Project Title: Development and Evaluation of Dynamic Vegetation Models for Grassland Fuels under Variable Fire and Grazing Regimes

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Abstract
Managing fire, especially wildfire, in grassland suffers currently from the inability to anticipate large wildfires, especially fuel curing, when live herbaceous vegetation transitions rapidly to dead fuel. To assess these herbaceous fuel dynamics in grassland, we conducted three studies: 1) a study that used a database of large wildfires in Oklahoma to examine the relationship of fire occurrence and fire size with soil moisture, 2) an intensive field-based study to quantify and subsequently model herbaceous fuel load and moisture content in grassland patches that differed in time since fire and, therefore, proportion of live and dead herbaceous fuel load, and 3) modeling the influence of herbaceous fuel dynamics and weather conditions on fire behavior in tallgrass prairie.

Wildfire occurrence in Oklahoma exhibits seasonally-dependent relationships with soil moisture conditions. Large growing-season wildfires in Oklahoma occur almost exclusively under conditions of low soil moisture, and growing-season fire probability is particularly high when less than 20% of the soil's available water capacity is filled. Dormant-season wildfire occurrence is also related to soil moisture conditions, although not as strongly. Both current soil moisture levels and soil moisture levels during the previous growing season influence wildfire probability during the growing season. The physical link between soil moisture and vegetation moisture, along with the increasing availability of soil moisture data, make soil moisture a strong candidate variable for monitoring wildfire risk, especially in the growing season.

In the intensive field study, we collected fuelbed data from a grassland research location with successional vegetation produced by fuel treatments of spatially and temporally variable fire and grazing. The data collected (and variables estimated from the data) include a suite of fuel variables (live and dead load, live and dead moisture content, particle density, etc.), soil moisture, soil temperature, and plant canopy spectral reflectance from a hand-held radiometer and from satellite. Results from our study on the relationship of soil moisture and wildfire occurrence informed our approach to modeling fuel dynamics. Candidate variables will focus on soil moisture and canopy reflectance to model fuel components that our research shows vary most over space and time.

Modeling fire behavior across the full range of potential fire conditions, including fuel characteristics, revealed complex behaviors that have not been accounted for in grassland fire management. We found that fire behavior changes in complex ways as grass curing progresses. Linear relationships became non-linear, and tipping points occurred that revealed rapid and sudden change in fire behavior at intermediate levels of grass curing.

Background and Purpose
Managing fire, especially wildfire, in grassland suffers currently from the inability to anticipate large wildfires, especially when live herbaceous vegetation transitions rapidly to dead fuel. Wildfire occurrence in Oklahoma exhibits seasonally-dependent relationships with soil moisture conditions.

Herbaceous fuels drive fire behavior in grasslands and in mixed fuel complexes where grasses are a component of the surface fuels such as in forests and shrub/grass landscapes. Grassland wildfire can be as wide ranging and as devastating as forest fires, as for example, when in the 2005-2006 fire season, thousands of quick-moving grassland fires claimed 25 lives in Texas and Oklahoma, destroyed over 1100 homes, and burned over 3 million acres (Mutch and Keller, 2010). Similar wildfire outbreaks occurred in the 2011, 2012, and 2016 fire seasons.

In their "dead fuel" phase, herbaceous fuels constitute 1-hour fuels, which contribute greatly to fire danger and fire spread. In their "live" phase, herbaceous fuels can serve as a heat sink depending on their fuel moisture. *Fire danger* systems such as the U. S. National Fire Danger Rating System (NFDRS) model the temporal dynamics of herbaceous fuels by shifting fuel loads between the live herbaceous class and 1-hour dead class throughout the annual cycle. In the 1978 NFDRS, this transfer is modeled by built-in algorithms that are a function of 1000-hour dead fuel moisture and that are triggered by manual input of green-up and curing dates (Bradshaw *et al*., 1983). In the 1988 NFDRS this transfer is modeled by user-input greenness factors from 0 to 20 (Burgan, 1988). In the Oklahoma Fire Danger Model used in the OK-FIRE system (Carlson *et al*., 2008), the dynamic fuel transfer is modeled as a function of satellite-derived "relative greenness" (Burgan and Hartford, 1993; Carlson *et al*., 2002). In the Australian and Canadian fire danger systems, estimates of degree of curing are provided as inputs.

