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Erik S. Krueger

Oklahoma State University, erik.krueger@okstate.edu

Tyson E. Ochsner

Oklahoma State University, Tyson.ochsner@okstate.edu

David M. Engle

Oklahoma State University, david.engle@okstate.edu

J. D. Carlson

Oklahoma State University

Dirac L. Twidwell

University of Nebraska-Lincoln, dirac.twidwell@unl.edu

See next page for additional authors

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Authors

Erik S. Krueger, Tyson E. Ochsner, David M. Engle, J. D. Carlson, Dirac L. Twidwell, and Samuel D. Fuhlendorf

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Erik S. Krueger*

Tyson E. Ochsner

Dep. of Plant and Soil Sciences
Oklahoma State Univ.
Stillwater, OK 74078

David M. Engle

Dep. of Natural Resources Ecology & Management
Oklahoma State Univ.
Stillwater, OK 74078

J.D. Carlson

Dep. of Biosystems and Agric. Eng.
Oklahoma State Univ.
Stillwater, OK 74078

Dirac Twidwell¹

Dep. of Agronomy and Horticulture
Univ. of Nebraska-Lincoln
Lincoln, NE 68588

Samuel D. Fuhlendorf

Dep. of Natural Resources Ecology & Management
Oklahoma State Univ.
Stillwater, OK 74078

The increasing availability of soil moisture data presents an opportunity for its use in wildfire danger assessments, but research regarding the influence of soil moisture on wildfires is scarce. Our objective was to identify relationships between soil moisture and wildfire size for Oklahoma wildfires during the growing (May–October) and dormant seasons (November–April). We hypothesized that soil moisture influences wildfire size when vegetation is growing but is less important when most vegetation is dead or dormant. Soil moisture, as fraction of available water capacity (FAW), and commonly measured weather variables were determined for 38,419 wildfires from 2000–2012. Wildfires were grouped by size class (<4.05 , ≥ 4.05 and <40.5 , ≥ 40.5 and <121 , ≥ 121 and <405 , and ≥ 405 ha), and the Kruskal–Wallis test with multiple comparisons was used to identify differences in each variable between wildfire size classes and seasons. Large fires occurred at lower FAW than small fires during both seasons ($P < 0.001$), but growing-season wildfires ≥ 405 ha occurred over a narrow range of FAW (0.05–0.46) whereas dormant-season fires of this size occurred across the entire range of FAW (0.05–1.05). For growing-season fires ≥ 121 ha, 91% occurred at FAW < 0.5 and 77% occurred at FAW < 0.2 . Our finding that large growing-season wildfires occurred exclusively under conditions of low soil moisture highlights the need to develop methods to use soil moisture data in wildfire danger assessments.

Abbreviations: AWC, available water capacity; FAW, fraction of available water capacity; KBDI, Keetch–Byram Drought Index; LFM, live fuel moisture; PAW, plant available water.

Innovative approaches to assessing wildfire danger may help increase wildfire preparedness and reduce the negative impacts that wildfires have on humans. While wildfires are a natural and necessary feature of most terrestrial ecosystems, their impact on human life and property can be dramatic, and the costs associated with wildfires can be high. In the USA, wildfire suppression costs have approached \$2 billion USD annually (NIFC, 2013), and the occurrence of large wildfires is increasing (Westerling et al., 2006).

One possible approach to improving wildfire danger assessments involves using soil moisture as a surrogate for live fuel moisture (LFM), a key influence on fire behavior (Yebra et al., 2013). Soil moisture may be a useful surrogate because it is physically linked to LFM through soil–plant interactions (Hillel, 1998). Large wildfires tend to occur during dry and windy periods with low relative humidity (Reid et al., 2010) and high temperatures (Littell et al., 2009), conditions that reduce fuel moisture and promote fire ignition and spread (Van Wagner, 1977; Bradshaw et al., 1983; Rothermel, 1983; Forestry Canada Fire Danger Group, 1992). However, direct measurements of LFM for the purposes of wildfire danger assessment are not widely available because fuel moisture sampling is labor inten-

¹Twidwell was a postdoctoral research associate, Dep. of Natural Resources Ecology & Management, Oklahoma State Univ., Stillwater, OK 74078.

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*Corresponding author (erik.krueger@okstate.edu)

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sive. Instead, LFM, and consequently wildfire danger, are estimated from weather data (Bradshaw et al., 1983; Forestry Canada Fire Danger Group, 1992; Viegas et al., 2001; Castro et al., 2003; Carlson et al., 2007; Dennison et al., 2008; Matthews, 2014), related to drought indices (Dimitrakopoulos and Bemmerzouk, 2003; Pellizzaro et al., 2007), or estimated using satellite remote sensing techniques (Chuvieco et al., 2002; Caccamo et al., 2012; Jurdao et al., 2012).

Wildfire danger assessments that incorporate soil moisture may improve existing techniques because the necessary LFM estimates would be grounded on physical interactions between soils and plants. Pellizzaro et al. (2007) provided evidence for the importance of soil moisture when they reported that soil moisture was more highly correlated with LFM than weather variables or drought indices in some plant species. Likewise, Qi et al. (2012) found that in situ soil moisture measurements were more strongly correlated with LFM than were remote sensing measurements. However, the soil moisture–LFM correlations were site specific in part because of spatial variability in soil properties. Their results highlight that soil moisture per se is an incomplete description of soil water status because soil physical properties such as texture and porosity dictate how much moisture is available for plant uptake, that is, plant available water (PAW). The maximum PAW that a soil can store, or available water capacity (AWC), varies greatly across soils. Therefore, a more meaningful soil moisture variable can be defined as the ratio of PAW/AWC, or FAW. Because it accounts for the impact of soil properties on moisture available to vegetation, FAW is a preferred means of estimating plant water stress from soil moisture (Allen et al., 1998).

