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Research Article

Seasonal Patterns and Drivers of Ashe Juniper Foliar Live Fuel Moisture and Relevance to Fire Planning

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ABSTRACT

Foliar live fuel moisture (LFM)—the weight of water in living plant foliage expressed as a percentage of dry weight—typically affects fire behavior in live wildland fuels. In juniper communities, juniper LFM is important for planning prescribed burns and wildfire response but can be time consuming to obtain regularly. Also, there has been little analysis of the ways in which juniper LFM varies seasonally or is affected by weather conditions, soil moisture, or other variables such as drought index. Using an eight-year dataset of Ashe juniper (*Juniperus ashei* J. Buchholz) LFM observations from four sites in central Texas, USA, we found that the interannual variability of Ashe juniper LFM differs among seasons. Throughout the eight-year sample period, winter LFM fluctuated within a narrow range between about 80% and 120% and was weakly related to Keetch-Byram

RESUMEN

La humedad foliar de tejidos vivos (LFM)—el peso del agua en el follaje vivo expresado como porcentaje de su peso seco—afecta típicamente el comportamiento del fuego en combustibles vivos de áreas con vegetación natural. En comunidades de junípero, el LFM es importante para la planificación de quemas prescriptas y la respuesta frente a incendios, aunque puede ser muy costoso el obtenerlo regularmente. Asimismo, ha habido muy pocos análisis sobre como el LFM del junípero varía estacionalmente o es afectado por las condiciones meteorológicas, la humedad del suelo, u otras variables como el índice de sequía. Mediante la observación de un conjunto de datos de ocho años de LFM del junípero (*Juniperus ashei* J. Buchholz) en cuatro sitios en el centro de Texas, EEUU, encontramos que su variabilidad anual difiere entre estaciones. A través del período de muestreo de ocho años, el LFM en invierno fluctuó entre 80% y 120% y se relacionó muy débilmente con el índice de sequía

Drought Index (KBDI). During summer, LFM fluctuated widely and was more strongly related to KBDI. KBDI below 315 was positively related to LFM, while KBDI above 526 was strongly negatively related to LFM. For this region, we offer a KBDI of about 500 as a threshold for fire planning, above which the potential for critically low Ashe juniper LFM becomes more likely.

de Keetch-Byram (KBDI). Durante el verano, LFM fluctuó ampliamente y se relacionó más fuertemente con el KBDI. El KDBI y el LFM se relacionaron de manera positiva para valores de KDBI por debajo de 315 y de manera negativa para valores de KDBI por encima de 526. Para esta región proponemos un KDBI cercano a 500 como un límite para el planeamiento de quemas, por encima del cual un muy bajo LFM del junípero se vuelve potencialmente crítico.

Keywords: Ashe juniper, fire planning, *Juniperus*, KBDI, live fuel moisture, prescribed burn, Texas, wildland fire

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INTRODUCTION

Ashe juniper (*Juniperus ashei* J. Buchholz) is an evergreen coniferous tree or shrub occurring primarily on limestone substrates from north-central Mexico to southwestern Missouri, USA, with the greatest concentration and abundance occurring on the Edwards Plateau of central Texas (Smeins and Fuhlendorf 1997; Figure 1; all botanical taxonomic nomenclature follows the USDA PLANTS database [USDA NRCS 2017]). Its native range overlaps with that of redberry juniper (*Juniperus pinchotii* Sudw.) to the west and eastern red cedar (*Juniperus virginiana* L.) to the north and east. Ashe juniper experiences localized mortality during severe droughts, does not resprout when the aboveground portion of the plant is mechanically removed or killed by fire, and produces fire-sensitive seeds (Reemts and Hansen 2008)—all characteristics that can limit its encroachment into or colonization of grasslands. Along with other *Juniperus* species of central and western North America, Ashe juniper is believed to have increased in range and abundance since European settle-

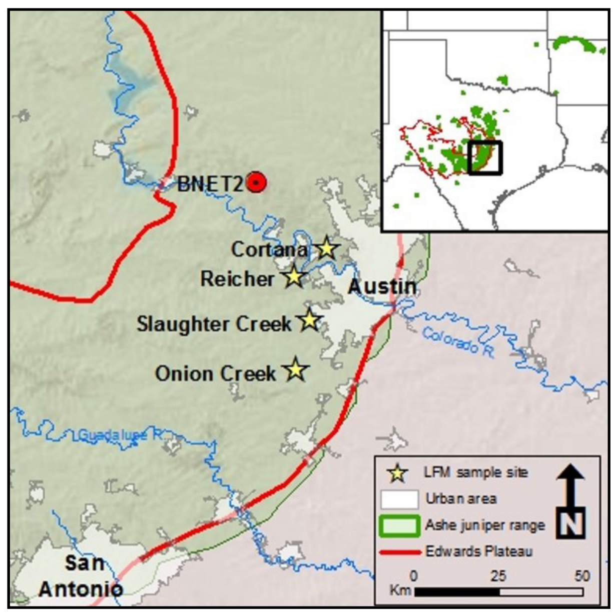

Figure 1. Live fuel moisture sample sites, Ashe juniper range, and the BNET2 remote automated weather station relative to the cities of Austin and San Antonio, Texas, USA. Inset map shows the complete geographic range of Ashe juniper.

ment due to climate change, fire suppression, and livestock overgrazing (Ansley and Rasmussen 2005). In the absence of regular control by fire or mechanical means, Ashe juniper seems to be capable of establishing on nearly any site on the Edwards Plateau and is one of the dominant woody species in the region.