With respect to live fuel moisture, a critical factor in fire behavior, similar schemes are used. The 1978 NFDRS models live herbaceous moisture as a function of 1000-hour dead fuel moisture between the period of green-up and curing, while the 1988 NFDRS models live herb moisture as a function of the greenness factors. The Oklahoma Fire Danger Model currently uses relative greenness to model live herbaceous moisture in a range of 60% to 200%.

For point or area *fire behavior* systems such as BehavePlus, FlamMap, FARSITE, and FSPro, the herbaceous fuels loads are constant in time, based on the fuel models chosen. Live herb moisture is also assumed constant in time. The Canadian Forest Fire Behavior Prediction System, while not explicitly modeling live herbaceous moisture, takes into account degree of curing in modeling the spread rate in grass fuels (Wotton *et al*., 2009).

Because many of the above-mentioned modeling schemes for live fuels are based on "greenness" (either satellite-based or visually estimated), other models have been created to predict greenness. Jolly *et al*. (2005), for example, developed a "Growing Season Index" based on day length, vapor pressure deficit, and minimum temperatures to model vegetation greenness. Martin et al. (2015) reported on an improved technique tested in Australian grasslands for estimating the degree of curing (the proportion of senescent material) using satellite data adjusted by visual observation on the ground, which corrects for the overestimation of curing if water is present in grassland fuels (Newnham et al. 2010).

Many of the methods mentioned above for modeling grass fuels have serious weaknesses, are unverified, and are based on the assumption that the dynamics of these variables (live fuel moisture, 1-h dead, and live fuel loads) are a function of overall vegetation greenness. However, a number of studies have shown that such methods have serious limitations (Joint Fire Science Program, 2009), especially with respect to live fuel moisture. In contrast to dead fuel moisture, the modeling of which is now sufficiently refined (Carlson *et al*., 2007), modeling of live fuel moisture remains crude at best.

In addition, these methods have largely ignored the effects of surface *weather* (such as precipitation) as well as *soil* conditions (moisture and temperature). Choler *et al*. (2010), for example, showed the importance of soil water in adequately predicting leaf dynamics in semi-arid perennial grasslands, and Qi et al. (2012) demonstrated that soil moisture was more strongly associated with live fuel moisture of shrubs than were remote sensing measurements. Soil data, including soil moisture, are rapidly increasing in spatial density and quality across the U.S. (Ochsner et al. 2013), yet the science to support the use of soil moisture data in fuel modeling, as in other applications, is lagging.

Furthermore, many of the modeling approaches have largely neglected the effects of *fuel treatments* on these variables so important to fire danger and behavior. In grasslands the primary fuel treatments consist of fire and grazing. How, for example, do 1-h dead and live fuel loads change as a function of time since fire and grazing? Therefore, from both a management and fire danger perspective, current fuel models and methodologies for handling the dynamics of grass fuels are largely inadequate.

Study Description and Location

A primary objective of this research was to provide insight into the transition to fire danger that accompanies the transition of grassland fuelbeds from live to dead. Although not a part of the original proposal, we pursued two projects that would provide insight.

We first used a wildfire database from 2000-2012 and corresponding Oklahoma Mesonet data on soil moisture to compare relationships between wildfire size and soil moisture in Oklahoma. We also used logistic regression to develop probabilistic relationships of soil moisture with growing-season and dormant-season wildfires in Oklahoma.

