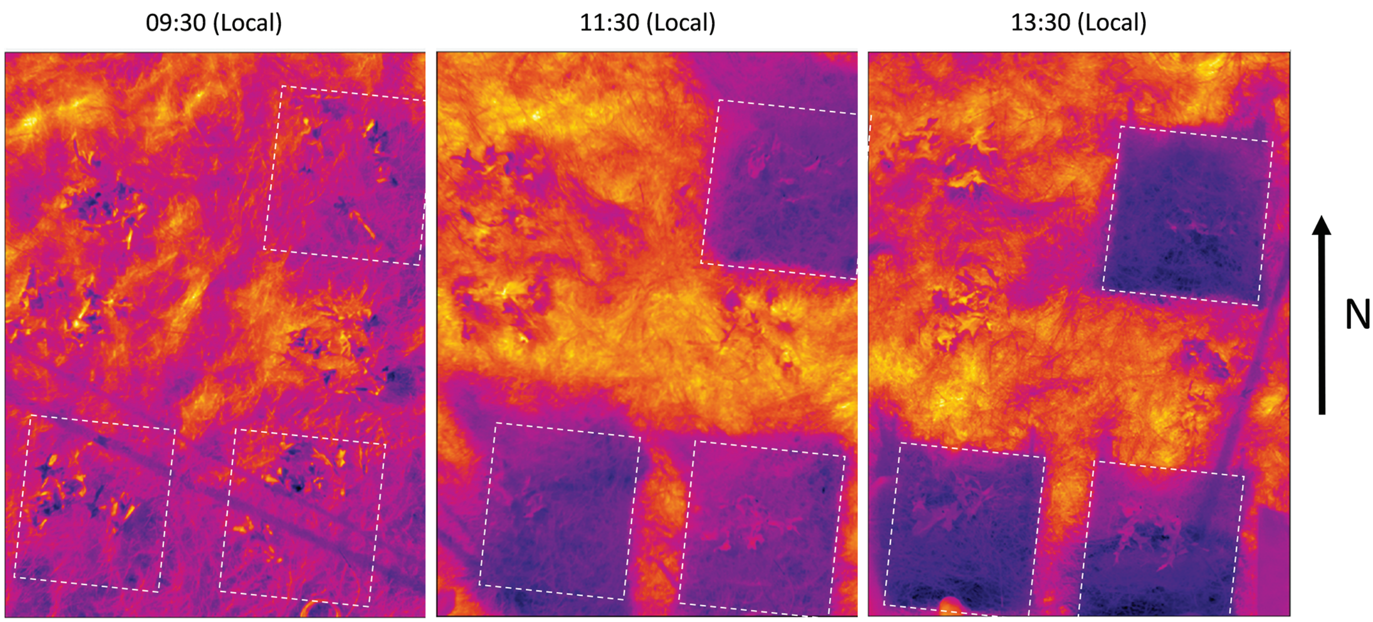


Fig. 6. Thermal infrared images of shaded and unshaded *Pinus palustris*, *Quercus stellata*, and *Q. falcata* litter during outdoor small-scale drying experiments (22 October 2016). Shading devices were removed immediately prior to image capture and their shadows are demarcated by the dashed lines. Lighter colors represent hotter surface temperatures compared with darker colors; however, temperature scales differ across the three sample times (0930, 7.7–22.0 °C; 1130, 12.2–33.0 °C; 1330, 15.8–43.4 °C).



Within-forest field experiment

Weather conditions during the within-forest experiments were consistently warm, reaching 30 °C on each of the three days, but while hourly averaged solar radiation reached almost 900 W·m^{-2} on the first two days, it only reached 615 W·m^{-2} on day 3 (Fig. 8; Table 2). Relative humidity dropped to 57%, 51%, and 66% on days 1, 2, and 3, respectively, typical for prescribed burning operations in the region. Within-forest fuel moisture patterns of diurnal drying largely tracked those of the mesocosm experiment. At the start of experiments, initial moisture content of *Pinus palustris* needles did not differ between sun and shade treatments (P = 0.439) or between litter positions (P = 0.659), averaging 22%. By 1400, however, there were significant main effects of canopy shade and understory position (Fig. 9). Shaded litter moisture averaged 8% at 1400, while litter exposed to the sun was significantly drier (P = 0.012), averaging only 4% moisture content. Elevated litter averaged 6% moisture content by 1400, but litter on the ground was slightly drier (P = 0.007), averaging 5%. There was no interaction between the effects of sun exposure and litter position (P = 0.309). Unshaded litter on the ground achieved the lowest moisture content (3%; Fig. 9) on day 1. While unshaded litter and litter on the ground appeared to become wetter overnight compared with shaded and elevated litter, respectively, afternoon litter moisture conditions on both days 2 and 3 followed the same drying trends as observed on day 1 (Fig. 9), with exposed litter and litter on the ground becoming drier than shaded and elevated litter, respectively.

