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RESEARCH ARTICLE

SEASONAL VARIATION IN FLAMMABILITY CHARACTERISTICS OF *QUERCUS MARILANDICA* AND *QUERCUS STELLATA* LEAF LITTER BURNED IN THE LABORATORY

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ABSTRACT

Historically, the Cross Timbers forest of Oklahoma, Kansas, and Texas burned frequently. Fire managers in the region often have varied success when conducting prescribed fires, with one hypothesis being that fuel quality varies with litter age. This study was designed to determine the time-since-leaf-fall flammability characteristics of the two dominant tree species in the Cross Timbers, *Quercus marilandica* and *Q. stellata*. Principal components analysis indicated that the burn characteristics of both species are strongly influenced by time since the onset of leaf fall. The percent consumption of leaf litter and flame time of the two species began to diverge at 123 days after leaf fall and continued throughout the remainder of the study. There was no difference between the other flammability characteristics of ember time, total burn time, average temperature, and maximum temperature. Fuel consumption and fire behavior in hardwood leaf litter fuels can vary considerably, possibly as result of fuel mass loss from decomposition, which may due to a loss of flammable material. Our results show that

RESUMEN

Históricamente, el bosque “Cross Timbers” de Oklahoma, Kansas y Texas se quemaba frecuentemente. Los gestores del fuego en esta región han tenido un éxito desigual en la implementación de quemas controladas, siendo una de sus hipótesis que la calidad del combustible varia con la edad de la hojarasca. Este estudio fue diseñado para determinar la inflamabilidad de estos combustibles desde la caída de la hoja para las dos especies dominantes en Cross Timbers, *Quercus marilandica* y *Q. stellata*. Un análisis de componentes principales indica que las características de combustión de ambas especies están influidas fuertemente por el tiempo transcurrido desde la caída de la hoja. El porcentaje de hojarasca consumido y el tiempo de duración de la llama de las dos especies comenzaron a divergir a 123 días de la caída de la hoja, manteniéndose durante el resto del estudio. No existieron diferencias en otras características de flamabilidad, como duración de las pavesas, tiempo total de consumo o temperatura media y máxima. El consumo y comportamiento del fuego en la hojarasca de latifoliadas puede variar considerablemente, posiblemente como resultado de la pérdida de masa debida a la descomposición, lo que puede ser causado por la pérdida de material inflamable. Nuestros resultathe longer the time period from leaf fall to burn, the greater the change in burn characteristics of these two *Quercus* species. By identifying these similarities and differences between the leaf litter of dominant tree species, fire managers can adjust fire prescriptions to better meet burn objectives.

dos muestran que en estas especies de *Quercus,* la combustión varía más a medida que pasa más tiempo desde la caída de la hoja. A través de la identificación de estas similitudes y diferencias entre la hojarasca de estas dos especies dominantes, los gestores del fuego pueden ajustar sus quemas controladas para cumplir mejor con sus objetivos.

Keywords: blackjack oak, litter consumption, prescribed fire, post oak

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INTRODUCTION

Fire and human activity have affected the past and present ecology of oak forests (Abrams 1992). With increased fire exclusion in the twentieth century, the majority of oak savannas and woodlands have transitioned to closed canopy forests with corresponding shifts in species composition (Dey and Hartman 2005, DeSantis *et al.* 2011). The Cross Timbers, or post oak (*Quercus stellata* Wangenh.)-blackjack oak (*Q. marilandica* Muenchh.), forest contains about 19 million ha of upland hardwood forest-tallgrass prairie, ranging from southeastern Kansas, through Oklahoma, and into north Texas (Engle 1994). Historically this region was prone to frequent fire (Stambaugh and Guyette 2006, Clark *et al.* 2007, Stambaugh *et al.* 2009), but due to settlement, landscape fragmentation, and fire suppression, the historic fire pattern has been interrupted.

As fire management personnel in the region reintroduce fire, they have experienced varied success. The flammability and fire behavior in the leaf litter fuels seem to be unpredictable (Sparks *et al*. 2007). From other studies and personal experience of the senior author, the traditional late winter to early spring fires often fail to spread or consume little of the leaf litter fuels (Engle and Strizke 1995, Sparks *et al.* 2002). Information is needed to determine if there is a time of year better suited to promote fire spread and consumption of these fuels, two major objectives of fire management in the region.