Just as fire played an important role in controlling the historic distribution of Ashe juniper (Weniger 1984, Fuhlendorf and Smeins 1997), fire is critical in restoring and maintaining grasslands at large scales (Noel and Fowler 2007). Land managers use prescribed fire for ecological restoration and land management activities, including controlling encroachment of juniper and other woody species into grasslands (Bryant *et al.* 1983, Twidwell *et al.* 2013). Foliar live fuel moisture (LFM; the weight of water in living foliar plant material expressed as a percentage of dry weight) is one established indicator of flammability of *Juniperus* species in the fire-prone western US (Wright and Bailey 1982) and, along with other factors, is used by fire managers to help prepare for wildfire response, minimize the potential for prescribed fires to escape containment, and to improve the likelihood of achieving prescribed fire effects that meet grassland restoration or management goals. Conversely, mature woodland dominated by Texas live oak (*Quercus fusiformis* Small), Texas red oak (*Quercus buckleyi* Nixon & Dorr), and Ashe juniper is important nesting habitat of the golden-cheeked warbler (*Setophaga chrysoparia* Sclater & Salvin) (Baccus *et al.* 2007), an endangered neo-tropical migratory songbird. Thus, fire managers are often concerned not only with controlling Ashe juniper in grasslands, but also with preserving it as an integral part of golden-cheeked warbler habitat or other mature woodland communities.

In our experience, Ashe juniper live fuel moisture of 100% is considered a rough threshold below which individual tree torching during moderate-intensity wildfire or prescribed burns becomes likely, while 80% is the rough threshold below which the potential for independent crown fire becomes substantial. (The incidence of tree torching or crown fire are, however, contingent upon other factors, especially surface fine dead fuel loading, wind speed, air temperature, and relative humidity.) Similarly, Weir and Scasta (2014) found that, in eastern red cedar, the time to flaming ignition begins to decrease and flame height begins to increase once LFM drops below 60% to 80%.

As important as LFM is for fire planning, the time required for frequent collection and measurement of LFM at a useful geographic scale can be prohibitive. Thus, any predictability to be gleaned by analysis of existing LFM data could be useful in future wildland fire planning. In examining an eight-year dataset of Ashe juniper LFM from four sites on the eastern Edwards Plateau, we noticed a pattern that seemed to show a much narrower interannual LFM range during winter than summer. During this time, we recorded summer LFM values from 46% to 186%, whereas, during the winter, we recorded LFM values no lower than 79% and no higher than 120%. This pattern counters the common assumption in the regional fire planning community that, except for a typical peak associated with generation of new foliage during the spring, Ashe juniper LFM is tied only to available soil moisture and not subject to predictable seasonal fluctuation (C. Schwope, US Fish and Wildlife Service, Marble Falls, Texas, USA, personal communication). We wanted to investigate the validity of this pattern and explore how Ashe juniper LFM may be tied to season, easily collected meteorological variables (air temperature and solar radiation), relative soil depth, and Keetch-Byram Drought Index (KBDI) as a proxy for soil moisture in order to improve our capacity to plan for prescribed fires and wildfire response. Thus, we tested the hypotheses that LFM is statistically related to the 14-day running average air temperature, the 14-day running average solar radiation, relative soil depth ("deep" versus "shallow"), and daily county-level KBDI.

METHODS

Study Area

Each of the four study sites (Table 1) is located on the eastern Edwards Plateau, west and southwest of Austin, Texas, USA (Figure 1). The climate is humid subtropical. Winters are mild and summers are hot. Average high and low temperatures range from 5.5 °C to 16.6 °C in winter, and 23.8 °C to 36.0 °C in summer. Precipitation exhibits a bimodal pattern (peaks in May and October) with an average annual total of 870 mm. Herbaceous fine fuels typically grow actively during spring and fall, partially cure during summer, and fully cure during winter.

Study Sites

Cortana study site. Vegetation is open woodland dominated by Ashe juniper, Texas live oak, flame-leaf sumac (*Rhus lanceolata* [A. Gray] Britton), evergreen sumac (*Rhus virens* Lindh. ex A. Gray), and Texas persimmon (*Diospyros texana* Scheele). Canopy cover varies from approximately 40 % to 70 %. Herbaceous cover is primarily discontinuous mixed shortgrass and midgrass dominated by little bluestem (*Schizachyrium scoparium* [Michx.] Nash), tall grama (*Bouteloua pectinata* Feath.), and seep muhly (*Muhlenbergia reverchonii* Vasey & Scribn.). Common forb species include zexmenia (*Wedelia texana* [A. Gray]), antelope horn (*Asclepias asperula* [Decne.] Woodson ssp. *capricornu* [Woodson]), prairie agalinis (*Agalinis heterophylla* [Nutt.] Small ex Britton), blackfoot daisy (*Melampodium leucanthum* Torr. & A. Gray), and four-nerve daisy (*Tetraneuris scaposa* [DC.] Greene).

Through the mid-twentieth century, the site was grazed by cattle and goats and maintained as an open savanna by mechanical cutting. By the late 1990s, the site had converted to open Texas live oak–Ashe juniper woodland and, at that time, much of the site was mechanically cut to restore shrubland habitat for the black-capped vireo (*Vireo atricapilla* Woodhouse). Adjacent areas have been maintained as woodland habitat for the golden-cheeked warbler.

Reicher study site. Woody canopy cover varies between approximately 40 % and 70 % and is dominated by Ashe juniper and Texas live oak. Texas red oak and escarpment black cherry (*Prunus serotina* Ehrh. var. *eximia* [Small] Little) occur on hillslopes and in canyons. Texas madrone (*Arbutus xalapensis* Kunth) composes a minor portion of the upland canopy. Herbaceous cover is predominately discontinuous shortgrass and midgrass

Table 1. Location and abiotic conditions at each of the four study sites.