Discussion

Solar radiation played a dominant role in both surface-fuel temperatures and moisture content of *Pinus* and *Quercus* litter examined in this study. Brief durations of exposure to infrared radiation and full sun resulted in dramatic declines in fuel moisture. Because of hysteresis (Blackmarr 1971), once fuel particles are

Fig. 7. Gravimetric moisture content of shaded and unshaded *Pinus palustris*, *Quercus stellata*, and *Q. falcata* litter during outdoor small-scale drying experiments. Three separate experiments were conducted on 12 September 2016 (left), 13 September 2016 (center), and 22 October 2016 (right).

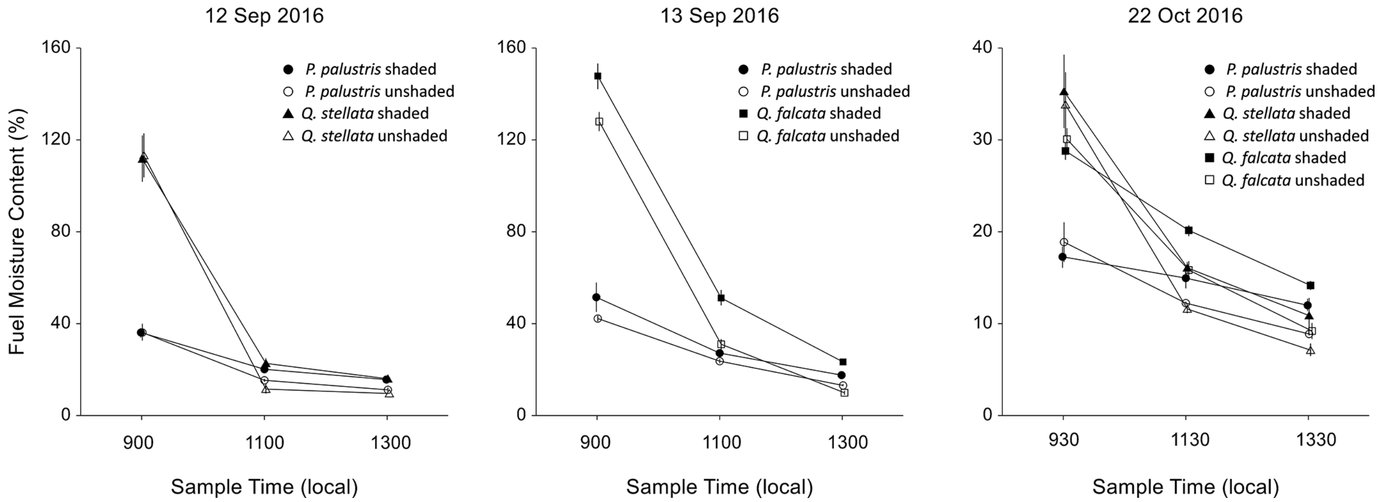


Fig. 8. Air temperature and solar radiation during within-forest experiments. Weather data are from a remote automated weather station located at Tall Timbers Research Station, Florida, USA.