In the second project, we used BehavePlus ver. 5.0.5 (Heinsch and Andrews 2010) to simulate the effect of prescribed fire policy and plant invasions on the potential magnitude and variation in surface fire behavior in tallgrass prairie. We used the SURFACE module in BehavePlus to customize the model parameters across a reasonable range of maximum and minimum values observed for fuel properties, wind speed, and slope (the factors driving surface fire behavior in BehavePlus) in tallgrass prairie. For example, fuel data values used to parameterize the model were obtained from the scientific literature, and minimum one-hour fuel moisture and maximum wind speed were determined using the Oklahoma Mesonet established in 1994. One-hour dead fuel moisture of 2% has been observed on several occasions, and maximum wind speed of 77 km hr^{-1} has also been observed. Using these minimum and maximum values, independent simulations were conducted for 11 scenarios of the transition from live to green in the fuelbed, or grass curing (ranging from 0 to 100% at 10% intervals, where 0 and 100% correspond to ‘‘green’’ grass fuels that are not cured and ‘‘brown’’ fully cured grasses, respectively). We evaluated sensitivity of fire behavior to the range of potential fire conditions and fire conditions constrained by prescribed fire policy, government burn bans, and plant invasions (juniper and tall fescue).

The intensive field study that was described in our proposal was located on the OSU Research Range (OSURR), co-located with the Marena Mesonet station in north central Oklahoma. Three replicates of grazed pastures in which six patches within each pasture are rotationally burned were included in the sampling scheme. Three patches (those burned in the summer) were studied in each replicate pasture. The research location is unique in that it was subject to a treatment regime that created spatially distinct patches that differ in the quantity of live and dead herbaceous vegetation. A severe drought in the preceding (2011) and first year (2012) of the study period provided a serendipitous opportunity to assess the effect of drought on fuel characteristics and spatial pattern (i.e., point versus patch versus pasture).

Fuelbed characteristics of patches were assessed periodically (biweekly) from the end of the dormant season (about March 1) until the end of the growing season (about November 15) in 2012 and 2013. We excluded sampling from November 15 to March 1 because these grasslands are dominated by C4, warm-season grasses, and little change in fuelbed characteristics occurs in the non-growing season (about November 15 to March 1). We collected data on important variables in grass fuelbeds - fuel load, production rate, and successional stage - as a function of time since fire and grazing, growing-season progression, and plant growth conditions. Fuel estimates were sufficiently detailed to describe the complexity of the fuelbed for fire behavior modeling. Our sampling approach followed Fuhlendorf and Engle (2004) to assess spatial variability/fuel continuity at different spatial scales. Fuel mass (by unit volume and unit area) was sampled by clipping as described by Engle et al. (1993). We used the constituent differential method (Gillen and Tate 1993) to calculate live and dead fuel loads, thus eliminating time-consuming hand separation of live and dead components and allowing more quadrat sampling along the biweekly transects. Fuelbed depth and surface area-to-volume ratio were determined for each fuelbed as well as packing ratio, calculated as the ratio of bulk density to particle density (Rothermel, 1972). Canopy reflectance in five wavelength bands was measured using handheld multispectral radiometer (MSR16#456, Cropscan, Inc., Rochester, Minnesota) from 2 m above ground.

Sampling of eastern redcedar foliage, as well as the litter and duff layers under the eastern redcedar trees, occurred during 2013 in an area just to the east of one of the replicate pastures. Eastern redcedar is a tremendous fire hazard in Oklahoma and which, under low live fuel moisture conditions, can ignite with great intensity, further intensifying the wildland fire. Canopy reflectance was also taken above the cedar canopy.

An Oklahoma Mesonet tower (Marena tower location) located on the OSURR provided weather, soil temperature, and soil moisture data. We assumed temperature, relative humidity, wind, and solar radiation regimes were uniform over the three replicates (all are within several miles of the Mesonet tower). However, to account for rainfall spatial variability, we installed a digital precipitation gauge in each replicate. We also installed digital soil moisture and temperature sensors in a representative soil at the approximate centers of three studied burn patches in each replicate because biomass accumulation varies also according to plant-available soil water and soil temperature. Data from these sensors were recorded on dataloggers in each replicate patch (n = 9 total). Because these soil moisture sensors provide volumetric water content (percent water), we also sampled and analyzed soil water retention to determine plant-available water at each datalogger location in each patch.

Finally, Landsat and MODIS satellite data at various resolutions (30-m for Landsat, and 250-m, 500-m, and 1-km for MODIS) were acquired to obtain fuelbed spectral reflectance at a number of wavelength bands, which were then used to construct 17 spectral indices related to the herbaceous plant canopy (i.e., the fuelbed) and the aforementioned eastern redcedar canopy.