Site	Latitude Longitude	Geology	Soil type / texture	Soil depth (cm)	Slope (%)
Cortana	30° 22' 19.2" N 97° 52' 37.2" E	Glen Rose limestone	Brackett-rock outcrop / gravelly clay loam	0 to 50	10
Reicher	30° 19' 2" N 97° 6' 52.8" E	Glen Rose limestone	Brackett-rock outcrop / gravelly clay loam	0 to 50	8 to 12
Slaughter Creek	30° 12' 18" N 97° 54' 25.2" E	Edwards limestone	Purves silty clay, Bracket-rock outcrop, and Crawford clay / clay, silty clay	0 to 102	1 to 3
Onion Creek	30° 4' 19.2" N 97° 56' 42" E	Edwards limestone	Rumple-Comfort / gravelly clay loam	30 to 91	4 to 6

dominated by seep muhly and tall grama. Common forbs include blackfoot daisy, zexmenia, four-nerve daisy, croton (*Croton monanthogynus* Michx.), white milkwort (*Polygala alba* Nutt.), and prairie agalinis.

Prior to 1940, the site was likely Texas live oak–Ashe juniper woodland. During the 1940s, the site was mechanically cut and maintained as open savanna through the mid-twentieth century. It is believed that grazing was light during this time. Since the early 1990s, the site has been allowed to begin converting to oak–juniper woodland. Canopy cover has increased modestly during this time.

Slaughter Creek study site. Woody canopy cover varies between approximately 30 % and 60 % and is dominated by Ashe juniper, Texas live oak, and cedar elm (*Ulmus crassifolia* Nutt.). Herbaceous cover is predominately continuous mixed tallgrass and shortgrass dominated by yellow bluestem (*Bothriochloa ischaemum* [L.] Keng), Texas wintergrass (*Nassella leucotricha* [Trin. & Rupr.] Pohl), little bluestem, and meadow dropseed (*Sporobolus compositus* [Poir.] Merr.). Common forbs include zexmenia, black-eyed Susan (*Rudbeckia hirta* L.), Indian blanket (*Gaillardia pulchella* Foug.), cucumber plant (*Parietaria pensylvanica* Muhl. ex Willd.), and prairie brazoria (*Warnockia scutellarioides* [Engelm. & A. Gray] M.W. Turner).

Prior to 1987, the site was grazed primarily by goats, continually at moderate to high stocking rates, but also intermittently by small numbers of sheep and cattle. Prescribed burns were conducted in open pastures and Ashe juniper abundance was kept low by periodic mechanical clearing. In 1987, livestock were removed and mechanical clearing ceased.

Onion Creek study site. Woody canopy cover varies between 10 % and 25 % and is dominated by Texas live oak and Ashe juniper. Herbaceous cover is predominately continuous mixed tallgrass and shortgrass dominated by yellow bluestem, Texas wintergrass, silver bluestem (*Bothriochloa laguroides* [DC.] Herter ssp. t*orreyana* [Steud.] Allred & Gould), and side-oats grama (*Bouteloua curtipendula* [Michx.] Torr.). Common forbs include zexmenia, croton, black-eyed Susan, Indian blanket, and horsemint (*Monarda citriodora* Cerv. ex Lag.).

Prior to 2000, the site was grazed continually by cattle under moderate stocking rates. Exotic ungulates (blackbuck [*Antilope cervicapra* Linnaeus] and axis deer [*Axis axis* Erxleben]) had been stocked and white-tailed deer (*Odocoileus virginianus* Zimm.) densities were high. Cattle were removed in 2000. Low-intensity prescribed burns were applied on 17 September 2007 and 25 July 2013. These burns resulted in little mortality and limited scorch of mature Ashe juniper.

Plant Material Collection and Processing

Beginning in February 2007 and continuing through 2016, Ashe juniper LFM at each study site were estimated approximately every two weeks to inform prescribed burn planning on City of Austin Water Quality Protection Lands and the City of Austin Balcones Canyonlands Preserve. Dates of collection at each site depended upon such factors as incidence of dry weather and availability of personnel to collect samples. This resulted in unequal numbers of LFM samples at each site (Table 2).

At each site, three Ashe juniper leaf samples of 25 g to 35 g each were taken. Samples were taken between 1300 hours and 1600 hours and not within 24 hours of the most recent rain or when foliage was wet from fog or dew in order to avoid contaminating samples with ephemeral moisture on leaf surfaces. Sites were sampled within two days of each other (usually on the same day) and each one-day to two-day period in which the samples were taken was classified as a single sample period. Each sample contained the newest leaf material, exclusive of branch material, from

Table 2. Summary statistics for live fuel moisture (LFM) and Keetch-Byram Drought Index (KBDI) at each study site. LFM means for each site did not differ significantly ($P = 0.30$).

	Site	*n*	Mean	Minimum	Maximum
LFM	Cortana	160	104.0[a]	47	166
	Onion Creek	135	106.1[a]	50	186
	Reicher	153	105.2[a]	50	177
	Slaughter Creek	142	109.0[a]	46	181
KBDI	Cortana, Reicher, Slaughter Creek	160	366.9	2	783
	Onion Creek	135	400.7	12	764

multiple sides and at various heights of six to 12 randomly chosen individual juniper trees. Fire managers specified the use of only the newest leaf material in order to make the protocol more sensitive to fluctuations in leaf moisture. Sample trees were open-grown, unshaded plants, 1 m to 4 m in height, and not within 10 m of roads, streams, or disturbed areas. Each leaf sample was placed in a stainless steel container and weighed in the field immediately after collection to within 0.1 gram. Samples were then transported to a drying oven (AF Model 30 Lab Oven, Quincy Lab, Inc., Chicago, Illinois, USA) located near the Reicher site and dried at 100 °C for 24 hours. After drying, samples were weighed again and the fuel moisture of each sample was calculated using the following formula:

$$LFM_s = \frac{W_w - W_d}{W_d} \times 100 , \qquad (1)$$

where LFM_s is live fuel moisture in an individual sample, W_w is the weight of the fresh sample in the field, and W_d is the weight of the dried sample. The live fuel moistures of each of the three samples (LFM_s) were then averaged to generate the site-level live fuel moisture (LFM). All analyses in this paper were performed using the averaged site-level LFM.