Little information is available on seasonal leaf litter flammability characteristics in the Cross Timbers forest or in other oak forest systems. Some studies have investigated fire effects on oak leaf litter, showing the importance of fuel moisture, leaf shape, and fuel loading (Graham and McCarthy 2006, Schwilk and Caprio 2011); others reported results of fire intensity, fire temperature, and total combustion, but not as an important component of the study, leaving us with limited information on flammability (Boyer 1990, Masters and Engle 1994, Engle and Strizke 1995, Clinton *et al.* 1998, Boerner *et al.* 2000). Also, these and other studies only evaluated burning at a single time of the year, not throughout the entire year (Kane *et al.* 2008, Engber and Varner 2012). Several of these studies were also conducted with fuels intermixed with pine or 10 hr timelag fuels, which can change the overall flammability of the fuel bed. We could not find any research that specifically addressed the seasonal flammability of oak leaf litter, specifically *Q. stellata* and *Q. marilandica*. Species-specific leaf flammability is an important component of total flammability (Fonda *et* *al*. 1998). In this study, we removed all of the field variation of temperature, relative humidity, fuel moisture, additional fuels, and burning in only one season to determine if there was any variation in flammability throughout the year of these leaf litter fuels, as well as differences in flammability between the two oak species. Based on our past field observations we hypothesized that time-since-leaf-fall will greatly affect the burn characteristics of both *Q. stellata* and *Q. marilandica,* and will do so relatively similarly between species. This study increases the knowledge base of oak litter flammability from this region and potentially elsewhere, and increases the effectiveness and predictability of prescribed fire.

METHODS

Leaf samples were collected monthly from leaf fall in November 2006 until the initiation of the next year's leaf fall in October 2007, on the Oklahoma State University Research Range, located 13 km west of Stillwater, Oklahoma, USA. Samples were randomly collected each time from the surface layer of litter within the same 50 m × 50 m area. The samples were separated by species, *Q. stellata* and *Q. marilandica*, and placed in paper bags to facilitate drying. Leaves were oven dried at 49 °C for a minimum of 72 hr prior to burning in the laboratory to ensure consistent fuel moisture content among all samples. To reduce sample variation due to absorption of moisture over time, samples remained in the drying oven until prepared for burning.

Flammability of the leaves was determined by methods modified from Taylor and Fonda (1990). Forty samples per species per month were burned in the laboratory for a total of 880 burns. Our fuel bed for each burn was composed of a sample of leaves weighed out to 10.00 g to 10.09 g and arranged so they would fit within a 25 cm × 25 cm area on a 35 cm × 35 cm flat metal tray, and all fuel beds were <4 cm deep. Fuel beds did vary over the sample time; earlier in the sample period fuel beds were thicker and less compact due to leaf size (3 cm to 4 cm deep). As time from leaf fall increased, leaves were often broken and more decomposed, which made the fuel beds more compact and thinner (2 cm to 3 cm deep). Each prepared sample was placed under a 62 cm × 98 cm laboratory fume hood with the vent running. Four 25 cm long pieces of 1.4 kg cotton string were soaked in xylene and placed overlapping each other on top of the sample, and within 2 cm of the sample edge, to achieve ignition. The string was ignited at a single point and the fume hood door closed. Initially the twine was placed under the samples, as described by Taylor and Fonda (1990), but consistent and even ignition of the samples could not be obtained using this method. A type K thermocouple of 24 AWG insulated wire was positioned 10 cm above the center of the tray then attached to a ExTech™ EasyView15 thermometer datalogger (FLIR Commercial Systems, Nashua, New Hampshire, USA) to record maximum and average burn temperatures (average of temperature from ignition to extinction of last glowing ember). In the darkened laboratory, flame time (time from ignition to extinction of last flame) and total burn time (time from ignition to extinction of last glowing ember) was recorded with a stopwatch. From these two readings we determined ember time (time from the extinction of last flame to the extinction of last glowing ember). After the sample had completed combustion, the percent consumption of the sample was determined by weighing the remaining residue. Individual leaf weights were determined just prior to burning by randomly selecting and weighing 50 individual leaves by species from each sample for each collection period ($n = 1110$).