In situ soil moisture data have not been used for wildfire danger assessment, and data relating measured soil moisture to wildfire occurrence are lacking. A significant roadblock to the use of soil moisture in wildfire research as well as operational fire danger rating systems such as the OK-FIRE system in Oklahoma (Carlson, 2010; Joint Fire Science Program, 2011) has been the absence of data, but the recent proliferation of large-scale soil moisture monitoring networks (Ochsner et al., 2013) has made soil moisture data more widely available. One such network is the Oklahoma Mesonet where soil moisture and weather variables are recorded at >100 sites across Oklahoma, USA (McPherson et al., 2007). These soil moisture data have been used for drought probability assessment related to crop production (Torres et al., 2013), with similar drought assessments being conducted elsewhere in the United States (Hunt et al., 2009) and internationally (Mozny et al., 2012) where soil moisture data are available.

We hypothesize that soil moisture is an important driver of wildfires during the growing season (May–October in Oklahoma) when it strongly influences LFM (Pellizzaro et al., 2007), and that soil moisture is less important during the dormant season when vegetation has senesced or is dormant. Soil moisture is often at its maximum during the dormant season because of low evaporative demand, yet at the same time fuel moisture is low because vegetation is primarily dehydrated plant material from the previous growing season (Wittich, 2011). Weather variables that dic-

tate dead fuel moisture (i.e., relative humidity and temperature) and drive wildfire spread (i.e., wind speed; Bradshaw et al., 1983; Nelson, 2000) are likely dominant drivers of dormant-season wildfires in Oklahoma. Our objective was to identify relationships between soil moisture and wildfire size for Oklahoma wildfires during the growing and dormant seasons. Our goal was to answer the fundamental but so far unanswered question, how is wildfire size related to soil moisture? To provide context, we also assessed relationships between commonly measured weather variables and wildfire size and identify seasonal differences in wildfire number and extent. This fundamental work is directed toward improving our understanding of the influence that soil moisture has on wildfire size, and it is an essential first step toward developing wildfire danger assessments that include soil moisture.

MATERIALS AND METHODS

Study Area

The climate of Oklahoma is continental, with statewide average monthly air temperatures ranging from 3°C in January to 27°C in July. More precipitation occurs during the growing season from May through October (573 mm) than during the dormant season from November through April (369 mm; SCIPP, 2014). Temperature and precipitation also vary geographically, with both increasing from the northwest to the southeast. Average annual temperature ranges from 13°C in the northwestern part of the state to 17°C in the south and southeast, while precipitation ranges from 432 to 1422 mm from northwest to southeast (OCS, 2014). Annual precipitation totals can vary greatly, and drought lasting from months to years is a recurring part of Oklahoma's climate (Stockton and Meko, 1983). The climate gradient of Oklahoma is a primary contributor to its diverse ecology, with parts of 12 U.S. Environmental Protection Agency (EPA) Level III ecoregions being present in the state (Woods et al., 2005). The Central Great Plains and Cross Timbers ecoregions are the largest, making up 40 and 19% of the state's land area, respectively. According to the 2011 National Land Cover Database, 72% of Oklahoma's vegetated land cover is made up of herbaceous plants, including grasslands (40% of vegetated area), cultivated crops (20%), and pasture (12%). Of the remaining vegetated area, 23% is forest, and 5% is scrub (Homer et al., 2015).

Wildfire Data

Wildfire data were obtained from the Oklahoma State Fire Marshal's Office for the Years 2000–2012, with data including date of fire ignition, area burned, and responding fire department. Prescribed fires were not included in the data set. Descriptions of vegetation type were available for only a portion of the wildfire data set (2008–2012). Of the 20,929 fires from 2008–2012, the most common types were “grass fire” (61%), “brush or brush/grass fires” (26%), and “forest, woods, or wildland fire” (5%). Assuming that wildfire types for the 2008–2012 subset of the data were representative of the data set as a whole, the percentage of forest fires in the entire data set was relatively small. Therefore, our results apply primarily to grass and brush/grass

fires. It was impossible to conduct separate statistical analyses for fires from each vegetation type because vegetation descriptions were not available for the entire data set. Furthermore, 30-m land cover data for Oklahoma shows that vegetation in Oklahoma is highly spatially variable (Homer et al., 2015). Consequently, large fires typically burn across multiple vegetation types and cannot be neatly categorized by a single vegetation type.

Fires were separated by dormant and growing season for separate seasonal analyses. The dormant season was defined as the months of November through April, which approximately corresponds with the months after vegetation has senesced and before substantial spring regrowth (Senay and Elliott, 2000). The growing season was defined as the months of May through October. Fire number and area burned were compared for each season and year to identify seasonal differences. Dormant-season data represent those fires from the season ending in the specified year. Therefore, dormant-season data from 2000 were excluded since they represent only a portion of that dormant season. The analysis was based on the fire data as received, with the knowledge that they may be incomplete and may contain inaccurate estimates of burn area, as is common with wildfire data (Brown et al., 2002). Results were checked using Oklahoma fires from a similar federal data set (Short, 2013), and the results were essentially unchanged.

Environmental Data

Daily environmental data were obtained from the Oklahoma Mesonet for each station from 1996 to 2012. Environmental data included maximum air temperature, minimum relative humidity, maximum wind speed (measured at 10 m), and reference temperature difference (Illston et al., 2008) from heat dissipation sensors (Model 229, Campbell Scientific Inc., Logan, UT) at the 5- and 25-cm soil depths. The reference temperature difference was converted to soil matric potential using a calibration function (Illston et al., 2008). Volumetric water content was then calculated from soil matric potential using van Genuchten parameters obtained from the Rosetta pedotransfer function. The necessary parameters were derived from soil water retention properties measured on soil samples collected at each Mesonet station location (Scott et al., 2013). Reference temperature difference data are available at the Oklahoma Mesonet Daily Data Retrieval webpage https://www.mesonet.org/index.php/weather/daily_data_retrieval subject to the Oklahoma Mesonet Data Access Policy (verified 14 Oct. 2015). The soil water retention database is available at <http://soilphysics.okstate.edu/data/> (verified 14 Oct. 2015).