Key Findings

Wildfire size in Oklahoma was strongly dependent on soil moisture, but the relationship was stronger during the growing season than dormant season.

The physical link between soil moisture and vegetation moisture, along with increasing availability of data, make soil moisture a strong candidate variable for wildfire research. We compared the relationship between wildfire size and soil moisture in Oklahoma from 2000-2012 (Krueger et al. 2015). Our goal was to answer the fundamental question, how is wildfire size related to soil moisture? To account for the control that soil physical properties have on soil moisture availability to vegetation, or plant available water (PAW), we represented soil moisture as fraction of available water capacity (FAW). FAW is the ratio of PAW to the maximum amount of available water a soil can hold, or available water capacity (AWC), and is calculated as PAW/AWC. Plants begin to experience moisture stress below a FAW value of about 0.5 (Allen et al, 1998), and a value of 0.2 is indicative of extreme drought (Sridhar et al., 2008).

We found that large fires occurred at lower FAW than small fires during both the growing (May – October) and dormant seasons (November – April), 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). During the growing season, fires ≥121 ha occurred almost exclusively at low FAW, with 91% occurring at FAW < 0.5 and 77% occurring at FAW < 0.2. 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 probability of a large wildfire (≥ 405 ha) occurring in Oklahoma was driven in part by concurrent soil moisture during the growing and dormant seasons as well as antecedent soil moisture during the growing season.

We used logistic regression to develop probabilistic relationships between growing and dormant season wildfires in Oklahoma (Krueger et al. 2016). During the growing season, when relative humidity and wind speed were at their threshold values for issuing a National Weather Service red flag warning (relative humidity = 20% and wind speed = 10.3 m s^{-1}), wildfire probability was only around 0.05 when FAW was 0.9 (near ideal for plant growth). But wildfire probability increased to 0.18 when concurrent FAW was 0.5 (threshold for plant moisture stress) and 0.60 when concurrent FAW was 0.2 (extreme drought). Conversely, when minimum relative humidity and maximum wind speed conditions were moderate (minimum relative humidity = 40% and maximum wind speed = 7.3 m s^{-1}), wildfire probability was only 0.02 even with FAW = 0.2. Dormant season wildfire probability was influenced by concurrent FAW and weather, but antecedent FAW was also important. Dormant season wildfire probability was 0.29 and 0.09 when FAW during the previous growing season was 0.9 and 0.2, respectively. Therefore, although a wet growing season coincided with reduced wildfire probability that season, it also coincided with increased wildfire probability the following dormant season.

We found that soil moisture and weather work in concert to support high wildfire probability, with each variable explaining a portion of the mechanism behind occurrence of large wildfires. During the growing season, low FAW decreases LFM and may cause herbaceous and deciduous woody fuels to transition from live to dead, low relative humidity lowers dead fuel moisture, and high wind speed drives fire spread. Low FAW and extreme weather (low relative humidity and high wind speed) were both required for wildfire probability to be high. Dormant season wildfire probability was increased by low concurrent FAW and high antecedent FAW, indicating that fuel accumulation from previous growing seasons supports dormant season wildfire.

Soil moisture is a good predictor of fuel moisture of herbaceous fuels in the growing season.
On our research grasslands, fraction of available water (FAW) and total fuel moisture content were significantly related in the growing season (r^2 = 0.59). Data will be analyzed further to determine the relationship of live fuel moisture content with FAW and other variables. Live plants that had regrown on recently burned patches on the research pastures often contained extremely high levels of moisture (i.e., in excess of 500% water on a dry-weight basis), so we anticipate that the samples collected in patches in which dead fuel was consumed completely by recent fire do not apply to objectives of this study. We are currently considering approaches to modeling the live moisture content on the pastures in which patches differ in time since fire by a few days to three years. Dead fuel generally increases over time since fire, but the dynamics (mass and moisture content) of the live component has not been documented until this study.