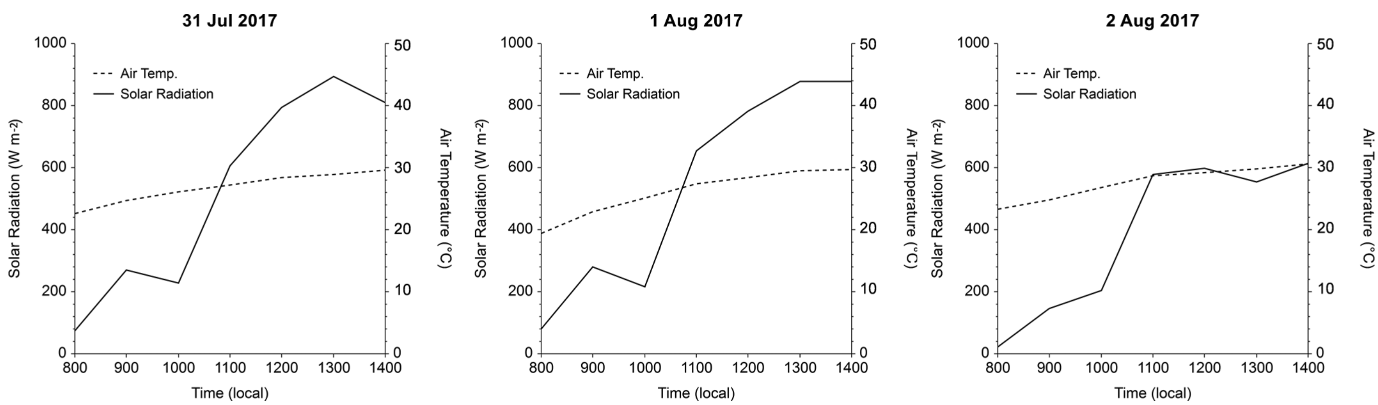
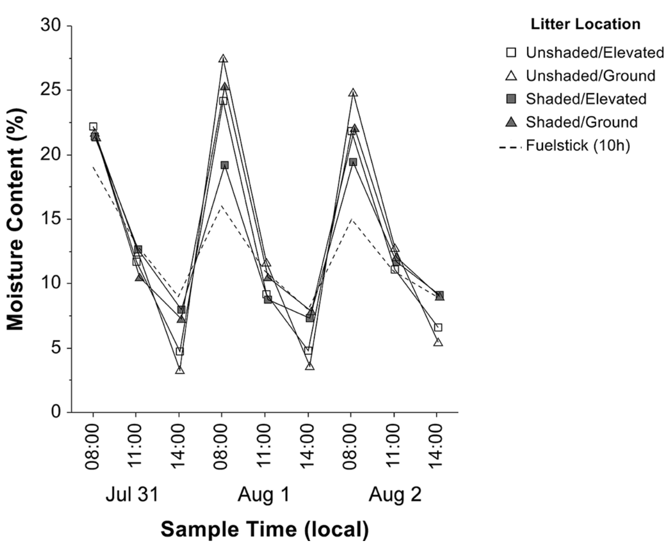


Fig. 9. Moisture content of elevated and ground-level *Pinus palustris* litterbeds that were either shaded or unshaded within a mature *P. palustris* forest. The dashed line indicates the moisture content of the 10-h fuelstick measurements from the nearest (approximately 100 m away) remote automated weather station.



driven below an equilibrium moisture content by solar radiation, they retain a drier state even as conditions become stable (indoor drying state). Thus, subsequent exposure to sun can result in aggregate drops in fuel moisture even in a forest of moderate canopy closure (gaps in this study averaged 41.3% openness).

Results of experiments conducted inside and outside of laboratory conditions consistently showed that exposure to solar radiation caused dynamic litter drying despite high-humidity conditions that typically exceeded 65%. Humid conditions occur year-round in this and other temperate regions where prescribed fire is widely applied and surface-fuel boundary-layer conditions are likely important where atmosphere conditions are otherwise moist. Moisture loss was more rapid in heated fuels, and these effects were more pronounced in *Quercus* spp. litter in comparison with *Pinus*, but by peak burning conditions in mid-afternoon, all litter types achieved fuel moisture values below 5% in full sun — far lower than fuel sticks or estimated fuel moisture using standard tables. Examination of *Pinus* litter moisture in the field revealed that both shading and fuel position (elevated vs. ground) influenced moisture dynamics.