At each Mesonet site, air temperature, relative humidity, and wind speed were measured continuously, and 5-min averages were recorded. Reference temperature difference was measured every 30 min. In our analysis, maximum air temperature, minimum relative humidity, and maximum wind speed were respective maximum and minimum 5-min averages for each day, and soil moisture was calculated from daily average reference temperature difference.

At a given soil moisture content, soils can vary in the amount of water available to growing vegetation. Therefore, soil moisture alone does not provide a complete description of soil water status. Instead, soil moisture conditions are better described by PAW:

$$PAW = (\theta - \theta_{WP})d \quad [1]$$

where θ is measured volumetric water content, θ_{WP} is volumetric water content at the permanent wilting point, and d is the thickness (mm) of the layer represented by the measurement. Permanent wilting point, the water content at which plants cannot remove additional water from the soil profile, was defined as the volumetric water content corresponding to a matric potential of -1500 kPa.

Mesonet sites vary greatly in maximum PAW, or AWC, with values in the top 400 mm of the soil profile ranging from 20 mm for a sandy loam to 70 mm for a clay to 113 mm for a silt loam. Available water content is calculated as $(\theta_{FC} - \theta_{WP})d$ where θ_{FC} is the field capacity. Based on visual inspection of matric potential data, field capacity, the water content at which drainage of water from the soil becomes negligible, was defined as the water content corresponding to a matric potential of -10 kPa. To normalize PAW across sites, FAW was calculated as the ratio of PAW/AWC:

$$FAW = (\theta - \theta_{WP}) / (\theta_{FC} - \theta_{WP}) \quad [2]$$

where FAW is fraction of available water capacity. In this study, FAW was calculated for the 0- to 10-cm layer using the data from the soil moisture sensor at 5 cm and for the 10- to 40-cm layer using the data from the soil moisture sensor at 25 cm. Then the depth-weighted average FAW for the 0- to 40-cm layer was calculated. Soil moisture below 40 cm was not considered because only 76 Mesonet stations have sensors below this depth.

Values of FAW are typically between 0 (no PAW) and 1 (maximum PAW) as θ varies from permanent wilting point to field capacity. Values of FAW less than approximately 0.5 indicate conditions of vegetative moisture stress (Allen et al., 1998). Values of FAW greater than one are possible for poorly drained sites and during or shortly after precipitation events when soil moisture is above field capacity. Under prolonged hot and dry conditions, evaporation from near-surface soil layers can result in moisture below permanent wilting point and FAW values less than zero.

Relating Environmental Conditions to Wildfire Size Class

Wildfires were assigned to one of five fire size classes ranging from <4.05 ha (fire size Class 1) to ≥ 405 ha (fire size Class 5; Table 1). Size classes were modeled after National Wildfire Coordinating Group (NWCG) standards (NWCG, 2012). Fires in size Class 1 include NWCG Classes A and B, and fires in size Class 5 include NWCG Classes F and larger. Size Classes

Table 1. Size class and number (*n*) of dormant-season (November–April) and growing-season (May–October) wildfires in Oklahoma from 2000 to 2012.

Fire size class	Fire size ha	Fire season		Total
		Dormant	Growing	
5	≥405	181	70	251
4	≥121 and <405	465	124	589
3	≥40.5 and <121	1096	342	1438
2	≥4.05 and <40.5	6688	3162	9850
1	<4.05	16102	10189	26291
Total		24532	13887	38419

2, 3, and 4 correspond to NWCG Classes C, D, and E, respectively. Environmental data for each fire were assigned for the day of fire ignition from the Mesonet station nearest the address of the responding fire department. Data from the next nearest station were used to fill missing soil moisture data when necessary because soil moisture is recorded at only 105 of Oklahoma’s 120 Mesonet stations (Illston et al., 2008). No attempt was made to fill any remaining missing environmental data, and data existed for 96% of fires.

The non-parametric Kruskal–Wallis test was used to identify differences in environmental conditions between wildfire-size classes and seasons. The Kruskal–Wallis test is similar to the parametric analysis of variance but is performed on data ranks rather than data values, is not restricted by the assumption of normality, and is appropriate for ordinal data sets (Kruskal and Wallis, 1952) like our wildfire size classes. A significant Kruskal–Wallis test result indicates that the sample population distribution of at least one sample differs from another. Strictly speaking, the Kruskal–Wallis test assumes variance homogeneity of ranks between samples (Vargha and Delaney, 1998), and there is some increased risk of Type I error when this assumption is violated. We tested variance of data ranks for homogeneity using the Brown-Forsythe test (Brown and Forsythe, 1974) and found

that the assumption was violated for all environmental variables in our data set. However, given the large sample sizes in each wildfire size class and the drastically different environmental conditions between seasons and between size classes, we expect the likelihood of Type I error is low. Significant differences ($P < 0.001$) were identified by the Kruskal–Wallis procedure for all variables, so post-hoc pairwise multiple comparisons of data ranks were performed to determine which samples differed from others. The Bonferroni method was used for multiple comparisons because it is appropriate for samples with unequal variances (Sidak, 1967). Results of within-season multiple comparisons on data ranks are presented in Table 2. For clarity, comparisons between seasons were excluded from the table, but these comparisons can be found in the box and whisker plots described below.