KBDI

The Keetch-Byram Drought Index (KBDI; Keetch and Byram 1968) was used as a proxy for soil moisture availability at each of the study sites. KBDI is used extensively in fire planning to index the moisture content of the upper soil layer as well as that of the duff layer, which affect potential fire intensity and difficulty of control. The index represents the net effect of precipitation and evapotranspiration on soil moisture content in the top 20.3 cm (8 in) of soil. For each day without more than 5.1 mm (0.2 in) of rainfall, the index is increased. More substantial increases are made when air temperature is high. The index is reduced for every 0.254 mm (0.01 in) above 5.1 mm (0.2 in) of rainfall received on the previous day. The minimum KBDI value is zero and the maximum value is 800.

Daily county-level average KBDIs were obtained from the Texas A&M Spatial Sciences Laboratory. Cortana, Reicher, and Slaughter Creek sites are located within Travis County, Texas, while the Onion Creek site is located in Hays County, Texas.

Solar Radiation and Air Temperature

Hourly air temperature and solar radiation were taken from the BNET2 remote automated weather station (30° 34' 1.2" N, 98° 2' 31.2" E) located at the Balcones Canyonlands National Wildlife Refuge northwest of Austin, Texas (mesowest.utah.edu, last accessed 23 August 2016). BNET2 was the closest non-urban weather station to the study area that contained data for the entire study period. Urban weather stations were avoided because of potential elevated air temperatures due to urban heat island effect.

Hourly data were averaged to produce daily average temperature and solar radiation. Running 14-day averages of solar radiation and temperature were then created, henceforth referred to as SR-14 and Temp-14, respectively.

Based on the dates of prescribed burns conducted near the study sites from 2006 to 2015, we defined the summer prescribed burn season as 23 June to 30 September, and the winter burn season as 15 December to 15 March.

Analysis

Data from incomplete calendar years were excluded from the beginning and end of the dataset (pre 2008 and post 2015) to ensure even comparison across years. Thus, only data from 1 January 2008 to 31December 2015 were used for analysis.

All statistical analyses were performed using JMP 11.0.0 (SAS Institute, Inc, Cary, North Carlina, USA) except for mixed-effects models, which were performed in R 3.4.1 (R Core Team, Vienna, Austria).

We used the Shapiro-Wilk W test as well as visual inspection of data distributions to test for normality. LFM, SR-14, Temp-14, and KBDI fail the Shapiro-Wilks test for normality, but non-normality was not severe with any of the variables. Residuals from the full mixed model displayed good constancy of variance. We used the Levene test for homogeneity of variance of LFM across prescribed burn seasons (Rx season). ANOVA was used to test for similarity of LFM means between all four sites. Finally, using the *lmer* function in the lmerTest package (Kuznetsova *et al.* 2016) in R, we used mixed-effects model to test for effects of our predictor variables on LFM (described below). To remove the effects of multicollinearity in these models, we used sequential regression (Graham 2003) to make our variables orthogonal. Finally, because SR-14, Temp-14, and KBDI vary cyclically throughout the year, we included a quadratic term for these variables to test for non-linear effects.

Our fully saturated linear mixed-effects model included LFM as the response variable; SR-14, Temp-14, KDBI, soil, Rx season, and all interactions between these as fixed predictor variables; and site and sample period nested within year as random effects. Because we had no prior information regarding what would be the best model, we tested all possible model combinations by iteratively simplifying the model by one parameter. Using AIC (Burnham and Anderson 2002), we compared competing models. The best model had the lowest AIC value, and models within two points of this were considered to predict LFM equally well.

To identify potential thresholds at which LFM may change its response to certain predictors, we used piecewise regression (Toms and Lesperance 2003) to identify these regions.

RESULTS

Summary Statistics

During the survey period, LFM typically increased with solar radiation in late spring and early summer except during drought years such as 2009 and 2011 (Figure 2). KBDI tends to reach its peak during mid to late summer (Figure 2), lagging behind the solar radiation peak during early to mid July.

LFM means (Table 2) and variances did not differ significantly between sites ($P = 0.30$ and 0.08, respectively). LFM means did not differ significantly between "shallow" (Cortana and Reicher) and "deep" soil sites (Slaughter Creek and Onion Creek) ($P = 0.12$). Thus, data were pooled across soil depth and also