Principal components analysis (PCA) (McCune and Grace 2002) was used to analyze burn characteristics (flame time, burn time, ember time, average temperature, and maximum temperature and consumption) collectively between *Q. stellata* and *Q. marilandica* leaves over the duration of the study period. Individual burn characteristics were not independent and had a mean partial correlation of r = 0.28 and ranged between 0.07 and 0.97 among pair-wise comparisons of variables. Therefore, they are not suitable for individual statistical analysis. We compared the mean PCA axis scores for each for *Q. stellata* and *Q. marilandica* leaves separately, with regression lines fit using functions of the elapsed time (days) since leaf fall at the end of the growing season. The Akaike's Information Criterion (AIC; McCune and Grace 2002) was used for selection among linear and polynomial models. To compare the change in collective burn characteristics over time between species, we used a two-tailed *t*-test to compare slopes of the fitted regression lines (Steel *et al*. 1997). Individual burn characteristics were fitted with regression models to indicate trends only. To compare collective burn characteristics between the two species at specific sampling dates, a two-tailed *t*-test was used to detect differences between the 40 mean axis 1 scores for both *Q. stellata* and *Q. marilandica* for each sampling period. To better understand the change in leaf physical properties over time, we compared the mean leaf weight for each species with regression lines using a similar AIC model selection process. A two-tailed *t*-test was used to detect differences in individual leaf weight between the two species at specific sampling dates. All analyses used $\alpha = 0.05$ to determine significance.

RESULTS

Output from the PCA revealed a strong ordination of the six burn characteristics of oak litter. Axis 1 accounted for approximately 52 % of the variation, axis 2 accounted for an additional approximately 20 % of the variation, and axis 3 comprised an additional ~14 % of the variation in oak litter flammability (86 % cumulative variation among the 3 axes). The mean scores from axis 1 for both *Q. stellata* and *Q. marilandica* were strongly correlated (r^2 = 0.93 and r^2 = 0.96, respectively) with time since leaf fall (Figure 1A). Neither axis 2 nor axis 3 scores produced a significant regression model for the two species. Average temperature was positively correlated with axis 1 (r = 0.69), while maximum temperature, burn time, ember time, and percent consumption each were strongly and negatively correlated with axis 1 scores (r = –0.63, r^2 = –0.91, r^2 = –0.93, and r^2 = –0.72, respectively) (Figure 1B).

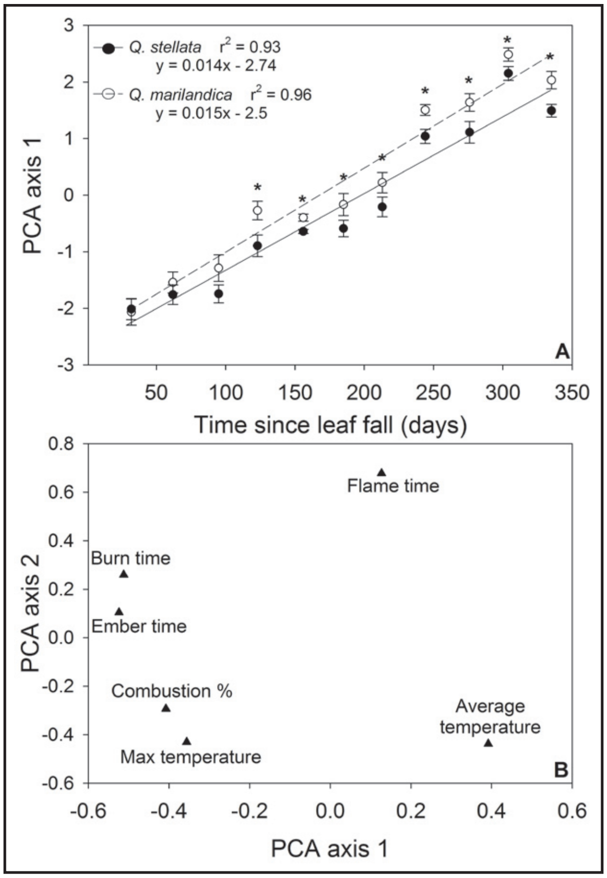

Figure 1. (A) Mean PCA axis 1 scores for *Quercus stellata* and *Quercus marilandica* burn characteristics at regular intervals after leaf fall. Asterisks indicate statistical differences ($P \leq 0.05$) between the two oak species. (B) The eigenvectors of burn characteristics for axis 1 and axis 2 represent a cumulative variation of 72 % across both oak species. Leaf litter samples were collected from the Oklahoma State University Range Research Station near Stillwater, Oklahoma, USA.