Visual summaries of data values for environmental conditions from each wildfire size class and season are presented using box and whisker plots. Each box depicts the 25th, 50th (median), and 75th percentile values, with the range of the data represented with whiskers. Maximum whisker length was calculated as 1.5 times the interquartile range (75th percentile–25th percentile; Frigge et al., 1989). Any data points beyond the whiskers were considered outliers and displayed as individual points. Confidence intervals on the medians are represented with notches on each box, with notch locations calculated as

$$M \pm 1.57 \left(\frac{R}{\sqrt{n}} \right) \quad [3]$$

where M is the median, R is the interquartile range, and n is the number of samples (McGill et al., 1978). If notches do not overlap, median data values are roughly significantly different at the 95% confidence level (McGill et al., 1978). Comparisons using notches are less rigorous than the Kruskal–Wallis analysis and multiple comparisons, but the plots are a useful means of presenting the data and allow between season comparisons. All

Table 2. Minimum, maximum, and median daily values of fraction of available water capacity (FAW), maximum air temperature, minimum relative humidity, and maximum wind speed for fires in each size class for Oklahoma wildfires from 2000–2012. The Kruskal–Wallis test was significant ($P < 0.0001$) for all variables. Letter designations for significant differences between median values are for post-hoc multiple comparison tests on data ranks.

Size class	FAW			Maximum air temperature			Minimum relative humidity			Maximum wind speed		
	Min	Max	Med†	Min	Max	Med	Min	Max	Med	Min	Max	Med
	unitless			°C			%			m s ⁻¹		
Dormant Season												
5	0.05	1.05	0.65 a	0.4	34.1	23.4 a	4.8	66.6	16.3 a	4.2	19.5	10.9 a
4	0.06	1.03	0.84 b	-2.8	37.0	21.7 b	4.3	76.1	21.9 b	2.8	22.7	9.5 b
3	0.06	1.03	0.89 c	-3.8	36.5	20.7 c	4.9	86.4	25.3 c	2.7	21.8	8.8 c
2	0.05	1.05	0.90 cd	-7.9	37.2	19.6 d	4.9	91.5	27.0 d	1.8	23.9	8.3 d
1	0.00	1.05	0.91 d	-10.8	37.8	18.2 e	4.9	96.7	28.6 e	1.9	23.9	7.8 e
Growing Season												
5	0.05	0.46	0.11 a	19.9	45.5	40.8 a	3.4	38.6	18.3 a	4.8	18.0	8.6 a
4	0.04	0.98	0.13 ab	19.1	44.3	38.6 b	12.3	55.9	21.8 ab	3.4	17.3	7.6 abc
3	0.00	1.02	0.14 b	12.2	45.1	37.2 b	7.3	70.8	24.3 b	2.8	19.0	7.7 b
2	0.00	1.03	0.18 c	10.0	46.1	35.0 c	6.6	90.2	27.4 c	1.9	20.9	7.1 c
1	0.00	1.07	0.25 d	9.2	45.7	33.9 d	3.5	92.9	30.3 d	1.9	23.3	6.5 d

† For a given season, median values followed by different letters are significantly different ($P < 0.05$) based on the Bonferroni multiple comparison test on ranks. Median data values are shown for clarity.

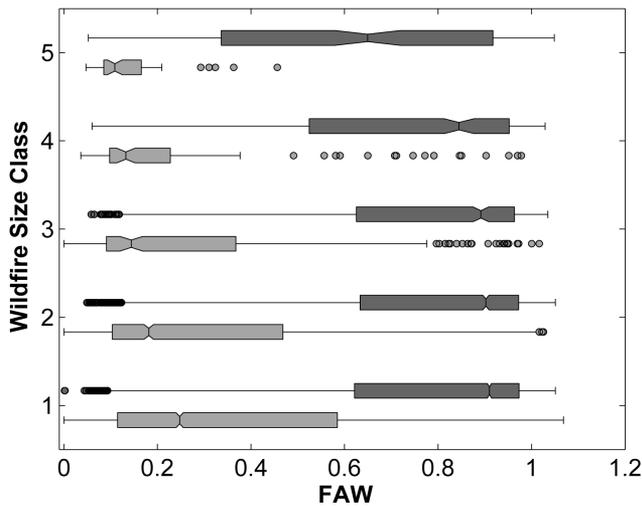


Fig. 1. Fraction of available water capacity (FAW) for fires in wildfire size Classes 1 (smallest) through 5 (largest) during the dormant season (dark gray boxes) and growing season (light gray boxes) for Oklahoma wildfires from 2000–2012. Median values are the black lines near the middle of each box, and notches are 95% confidence intervals on the medians. Median values are roughly significantly different ($P < 0.05$) if notches do not overlap. The 25th and 75th percentile values are the left and right sides of boxes, respectively; the data range excluding outliers is indicated by whiskers extending from each box; and outliers are individual points. All growing season size Class 5 fires (≥ 405 ha) occurred at $FAW < 0.5$ and the great majority occurred at $FAW < 0.2$.

statistical analyses were conducted with Matlab R2012a (The MathWorks, Inc., Natick, MA).

RESULTS

After significant seasonal and size class differences for FAW were identified (Kruskal–Wallis, $P < 0.001$), multiple comparisons confirmed that large fires occurred at lower FAW than smaller fires for both growing and dormant seasons (Table 2). The median FAW for the largest growing-season wildfires (size Class 5, ≥ 405 ha) was 0.11, indicating extremely low soil moisture levels and severe plant water stress. These size Class 5 wildfires occurred over a narrow range of FAW (0.05–0.46) relative to the range of FAW for all growing season fires (0.0–1.07; Fig. 1). The range of FAW for dormant-season size Class 5 fires was 0.05 to 1.05, which is nearly the entire range of FAW for all fires, and median FAW was 0.65, above the 0.5 threshold for moisture stress in plants (Allen et al., 1998). Unlike large fires, small fires occurred across the entire range of possible FAW values even during the growing season.