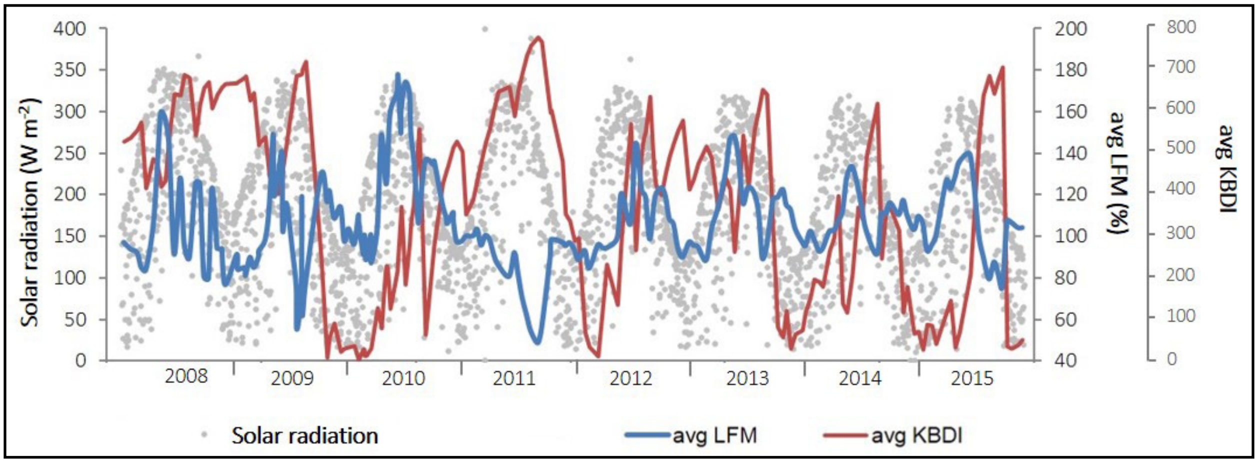

Figure 2. Solar radiation (W m^{-2}; taken from the BNET2 remote automated weather station; gray dots), live fuel moisture (LFM; %; blue line) averaged across each of the four study sites, and Keetch-Byram Drought Index (KBDI; red line) averaged across the two counties in which the study sites are located.

across site for all tests except when examining within-sample period range.

While all sites exhibited similar LFM means across the study period, site-to-site LFM differences within sample periods were often substantial (Figure 3). The median within-sample period range (the difference between the high and low site-level LFM for each sample period) was 13 percentage points (e.g., low = 95 %, high = 108 %). The 75th percentile within-sample period range was 19. Ten percent of the sample periods showed a site-to-site LFM range of greater than 30 percentage points. The maximum observed within-sample period range was 79 percentage points.

Within-sample period range was not significantly related to average (within sample period) KBDI ($P = 0.45$) but was significantly (positively) related to LFM, SR-14, and Temp-14 ($P < 0.0001$ in each case), although R^2 values were small (0.11, 0.09, 0.09, respectively). The majority (88 %) of sample periods with high site-to-site variability (within-sample period range of greater than 30 percentage points) occurred during the spring (April, May, and June). The remainder (12 %) of high-variability sample periods occurred during July and August.

LFM calculations and raw data for sample periods demonstrating a site-to-site range of greater than 50 percentage points were double-checked and determined to be valid based on good agreement between the three LFM_s values for each site. Additionally, the continuity of values in the distribution of within-sample period range data (Figure 3) also suggested that the high outliers were valid.

LFM and KBDI Interannual Patterns

During the study period, LFM variance was much narrower during winter prescribed burn seasons than during summer prescribed burn seasons (Levene test, $P < 0.0001$). LFM began the winter in a relatively narrow range between 79 % and 120 % (Figure 4a), while KBDI was highly variable through the winter and spring (Figure 4b). LFM generally increased through the spring and declined through the summer, although the variability during this time was substantial (Figure 4a). KBDI remained highly variable through the spring, but in general rose through the summer (Figure 4b). Through the fall, LFM moderated and the variability was reduced leading into the winter (Figure 4a), while KBDI variability was substantial throughout the fall (Figure 4b).

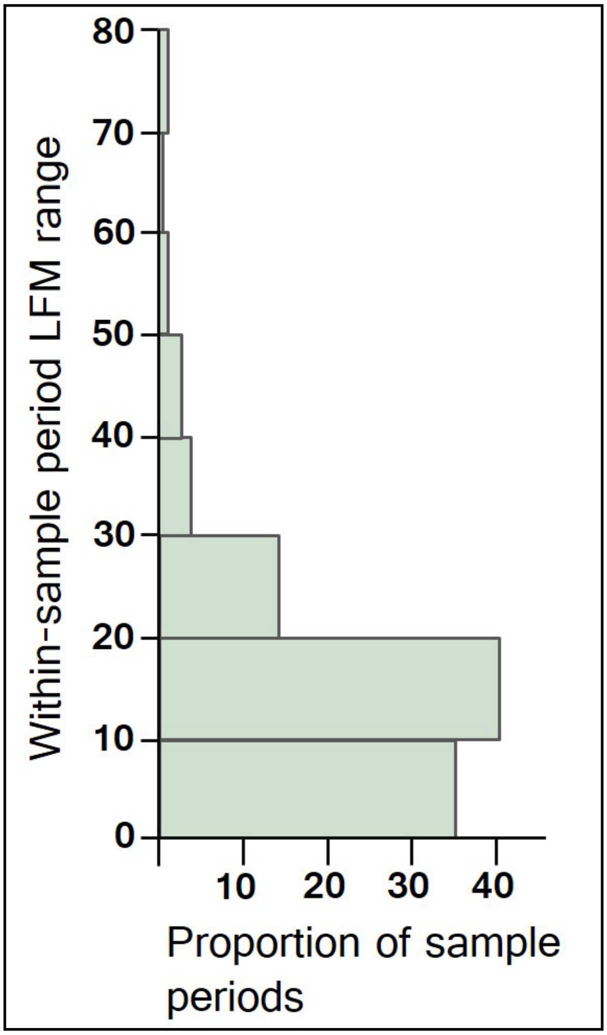

Figure 3. Distribution of within-sample period live fuel moister (LFM) range. Ashe juniper foliar samples were taken at each of the four study sites typically within two days of each other. Each 48-hour sampling window constituted a single sample period. The within-sample period range is the difference between the highest and lowest site-level LFM calculated in each sample period. The majority of sample periods (75%) had an LFM range of 19 or less. However, 10% of sample periods had an LFM range of 30 or greater.