Flame time was the only variable that was not strongly correlated with axis 1 in the analysis (r = 0.22), but was correlated with axis 2 (r = 0.75).

Burn characteristics for *Q. marilandica* and *Q. stellata* were similar initially, but diverged beginning 123 days after leaf fall (Figure 2A). Differences in percent consumption were observed with *Q. marilandica* averaging 71% and *Q. stellata* averaging 66% consumption across all sampling periods (Figure 2A). Their variation in total flame time was greater than ember time and total burn time measurements, and began to separate the two species

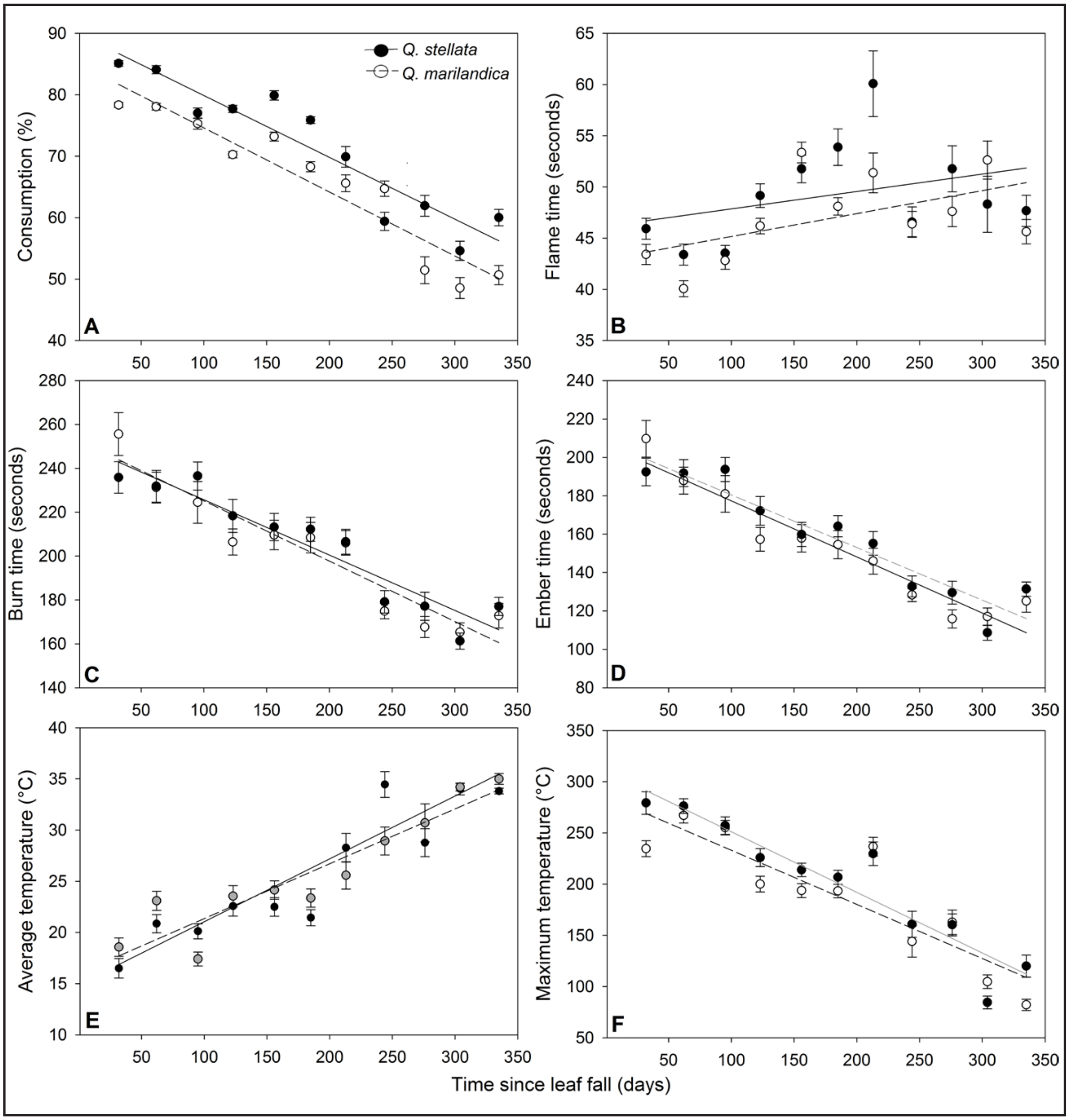

Figure 2. Trends of burn characteristics of *Quercus stellata* and *Quercus marilandica* at regular intervals after leaf fall. Leaf litter samples were collected from the Oklahoma State University Range Research Station near Stillwater, Oklahoma, USA.

123 days after leaf fall (*Q. marilandica* 46 sec, *Q. stellata* 49 sec) (Figure 2B).

Flammability of the two oak species declined with time since leaf fall in all but one of the parameters sampled (Figure 1A). From leaf fall in November to leaf fall the following September, consumption of both *Q. marilandica* and *Q. stellata* declined. Consumption of *Q. marilandica* was initially 85 % declining to 60 % by the end of the sample period, while *Q. stellata* declined from 78 % to 51 % during the same time (Figure 2A), a decline of 25 % to 27 % reduction in consumption over the 335 day study. Total burn time also declined over the study period for both species (Figure 2). Total burn time averaged 255 sec for *Q. stellata* and 235 sec for *Q. marilandica* 32 days after