Growing-season wildfires ≥ 121 ha rarely occurred when FAW was above 0.5, and most occurred below a threshold FAW of about 0.2 (Fig. 2). During the growing season, 91% (159 of 174 fires with soil moisture data) of fires ≥ 121 ha (size Classes 4 and 5) occurred at $FAW < 0.5$, and 77% (134 of 174) occurred at $FAW < 0.2$ (Fig. 2). The strong relationship between low FAW and wildfire occurrence in the growing season is further illustrated by examining statewide average FAW for high and low wildfire years. For 2012, when growing-season wildfire extent was greatest (93,043 ha), statewide average FAW was well

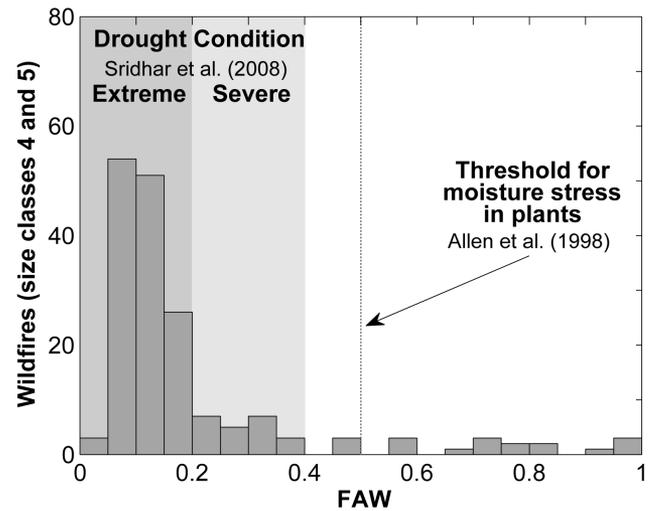


Fig. 2. Frequency distribution of fraction of available water capacity (FAW) for growing-season wildfires in size Class 4 (≥ 121 and < 405 ha) and 5 (≥ 405 ha) combined in Oklahoma from 2000–2012. Most fires (159 of 174 fires for which soil moisture data were available) occurred at $FAW < 0.5$, with some occurring under severe drought (22 fires) and most occurring under extreme drought (134 fires).

below average during most of the growing season, while in 2007, a year of low growing-season wildfire extent (3214 ha), FAW was generally above average (Fig. 3). In 2012, FAW was below 0.5 early in the growing season and was near or below 0.2 for most of July and August, with these months respectively accounting for 21% (19,539 ha) and 77% (71,643 ha) of total growing-season wildfire area burned that year (data not shown).

Large growing and dormant-season wildfires occurred at higher maximum air temperatures (Kruskal–Wallis test $P < 0.001$), lower minimum relative humidity ($P < 0.001$), and higher maximum wind speeds ($P < 0.001$; Table 2) than small fires. Minimum relative humidity varied over a narrow range for grow-

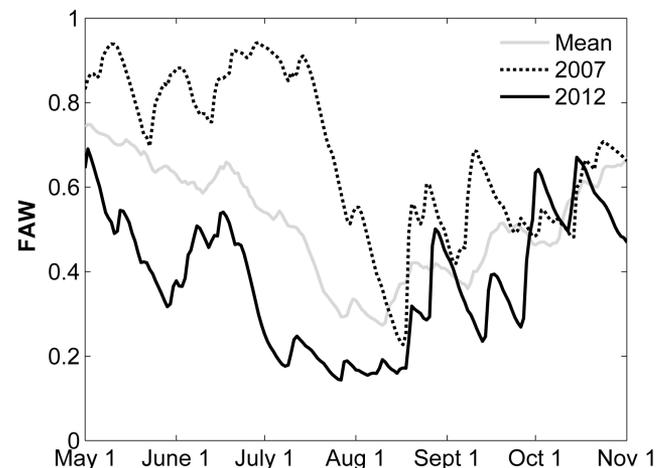


Fig. 3. Oklahoma statewide average growing-season fraction of available water capacity (FAW) during a year of low wildfire occurrence and area in the growing season (2007, 3214 ha), a year of high wildfire occurrence and area in the growing season (2012, 93043 ha), and the long term mean FAW (1996–2012). In 2012, FAW was well below average much of the growing season including the peak wildfire months of July and August, whereas FAW in 2007 was nearly always greater than average.

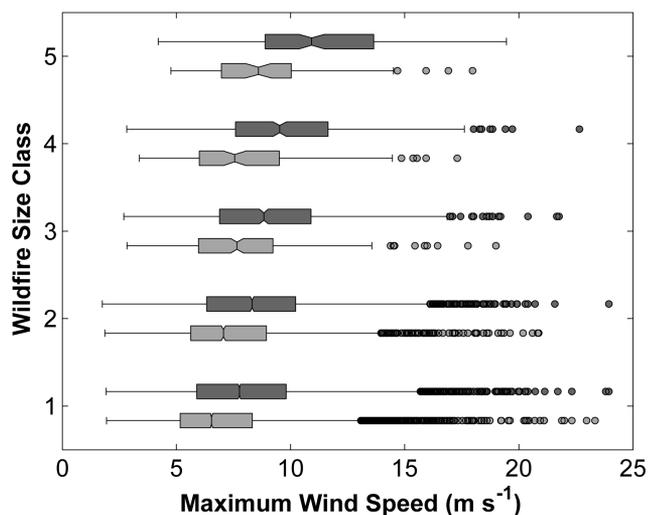


Fig. 4. Maximum daily wind speed for fires in wildfire size Classes 1 (smallest) through 5 (largest) during the dormant season (dark gray boxes) and growing season (light gray boxes) for Oklahoma wildfires from 2000–2012. Median values are the black lines near the middle of each box, and notches are 95% confidence intervals on the medians. Median values are roughly significantly different ($P < 0.05$) if notches do not overlap. The 25th and 75th percentile values are the left and right sides of boxes, respectively; the data range excluding outliers is indicated by whiskers extending from each box; and outliers are individual points.