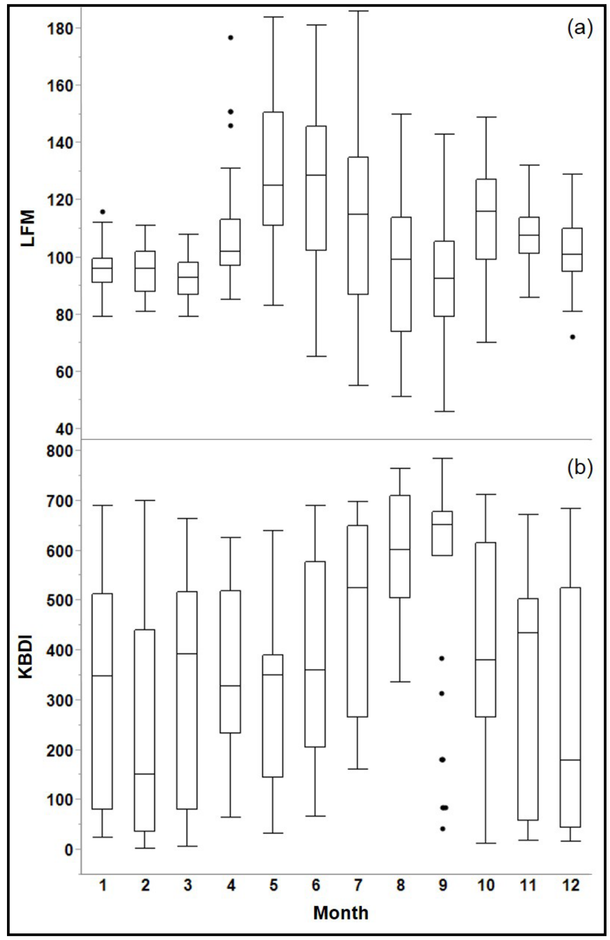

Figure 4. Box and whisker plots for (a) live fuel moisture (LFM) and (b) Keetch-Byram Drought Index (KBDI) for each month throughout the study period. The center line of each plot is the median value. Boxes represent the first and third quartile (25th and 75th percentiles). Error bars denote the range and black dots indicate outliers.

Mixed-Effects Model

Our best model, which had the lowest AIC value by 41.2 points, included Temp-14, KBDI, soil, Rx season, and the interactions between KBDI and soil, KBDI and Temp-14, KBDI and Rx season, and Temp-14 and Rx season as fixed factors (Table 3). Both Temp-14 and KBDI were better explained by quadratic rather than linear terms. Our refined mixed-effects model explained 85.3% of the variance in LFM. KBDI, Rx season, and the interaction between KBDI and Rx season had the strongest relationship with LFM.

100% and 80% Thresholds

Throughout the eight-year dataset, we saw LFM below 100% across the KBDI range (Figure 5). Thus, LFM values below 100%

Table 3. Fixed effects from final mixed-effects model. Model R^2 = 0.853. Number of observations = 590. For each model term, df = degrees of freedom, and df den = denominator degrees of freedom.

Model term	df	df den	*F* ratio	*P*-value
Temp-14	2	182.13	1.775	0.172
KBDI	2	177.25	71.986	<0.0001
Soil	1	2.37	12.110	0.057
Rx season	2	165.19	25.025	<0.001
Temp-14 × KBDI	4	166.49	3.692	0.007
Temp-14 × Rx season	4	180.67	3.252	0.013
KBDI × soil	2	438.04	4.340	0.014
KBDI × Rx season	4	169.15	29.232	<0.0001

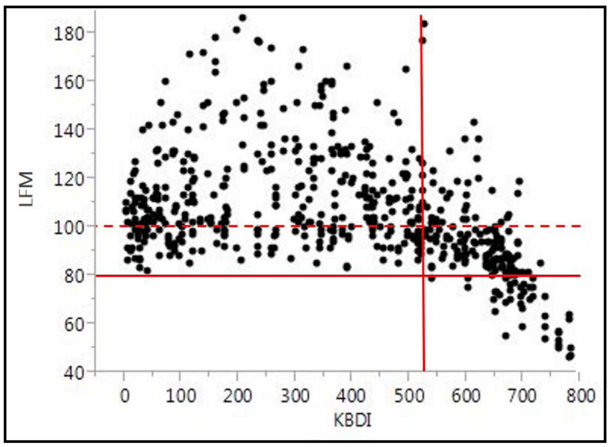

Figure 5. Scatterplot of live fuel moisture (LFM) versus Keetch-Byram Drought Index (KBDI) for the full dataset. The dashed line delineates the 100 % LFM trigger point, below which individual tree torching becomes common during moderate-intensity fires. The solid horizontal line delineates the 80 % LFM trigger point, below which the likelihood of independent crown fire becomes substantial. The vertical line marks the KBDI (526) above which LFM becomes negatively associated with KBDI for the study area, as identified by piecewise regression.

were possible even during times of high soil moisture availability. However, all instances of LFM values at or below 100 % during times of very high soil moisture availability (KBDI at or below 100) occurred between late fall and the end of winter (between 18 November and 21 March). We did not record LFM below 79 % during any winter Rx season. Further, we only recorded LFM below the 80 % threshold in the full dataset when KBDI was above 540.

Piecewise regression identified a KBDI of 526 (95 % confidence interval = 490.6 to 564.0) as an important threshold, with LFM decreasing sharply above this value (P < 0.0001; Figure 5). Piecewise regression also identified a KBDI of 315 (95 % confidence interval = 155.8 to 376.0) as another important threshold, with LFM increasing up to this value (P = 0.03). Between KBDI 315 and 526, LFM appears to decrease, although the relationship was non-significant (P = 0.10).

DISCUSSION

Seasonal Patterns of LFM and KBDI

Some aspects of the pattern of LFM variability were not surprising. Fire planners in the study area have been aware of the general pattern of rising LFM during the spring and declining LFM during summer. However, the high interannual LFM variability during the summer and comparatively low interannual LFM variability during the late fall and winter is a pattern that had not been realized.