The pronounced effects of shading and radiation input on litter moisture across these experiments reveal the dominant role of solar heating on fine fuel moisture dynamics in high-humidity fuel types. Litter drying rates increased when litter was exposed to the sun at fine temporal scales (<1 h). Even during outdoor studies where clouds occurred intermittently throughout the drying periods, solar input resulted in significantly drier litter than shaded litter. Infrared imaging revealed substantial solar heating of surface fuels exposed to the sun. Increases in litter temperature resulting in drier fuels have been previously observed (Byram and Jemison 1943), and the spikes in temperature recorded with infrared imagery measured in excess of 55 °C in our laboratory experiments. Such spikes in surface temperature are expected to reduce potential fuel equilibrium moisture content through boundary-layer changes in vapor pressure deficit (Byram and Jemison 1943); saturation vapor pressure, and thus vapor pressure deficit, increases exponentially with temperature (Will et al. 2013). Rapid drying of radiated litter during indoor laboratory experiments was also followed by a hysteresis effect (Blackmarr 1971; Nelson 1984) — evident in our data for hours after temporary exposure to radiation — in which adsorbing litter does not become as wet as drying litter under similar atmospheric conditions. Such a dynamic of rapid drying followed by hysteresis would create a phenomenon of additive reductions of fine dead fuel moisture when exposed to sunflecks and intermittent shade under relatively closed canopies. The longleaf pine canopies here were of modest density, with an average overall 44% canopy openness, but despite readings of minimum afternoon relative humidity in the 60% to 80% range, fuel moistures measured only 4%–5% in no-shade treatments (Fig. 9).

Similar to laboratory observations of Nelson and Hiers (2008), pine needle position within the fuelbed was also significant. Observed interactive effects of shading and litter position (ground vs. elevated) on moisture dynamics in conjunction with the above effects highlight the complexity of fuel drying and how vegetation structure may impact forest floor moisture content through fine-scale heterogeneous patterns (Hiers et al. 2009). Position at the surface of the ground provides greater shading from the lowest sun angles and modifies the evaporative cooling from surface winds during peak sun. Without shading, the ground fuels quickly equal or drop below the moisture content of perched litter as sun angles increase with mid-day exposures (Fig. 9). The fact that fuelbeds on the forest floor achieved lowest fuel moisture observed in this study further points to the importance of local boundary conditions on fuel temperature as a driving mechanism for moisture loss. If exposed needles above the forest floor are cooled by ambient wind, their local boundary conditions may represent lower vapor pressure deficits, and thus higher humidity, under the same solar exposure. Given cooler and wetter boundary-layer conditions near litter surfaces exposed to wind, higher equilibrium moisture content would be expected (Byram and Jemison 1943). The complexities of wind effects on surface-fuel moisture highlight the importance of boundary-layer conditions, particularly in these humid environments.

Litter moisture was higher than the weather station's 10 h fuel stick, particularly in *Quercus* litter, in the mornings of the within-forest experiments, as well as on the mornings of the outdoor mesocosm experiments, presumably a result of not only high humidity, but also dew formation (Matthews 2014). This dew appears to account for the greater diurnal dynamism of *Quercus* fuel moisture content. *Quercus* litter was significantly wetter than *Pinus* litter on the mornings of these experiments. Leaf morphology and resultant impacts on fuelbed properties (e.g., bulk density) influence drying rates among forest litter in the region (Kreye et al. 2013), and the differences observed here highlight needle vs. broadleaf differences in moisture holding capacity and dew interception. Moreover, *Quercus* litter dried more rapidly than *Pinus* litter in the outdoor experiments, and both *Quercus* and *Pinus* litter were sufficiently dry by early afternoon. While solar radiation increased moisture loss across species, the effect on *Quercus* litter was even more pronounced. The role of certain *Quercus* spp. litter in the flammability of fire-adapted *Pinus palustris* ecosystems may often be underappreciated (Kane et al. 2008; Kreye et al. 2013). Early ignition times, typical of prescribed burns, may mean that *Quercus* litter is less likely to ignite compared with *Pinus* litter, but diurnal drying patterns suggest increased flammability later in the day as prescribed burns progress, especially where deciduous oaks allow solar radiation input to forest floor fuels following litterfall.