leaf fall, but averaged 173 sec and 177 sec, respectively 335 days after leaf fall, a decrease of 82 sec for *Q. stellata* and 58 sec for *Q. marilandica* (Figure 1). Flame time increased slightly over time in both *Q. stellata* and *Q. marilandica*, with flame time ranging from 43 sec to 60 sec for *Q. stellata* and 40 sec to 53 sec for *Q. marilandica*. Ember time declined during the study for both species, from 210 sec (*Q. stellata*) and 192 sec (*Q. marilandica*) at leaf fall to 125 sec (*Q. stellata*) and 131 sec (*Q. marilandica*) at nearly 350 days after leaf fall. Surprisingly, average and maximum measured temperatures for both species followed opposite trends with increased average temperatures with time since the onset of leaf fall, but lower maximum temperatures (Figure 2E and 2F).

Mean individual oak leaf weight declined for both species over the 335 day study. Initially, leaves weighed 0.22 g and 0.24 g for *Q. stellata* and *Q. marilandica,* respectively. By the next fall, mean leaf weights declined to only 0.14 g and 0.13 g for *Q. stellata* and *Q. marilandica,* respectively, a 36 % and 46 % decline in each, respectively (Figure 3). However, there were no differences in leaf weights between the two species at any individual sampling date.

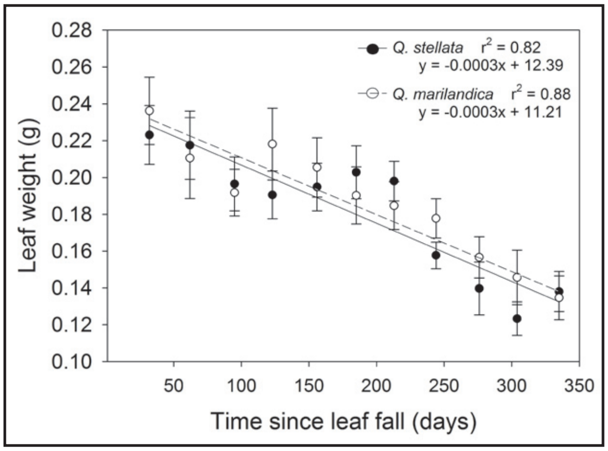

Figure 3. Mean weight (g) of individual *Quercus stellata* and *Quercus marilandica* leaves collected at regular intervals after leaf fall. Leaf litter samples were collected from the Oklahoma State University Range Research Station near Stillwater, Oklahoma, USA. Weights for the two species were not different at any single sampling date (P > 0.05).