The same pattern also seems to hold for redberry juniper. For example, between 2009 and 2015, redberry juniper LFM from Gillespie County, Texas, fluctuated within a narrower range during the winter (79% to 104%) than during spring and summer (65% to 115%) (United States Forest Service 2016). Similarly, between 2004 and 2015, redberry juniper LFM from Comal County, Texas, varied between 71% and 117% in winter and 55% and 115% in summer (United States Forest Service 2016).

Texas live oak in this area, however, did not seem to exhibit the same pattern. For example, between 2009 and 2015 in Gillespie County, Texas, Texas live oak LFM exhibited a peak during April between 94% and 240%, while, during summer, fall, and winter, LFM remained between 70% and 102% (United States Forest Service 2016). Texas live oak in Comal County, Texas, exhibited a similar pattern between 2004 and 2015, peaking to between 87% and 220% during April but remaining between 67% and 132% during summer, fall, and winter (United States Forest Service 2016). These LFM peaks in April correspond to the time of year when Texas live oak typically generates new leaves.

As for KBDI, the general pattern of relatively high values and low variability during the late summer (Figure 4) had also been intuitively realized by fire planners in this area, but to our knowledge had not been demonstrated. This pattern is likely due to the low average rainfall and high temperatures in the area during mid to late summer. The low outliers in September (Figure 4) were recorded after large rain events.

Regional LFM Variability

The geographic distribution of the four LFM sampling sites allows us to understand the variability in LFM on a scale at which many fire planners operate. The statistical similarity of the site-level LFM means was surprising given the degree to which the sites differ topoedaphically. At the Slaughter Creek and Onion Creek sites, soils are deep (up to 102 cm) and topography is flat (1% to 6% slope), whereas at the Cortana and Reicher sites, soils are shallower (15 cm to 50 cm) and slopes are steeper (8% to12%).

Daily between-site differences (Figure 3), however, are likely to substantially influence fire planning. Ten percent of all sample periods exhibited a mean LFM range of 30 percentage points or more. Such site-to-site variability can result in instances in which LFM at one site is well above a trigger point while LFM at another site is well below. For example, on 8 August 2009, LFM at Slaughter Creek was 119% while LFM at Cortana, 21 km away, was 59%. High within-sample period LFM variability appears to occur during times of seasonal transition, such as during the spring, when LFM at either the northern (Cortana and Reicher) or southern (Slaughter Creek and Onion Creek) sites begins rising before or faster than that of the others. The majority (88%) of sample periods with a LFM range of 30 percentage points or greater occurred during April, May, and June. Such within-sample period variability may be attributable to differing times of leaf generation between sites and the stochastic nature of highly localized rainfall events.

LFM Drivers

KBDI and Rx season as well as the KBDI × Rx season interaction were the strongest predictors of LFM. Ecologically, as well as from a fire management perspective, we believe the KBDI × Rx season interaction to be the most significant dynamic driving LFM at our study sites. In the mixed-effects model, KBDI was the most significant predictor of LFM, but the strength of the relationship varied by season. During summer Rx seasons, LFM varied widely from year to year (Figure 4) and was more strongly related to KBDI (quadratic fit, $P <$ 0.0001, $R^2 = 0.73$), especially when KBDI was above about 500 (Figure 6a). In contrast, during winter, LFM remained within a narrow

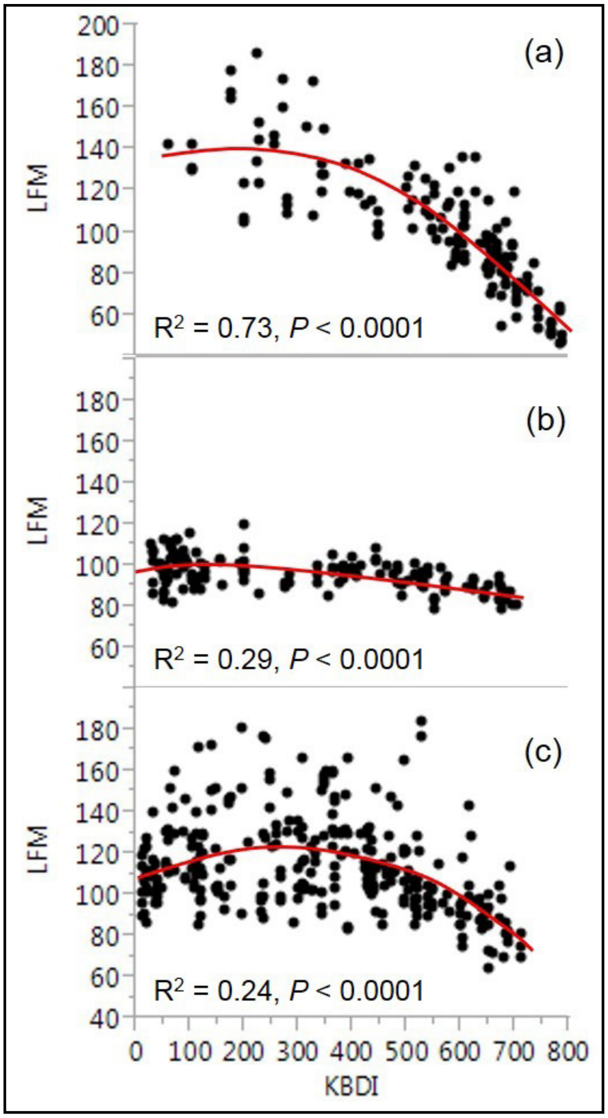

Figure 6. Scatterplots of live fuel moisture (LFM; %) versus Keetch-Byram Drought Index (KBDI) during a) summer and b) winter prescribed burn seasons (23 June to 30 September, and 15 December to 15 March, respectively), and during c) all other times of year. Red lines indicate quadratic fits.

range between about 80 % and 120 % (Figure 4) and was weakly related to KBDI (quadratic fit, $P < 0.0001$, $R^2 = 0.29$; Figure 6b). During all other times of the year, LFM fluctuated widely throughout the KBDI range (Figure 6c) and was weakly related to KBDI (quadratic fit, $P < 0.0001$, $R^2 = 0.24$).