ing-season size Class 5 fires (3.4–38.6%) relative to all other size classes (3.5–92.9%). For large dormant-season fires, the range of each weather variable was small relative to its respective possible range, unlike FAW which varied across its entire range even for large fires. For example, minimum relative humidity ranged from 4.8 to 66.6% for size Class 5 fires, while the range for all

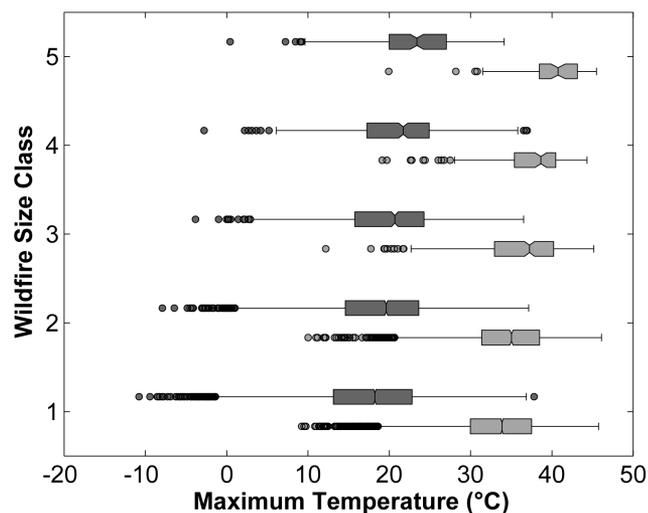


Fig. 5. Maximum daily air temperature for fires in wildfire size Classes 1 (smallest) through 5 (largest) during the dormant season (dark gray boxes) and growing season (light gray boxes) for Oklahoma wildfires from 2000–2012. Median values are the black lines near the middle of each box, and notches are 95% confidence intervals on the medians. Median values are roughly significantly different ($P < 0.05$) if notches do not overlap. The 25th and 75th percentile values are the left and right sides of boxes, respectively; the data range excluding outliers is indicated by whiskers extending from each box; and outliers are individual points.

dormant season fires was 4.3 to 96.7% (Table 2). For dormant season size Class 5 fires, the median minimum relative humidity (16%) and maximum wind speed (10.9 m s^{-1}) were consistent with National Weather Service (NWS, 2015) criteria for Rangeland or Grassland Fire Danger Statements, which include relative humidity $\leq 20\%$ and wind speed $\geq 10.3 \text{ m s}^{-1}$ (adjusted to 10-m measurement height [Turner and Lawson, 1978]). This is in direct contrast with FAW, for which the median value (0.65) for dormant-season size Class 5 fires suggested adequate soil moisture. In general, the range of conditions over which wildfires occurred was greater during the dormant season than growing season for all variables.

Typical of the climate of Oklahoma, FAW, maximum air temperature, and maximum wind speed varied greatly by season, with FAW (Fig. 1) and wind speed (Fig. 4) being lower during the growing season and temperature being higher (Fig. 5). Minimum relative humidity did not show the seasonality of the other variables, with seasonal differences in median values occurring only for the smallest wildfires (size Class 1; Fig. 6). In general, relative humidity does not demonstrate the same seasonal variability as other variables, with minimum relative humidity averaging 41 and 40% for all days during the dormant and growing seasons, respectively.

Dormant-season fires outnumbered growing-season fires for all fire size classes (Table 1). Wildfire number and area were generally greater during the dormant season than growing season each year, with the exception of 2012 when growing-season wildfire area was much larger than area burned in the dormant season (Fig. 7). Over the 13-yr data record, 36% of wildfires and 30% of area burned occurred during the growing season, but recently,

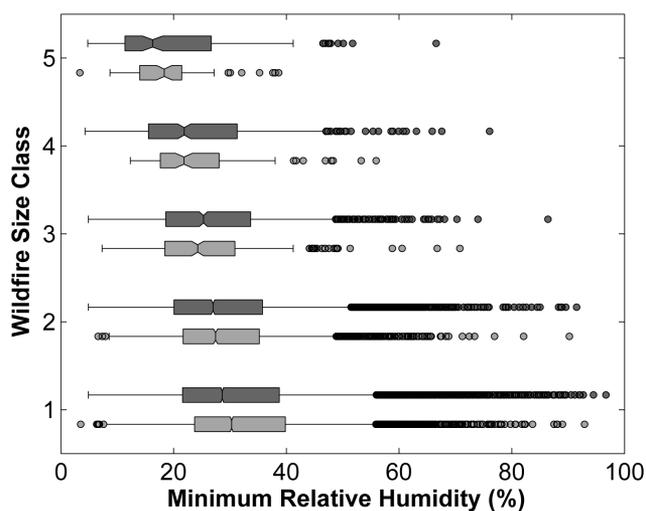


Fig. 6. Minimum daily relative humidity for fires in wildfire size Classes 1 (smallest) through 5 (largest) during the dormant season (dark gray boxes) and growing season (light gray boxes) for Oklahoma wildfires from 2000–2012. Median values are the black lines near the middle of each box, and notches are 95% confidence intervals on the medians. Median values are roughly significantly different ($P < 0.05$) if notches do not overlap. The 25th and 75th percentile values are the left and right sides of boxes, respectively; the data range excluding outliers is indicated by whiskers extending from each box; and outliers are individual points.

growing season fires have been more numerous and widespread. From 2000–2010, 32% of fires and 16% of area burned occurred during the growing season, but during the severe drought years of 2011 and 2012, growing-season fire number and area burned were 51 and 70% of the total, respectively.