DISCUSSION

The objectives of this study were to determine the flammability characteristics of *Q. stellata* and *Q. marilandica* leaf litter from initial leaf fall to nearly 350 days after leaf fall. In a similar study, but only with leaf litter collected right after leaf fall, consumption and flammability results for *Q. stellata* were comparable to our results right after leaf fall (Kane *et al.* 2008), thus showing similar flammability characteristics for this species across regions. We hypothesized that leaf litter flammability would be affected by time-since-leaf-fall equally between the two species. *Quercus marilandica* had greater consumption than *Q. stellata*, but consumption declined for both species over the year. There were no interspecific differences between *Q. marilandica* and *Q. stellata* in flame time, ember time, total burn time, or average burn temperature.

We maintained constant leaf litter fuel load and moisture content for each species and sample during the study, which suggests that other mechanisms for the observed differences in consumption were at play over the duration of the study. Individual leaf weights declined sharply over the study duration for both species: 36 % for *Q. stellata* and 46 % for *Q. marilandica.* These decreases in litter mass are consistent with previous findings on oak species (Howard and Howard 1974, Kelly and Beauchamp 1987, Kuperman 1999). While not measured in this study, oak leaf litter chemical composition has been reported to change following leaf fall (Howard and Howard 1974), and this loss of mass and change in chemical composition over time could possibly be a contributing factor to the reduced consumption we recorded in this study. It has been found that the loss of flammable substances in plants (cellulose, lignin, waxes, oils, fats, and terpenes) through decay over time can reduce flammability of different fuels (Philpot 1969*a*, *b*). Additionally, several studies have been conducted on hardwood leaf litter decomposition and changes in mineral content (Kucera 1959, Thomas 1970, Dwyer and Merriam 1984, Kelly and Beauchamp 1987), but none have explicitly evaluated these changes with respect to fuel quality.

As hypothesized, we found that the longer the time period from leaf fall, the greater the decline in flammability of *Q. stellata* and *Q. marilandica* leaf litter fuels. The longer these leaf litter fuels decompose before burning, the less effective the burn may become (as measured by fuel consumption and total burn time; Figure 2). In the Cross Timbers region, most of the prescribed fires occur from February to April, a delay of three to six months after leaf fall. This lag following leaf fall may explain the difficulty fire managers have in igniting and sustaining prescribed fires in this region. Historic accounts tell of Native Americans burning hardwood timber following leaf fall (Stewart 2002). In the western Cross Timbers of Oklahoma, Stambaugh *et al.* (2009) reported that 97 % of the fire scars from 1712 to 2006 occurred in the dormant season, September to March. Our results suggest that these historic burning seasons likely resulted in greater fuel consumption and spread than fires ignited later. Contemporary prescribed fires ignited shortly after leaf fall should be the most successful in Cross Timbers oak leaf litter fuels, their effectiveness diminishing with leaf litter decomposition over time.

The architecture or arrangement of fuels can also be a factor in determining flammability (Rothermel 1972). It has been noted that the longer hardwood leaf litter is on the ground, the more compacted it becomes from local weather events, making it less likely to burn (Weir 2009). Additionally, it has been found that leaf shape and size, along with fuelbed depth of various oak species, can influence flammability (Engber and Varner 2012). Even with fuelbeds in this study being freshly arranged each time they were burned, changes in leaf physical properties and mass loss over time caused variations in our laboratory fuelbeds. Casual observations indicated that our fuelbed height declined with increased time since leaf fall and became more compact. This suggests the decline in flammability is, in part, caused by changes in physical properties and arrangement of oak leaf litter fuels over time.

Fuel loading and fuel moisture play important roles in fire behavior and the combustibility of fuels. Aside from these variables, our results suggest that time since leaf fall is another primary factor determining how well these fuels will burn. It appears that, for prescribed fires to have the greatest consumption and intensity, fire managers should burn as soon after leaf fall as possible, approximating the historic fire season in the region (Stambaugh *et al.* 2009). This information could assist land managers and fire professionals with determining the best time of year to conduct prescribed burns in the Cross Timbers region. Further, our method may have utility in other areas where leaf litter fuels sustain surface fire regimes.

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