These results differ from those of Pellizzaro *et al.* (2007) who found that LFM in *Juniperus phoenicea* L. correlated to both 60-day and 90-day cumulative precipitation but not to Canopy Drought Stress Index, which is similar to KBDI in that it incorporates both precipitation and temperature. Pellizzaro *et al.* (2007) may have found *J. phoenicea* LFM not to be responsive to Canopy Drought Stress Index because their Mediterranean study site (Sardinia, Italy) experiences relatively moderate daily and annual temperature changes compared to that of our study site. *J. phoenicea* LFM may also simply be less physiologically sensitive to changes in temperature than *J. ashei*.

Woody plant establishment in grasslands and savannas throughout the world is often most constrained by soil moisture (McPherson 1997). High temperatures and low precipitation combine to create high plant water stress during most summers in many North American grasslands (McPherson 1997). Further, herbaceous plants are most competitive during the warm season because of their ability to exploit small precipitation events (Scholes and Archer 1997, Riginos 2009). Because Ashe juniper often continues to transpire except during severe drought (Dammeyer *et al.* 2016), low rainfall and high evaporative demand during typical dry summers likely create strong water limitation (McPherson 1997), which may be exacerbated by belowground competition from herbaceous plants for shallow-soil water (Scholes and Archer 1997, Riginos 2009). Our results suggest that such water limitation may substantially drive down LFM, at least during the summer. In contrast, during wet summers, Ashe juniper water stress appears to be alleviated by available soil water, which allows for higher LFM.

During the winter, low temperatures, plant physiology, and phenology may combine to constrain LFM. Although Ashe juniper has been shown to photosynthesize at moderate to high rates during the winter (Owens 1996, Bendevis *et al.* 2010), lower temperatures likely reduce evaporative demand, which, along with reduced competition from herbaceous plants, may limit water stress and prevent low LFM even during drought. But why do we not see high LFM during the winter when soil moisture is abundant? Jolly *et al.* (2014) found that older leaves of *Pinus contorta* Douglas ex Loudon exhibited higher proportional dry mass ($kg \cdot kg^{-1}$) and lower proportional water mass ($kg \cdot kg^{-1}$) than newer leaves, and that the higher proportional dry mass was related to foliar starch, sugar, and crude fat content. They conclude that, in *Pinus contorta,* changes to dry matter exert a stronger control on seasonal LFM than changes in leaf water content. Older leaf material may also simply have a reduced capacity to store water because of its higher proportional dry mass. Thus, although our results demonstrate that Ashe juniper LFM is strongly related to soil moisture availability (KBDI) during the summer, especially when soil moisture is limited (high KBDI), during the winter Ashe juniper LFM may be related more strongly to physiological processes, metabolites stored in older leaf material, and higher proportional dry mass in older leaf material than to soil moisture availability.

Temp-14 displayed a weakly significant interaction with Rx season. Temperature was negatively related to LFM during winter and summer (P = 0.007 and <.0001, respectively) but these relationships were weak (R^2 = 0.07 and 0.l9, respectively). In contrast, temperature was positively related to LFM during all other times of year (P <.0001), and this relationship was weak as well (R^2 = 0.08). This may be due in part to the pattern of LFM typically rising sharply during early spring as the temperature warms and gradually falling during fall as the temperature cools (Figure 4)

Temp-14 also displayed a moderately significant interaction with KBDI. This appears to be the result of a significant positive relationship between temperature and LFM at low to moderate KBDI values and a significant negative relationship at high KBDI values. For example, at or below KBDI of 600, Temp-14 and LFM are positively related (P < 0.0001), but above KBDI 600, Temp-14 and LFM are negatively related (P = 0.01).

Lastly, KBDI displayed a weakly significant interaction with soil depth. At low KBDI values, LFM at shallow and deep soil sites appears to diverge slightly (higher LFM at deep soil sites). Soil depth may have a slight influence on LFM at our sites, but this effect appears to be overcome by drought stress at high KBDI.

Fire Planning

The finding that Ashe juniper LFM in this region is strongly related to KBDI during the summer and especially above a KBDI of about 500 is important for fire planning. We also see that the relationship between KBDI and LFM during the summer is quadratic. That is, LFM decreases ever more rapidly as conditions become drier.

For our sites, LFM was observed to increase up to a KBDI of 315 and to decrease above a KBDI of 526. LFM between 80% and 100% were observed throughout the KBDI range. By contrast, all LFM values below 80% were observed above KBDI 526 (Figure 5). So, low KBDI does not guarantee high LFM, but high KBDI during the summer makes critically low LFM much more likely.

Implications for Management

Our results suggest that, during the winter in this region, Ashe juniper LFM may reliably fall within the range of 80% to 120%, which may aid in prescribed burn planning. During the summer, however, LFM will depend heavily on soil moisture, as affected by temperature and precipitation.

This research also illustrates how variable LFM can be, not only seasonally, but also spatially. Highly variable within-sample period LFM observations occurred predominately in the spring (88 %), with the remainder occurring in the summer. Within-sample period LFM variability was much lower in winter, with no occurrences of greater than 30 percentage points.

During the summer, KBDI may be a useful area-wide planning tool, but we still cannot predict or model LFM with sufficient accuracy to inform fire planning. Thus, recent LFM estimates taken from as near as possible to a planned prescribed burn or from several locations throughout a response area is important for anticipating fire behavior in Ashe juniper and especially important when KBDI is above about 500. When KBDI is above this value, Ashe juniper LFM decreases rapidly, and the rate of that decrease accelerates as KBDI increases further.

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