DISCUSSION

The physical link between soil moisture and LFM and the increasing availability of data make soil moisture a strong candidate variable for wildfire research. Our primary goal was to answer the fundamental question, how is wildfire size related to soil moisture? We hypothesized that soil moisture, expressed as FAW, is an important driver of wildfires during the growing season when plants are actively growing but is less important during the dormant season when most plants are dead or dormant. We found that FAW is strongly related to wildfires during the growing season, with the largest fires occurring almost exclusively at low FAW. During the dormant season, large fires generally occurred at lower FAW than smaller fires, but unlike during the growing season, large dormant-season fires occurred even under conditions of high soil moisture.

The narrow range of FAW over which size class 5 (≥ 405 ha) growing-season wildfires occurred is remarkable, especially given the spatial variability of soil moisture and the influence other factors such as weather, ignition source, fuel characteristics, and suppression efforts have on wildfire occurrence and size. All size Class 5 fires occurred at $FAW < 0.5$, the threshold below which moisture stress in plants generally occurs (Allen et al., 1998), and 87% of fires occurred when FAW was < 0.2 (Fig. 2). The FAW derived Soil Moisture Index has been used to assess drought conditions in agricultural settings (Sridhar et al., 2008; Hunt et al.,

2009), with $FAW < 0.4$ being classified as severe drought and $FAW < 0.2$ being extreme drought (Sridhar et al., 2008). Based on these criteria, size Class 5 fires (≥ 405 ha) were nearly always associated with extreme drought (Fig. 1), and extreme drought conditions existed for most (77%) fires in size Classes 4 and 5 combined (≥ 121 ha; Fig. 2). This strong relationship is a consequence of the direct influence that soil moisture has on growing plants. When soil moisture is sufficient, LFM is high and flammability is low, but as soil moisture decreases, so does LFM (Pellizzaro et al., 2007), with vegetation eventually transitioning from heat sink to heat source (Cohen and Omi, 1991). The impact of soil moisture on LFM may be especially important for vegetation prone to fluctuations in moisture content (Pellizzaro et al., 2007), including rangeland and pasture.

While $FAW < 0.2$ was a common characteristic for the great majority of large growing-season wildfires in this data set, it was not absolute. For example, a 2833-ha fire occurred near Guymon, OK on 24 May 2011 when FAW was 0.36, maximum air temperature was high (31°C), and relative humidity (11%) and maximum wind speed (17 m s^{-1}) were near their respective extremes (Fig. 4 and 6). For this fire, weather conditions were likely the dominant drivers in already moisture stressed vegetation. The impact weather has on wildfire occurrence is well established (Littell et al., 2009; Reid et al., 2010), and is supported by significant relationships between weather variables and wildfire size during both the growing and dormant seasons in our study. Each of our measured variables explains a portion of the mechanism driving interactions at the soil-fuel-atmosphere interface. For example, higher air temperature speeds fuel drying and supports wildfire ignition and propagation, wind aids fuel drying and drives fire spread, and relative humidity controls moisture of senesced plants. Large growing-season wildfires resulted from additions of dead fuel because of low soil moisture, low relative humidity reducing moisture of dead fuel, and high winds driving fire spread.

Some large growing season fires occurred when FAW was in the midst of rapid change. In one instance, a 405-ha fire occurred near Dewar, OK on 29 July 2012 when FAW was 0.46 (Fig. 1), but 37 mm of precipitation 3 d before fire ignition relieved a period of more than 6 wk when $FAW < 0.2$. This prolonged period of extreme drought likely led to senescence of vegetation, after which increased soil moisture had little impact on fuel moisture, and weather variables dictated moisture of dead fuels and wildfire spread (Bradshaw et al., 1983; Nelson, 2000). This example suggests that wildfire danger can be high after long drought periods during the growing season even after near surface moisture deficits are replenished. Including soil moisture data from below 40 cm might be beneficial in this context by effectively increasing the “memory” of the soil moisture data.

Other fires occurred at the onset of “flash droughts”. Flash droughts are short-term severe events characterized by moisture deficits and abnormally high air temperatures (Senay et al., 2008), lasting no less than 3 wk, and characterized by a FAW decrease of at least 0.5 (Hunt et al., 2009). For example, an 809-ha

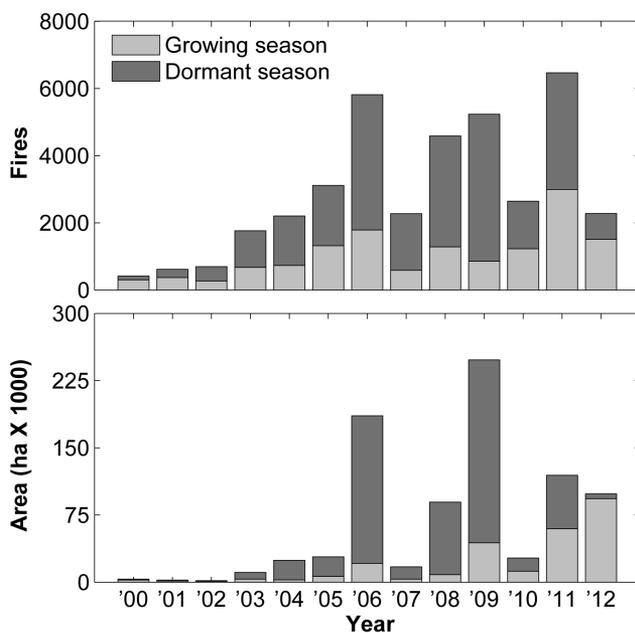


Fig. 7. Growing-season and dormant-season wildfire number and area burned (in thousands of ha) for wildfires in Oklahoma from 2000–2012. Dormant season is from November through April ending the indicated year.

fire occurred near Waynoka, OK on 5 Sept. 2010 when FAW was 0.32. Two weeks prior, FAW was 1.0 and steadily decreased to <0.2 several days after fire occurrence, where it remained for nearly 8 wk. In agricultural settings, it has been suggested that this rapidly declining soil moisture should inform producers of impending drought (Mozny et al., 2012). Similarly, the onset of flash drought could trigger an alert for the increased wildfire potential in wildfire danger assessments. Finally, FAW < 0.4 early in the growing season may be an early warning sign of high wildfire danger later in the year, as was the case in 2012 (Fig. 3). Similarly, low soil moisture at the beginning of the growing season has been suggested as an early warning sign of negative drought impacts on crops later in the growing season (Hunt et al., 2009).