Our contrasts between shade, sun, and litter position suggest that current NFDRS predictions may not be sufficiently accurate for many prescribed fire planning purposes. *Pinus* and *Quercus* litter, along with herbaceous vegetation, dominate surface fuels burned in much of the fire-prone pyrophytic ecosystems of the southeastern US. The use of 10 h wooden dowels, either measured in situ or modeled, as a surrogate is further complicated for such applications and may underscore the importance and effects of solar radiation on fine dead litter fuels. The surface area to volume ratio of 10 h fuel sticks is much lower than that of forest litter, and changes in fuel surface temperature and fuel–atmosphere humidity, brought on by solar heating, would likely be less impactful on energy and moisture exchanges than that of fine litter (Nelson 2000). *Pinus* litter, despite its small diameter needles, reacts as a ≥10 h fuel in a horizontal fuelbed (Nelson and Hiers 2008), confirmed here in shaded environments. Under solar heating, however, these compact fuels appear to react more quickly and *Quercus* leaves react much more quickly to irradiance. Fine-scale spatial heterogeneity and temporal dynamics of forest floor moisture are not taken into account in NFDRS predictions and are likely important for understanding heterogeneous fire behavior and effects.

Given the significant solar impact on surface-fuel temperatures observed in these experiments, it is important to consider boundary conditions at the fuel surface for predicting fuel moisture dynamics rather than simply atmospheric conditions. Byram and Jemison (1943) understood that boundary conditions at the fuel surface were the environmental conditions that controlled fuel moisture. Because the temperature of the fuel dictates the boundary layer's relative humidity and vapor pressure deficit (Byram and Jemison 1943; Nelson 2000), it is important to accurately capture boundary conditions to correctly estimate fuel moisture using equilibrium moisture content (EMC) theory. Large differences between atmospheric and fuel surface conditions would be expected in humid environments with significant exposure of fuels to the sun such as the southeastern US. The flammability of fuels in these humid environments may be better understood through incorporating dynamics at fuel boundary-layer conditions. In arid environments, such differences may be less pronounced. In semiarid ponderosa pine forests of northern Arizona, Faiella and Bailey (2007) did not observe differences in fine dead fuel moisture between thinned and unthinned sites between June and October, when fuels were typically dry. In the mixed-conifer forests of California, Estes et al. (2012) revealed little differences in woody moisture between thinned and unthinned stands but did indicate that seasonal drying was most important. Banwell et al. (2013) showed that litter and woody fuels were consistently dry during fire seasons in Sierra Nevada Jeffrey pine – white fir forests regardless of spatial position, beneath canopy or in the open, but that duff was wetter beneath trees compared with at or beyond their driplines. They did, however, reveal considerable variability of forest floor fuel moisture at fine temporal scales (hours). Impacts of solar heating on fine fuel moisture dynamics may vary across regions of disparate climates as a result of varying divergence patterns between that of surface boundary conditions and within- or above-canopy atmosphere.

The rapid response of fine dead forest floor litter to varied environmental conditions and the spatial heterogeneity likely to occur as a result of the patterns observed here mean that prescribed fire planning would benefit from more localized predictions (Pook and Gill 1993). Solar heating, fuel position, and *Pinus* vs. *Quercus* species influenced moisture dynamics of forest litter at laboratory and field scales. Better incorporating the sun's influence and the differential response of litter fuels in regional models would be useful. At more localized scales, stand mapping may be helpful for predicting forest floor solar exposure, litter composition, and patterns and dynamics of forest floor moisture. While alterations to canopy structure, via forest management or fuels treatments, are unlikely to impact surface-fuel moisture in arid environments (Faiella and Bailey 2007; Estes et al. 2012), because fuels are dry, such impacts are likely to be more important in humid regions. Recent advances in fine-scale geospatial applications, e.g., LIDAR (Hudak et al. 2016), could be used in conjunction with fine-fuel moisture models (Matthews 2014) to more precisely predict moisture dynamics in these litter-dominated fuels. Models developed to predict spatial heterogeneous patterns of surface-fuel moisture would benefit from representing the complexity of vegetation structure. Spatial representation of surface fuels, e.g., needle or broadleaf fuel models, could be assumed given spatially explicit overstory mapping. Additional research and modeling needs include making better use of gridded weather forecasts, better understanding of the moisture exchange between litter and organic–mineral soils, and incorporating uncertainty into fuel moisture predictions. Observations made in this study should be more broadly examined to better understand fine-scale surface-fuel moisture dynamics and to aid managers in more precisely applying prescribed fire to meet management objectives.

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