Fires that occurred early or late in the growing season were less dependent on FAW, likely because plant phenology was more important to fuel moisture than was soil moisture. Six growing-season size-Class 4 fires occurred with FAW > 0.8 (Fig. 1), moisture levels that approached field capacity and that were near optimum for plant growth. Of these, four occurred on or after 23 September and one occurred on 14 May. These fires occurred outside of the period of peak greenness for vegetation in Oklahoma (Senay and Elliott, 2000), and it is likely that fuels were, at least partially, dead remnants of the previous year's growth (spring fires) or mature vegetation from the current year (fall fires; Wittich, 2011). Dimitrakopoulos and Bemmerzouk (2003) successfully used the Keetch-Byram Drought Index (KBDI) to predict LFM from June through August, but found that relationships were poor in May and September when plant phenology dictated fuel moisture. These results suggest that the growing season FAW-wildfire size relationship is strongest during June, July, and August, the times of peak vegetative greenness in Oklahoma (Senay and Elliott, 2000).

Similarly, plant phenology also explains the occurrence of large dormant-season wildfires when FAW was high. Vegetation on these landscapes is primarily dead or dormant during the cool part of the year, with senescence beginning in early October and spring regrowth reaching its maximum in June (Senay and Elliott, 2000). During the dormant season, weather variables dictate wildfire occurrence and size because fuels are dominated by the dead fine fuel that drives ignition and energy release during combustion, with dead fuel moisture being dictated primarily by air temperature, relative humidity, and precipitation while wildfire spread is influenced mostly by wind speed (Bradshaw et al., 1983).

Nonetheless, large dormant-season wildfires occurred at significantly lower FAW than small fires, likely in part because of the influence soil moisture has on live fuels during the dormant season. For example, leaf moisture content of eastern redcedar trees decreases as soil moisture decreases, even during the dormant season (Engle et al., 1987). Reduced leaf moisture content increases eastern redcedar flammability (Weir and Scasta, 2014) and therefore wildfire probability (Ursino and Rulli, 2011). The dormant-season soil moisture-wildfire relationship may also have resulted because of the onset of spring regrowth before the end of our defined dormant season. Spring regrowth generally begins in

March (Senay and Elliott, 2000) and could be inhibited by low FAW during this period, resulting in a lower proportion of live fuels and increased wildfire probability. Furthermore, the moisture of long lag-time dead fuels (i.e., 100-h and 1000-h fuels) decreases during drought (Bradshaw et al., 1983). Our observed relationship between low soil moisture and large dormant season wildfires, where 100-h and 1000-h fuels are involved, may therefore in part be explained by the low dead fuel moisture of these fuels, which coincides with low soil moisture during drought.

Our results suggest that growing-season wildfire danger assessments may be improved by including soil moisture data in the absence of LFM data. Moisture modeling in dead fuels is well refined, and wildfire danger assessments during the dormant season when fuels are primarily dead are well established (Carlson et al., 2007). In contrast, LFM modeling and current understanding of wildfire behavior in live fuels is lacking, which hinders growing-season wildfire danger assessment (Joint Fire Science Program, 2009). Often, estimates of soil moisture like KBDI are used as surrogates for LFM, such as in the United States Forest Service Wildland Fire Assessment System (Wildland Fire Assessment System, 2013). In Oklahoma, KBDI is a component of the Oklahoma Fire Danger model, an operational tool for fire danger rating designed to assist fire managers with assessing fire danger across Oklahoma (Carlson et al., 2002; Carlson and Burgan, 2003). In some cases, soil moisture measurements have been shown to be more strongly correlated to LFM than soil moisture estimates such as KBDI (Pellizzaro et al., 2007). The importance of reliable growing-season wildfire danger assessments is highlighted by the increased growing-season wildfire occurrence and area in Oklahoma in 2011 and 2012 compared with prior years (Fig. 7). As spatial coverage of soil moisture data increases, due to the proliferation of in situ networks and the development of satellite-derived global soil moisture monitoring (Ochsner et al., 2013), improved large-scale wildfire danger assessments may be possible.

IMPLICATIONS

In light of our finding that soil moisture strongly affects growing-season wildfire size, we recommend that soil moisture be included in wildfire danger assessments for live fuels in Oklahoma and neighboring rangeland states. During the dormant season, on the other hand, when the occurrence of large wildfires was not strictly dependent on low FAW, our results support the methodology behind current dormant-season wildfire danger assessments that rely on weather variables known to drive wildfires in dead fuels. Currently, no wildfire danger models incorporate soil moisture, but increasing availability makes its inclusion in growing-season wildfire danger assessments more feasible. Live fuel moisture modeling remains one of the key challenges to producing reliable wildfire danger assessments, and soil moisture may be a useful surrogate for LFM given their physical coupling. During prolonged periods of soil moisture stress, live herbaceous and deciduous woody vegetation senescences, transitioning to dead fuel, while live evergreen woody vegetation decreases in fuel moisture, both of

which can lead to conditions conducive to the spread of wildfire. Our findings support this assertion, with the occurrence of large wildfires being highly correlated with extreme drought as indicated by low FAW. The strong soil moisture–growing-season wildfire relationship that we observed in Oklahoma likely exists in other areas with similar climate and herbaceous vegetation, including much of the U.S. Great Plains region. Relative to the more rapidly fluctuating weather variables, FAW also exhibits greater temporal stability and may therefore have unique potential for forecasting wildfire danger.

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