Local remote sensing can be useful for estimating certain fuelbed variables
Using canopy reflectance from the hand-held spectrometer that was used in our research, 17 spectral indices were calculated and compared to measured/calculated fuelbed variables in our grassland plots as well as in an area dominated by eastern redcedar. Preliminary findings show promise for some spectral indices to estimate total mix fuel moisture (r^2 up to 0.6), live fuel load (r^2 up to 0.5), and live fuel moisture (r^2 up to 0.4). Results were particularly impressive for eastern redcedar foliage fuel moisture, with r^2 up to 0.8, although the range of measured live fuel moisture was rather narrow over the 2013 sampling period. NDVI was one spectral index that performed consistently high for the variables listed above.

Dynamic models are needed to capture the high temporal variability of grassland fuel properties and improve upon assumptions of static fuel models.
We compared the relative amount of information lost when using static fuel models, which assume a constant fuel bed, with a dynamic fuel modeling approach. Static and dynamic models were compared using an information theoretic approach. Applying a dynamic modeling approach common in ecology

(General Additive Models; GAM) improved the intra-seasonal characterization of nearly all tallgrass prairie fuel properties compared to traditional static models. Only surface area-to-volume ratio and bulk density were relatively constant over space and time. Other fuel properties exhibited high temporal variability.

The mean value of a given fuel property is misleading and should not be the default value for customizing herbaceous fuel properties in landscapes with intact disturbance regimes.
The mean value of a given fuel property is often used to establish the representative value of fuelbeds in grassland landscapes. During some periods of the year, and for nearly every fuel property measured in this study, the mean, calculated as the average value that occurred over two years of biweekly sampling, did not occur in the fuel bed or was present in less than 5% of samples. Interactions among drought, fire, and grazing contributed to high departures from the mean, and the mean (which is used in static fuel models) is unable to capture important variability in fuels properties during periods when wildfire occurrence is transitioning from low to high (e.g. at the onset of severe drought).

The relative amount of information lost using a static model was similar for fuel bed depth, particle density, live herbaceous fuel load, and live herbaceous moisture content.
Dynamic fuel models rely on variability in live herbaceous moisture content to provide more realistic modeling of fire behavior in herbaceous fuels, but dynamic modeling approaches were just as important in capturing intra-seasonal variability in fuel bed depth, particle density, and live herbaceous fuel load as they were for capturing variability in live herbaceous moisture content.

Severe drought in 2012 triggered a switch in the spatial scale at which grassland biomass varied across the landscape.
In our study on a long-term experimental landscape, we have shown (e.g., Fuhlendorf and Engle 2004) that the fire-grazing interaction increased spatial variability in aboveground grassland biomass among patches, yet the interaction decreased spatial variability (i.e., increased uniformity) within patches. During the drought, a scaling switch was observed in which variability in fuel load was greatest within patches, and fuel load among patches converged, resulting in greater uniformity at the landscape-scale.

Modeling fire behavior across the full range of potential fire conditions, including fuel characteristics, revealed complex behaviors that have not been accounted for in grassland fire management.
We used BehavePlus to model, for the first time, the full range of theoretical fire behavior that could be expected from tallgrass prairie fuels (Twidwell et al. 2016). This model revealed complex changes in fire behavior as grass curing progresses. Linear relationships became non-linear and tipping points occurred that revealed rapid and sudden change in fire behavior at intermediate levels of grass curing.

Fire and its potential as a driver of ecosystem dynamics have been simplified in the study and management of rangelands.
Social policies and practices are changing fire behavior in tallgrass prairie as much, or more, than biological invaders, but they have received considerably less attention. Scientific investigations have operated under these socially imposed constraints and may be contributing to misleading conclusions

on the potential responses of many highly researched environmental priorities. We emphasize the need to study change in fire dynamics, as a function of both social and ecological drivers, in an effort to advance our basic understanding of the role of fire in nature and its potential usefulness in ecosystem management.

Management Implications

- Wildfire danger assessment does not currently incorporate soil moisture because the soil moisture data have been lacking at operational scales. Our research findings provide scientific justification for using soil moisture data from in situ monitoring networks in fire danger rating systems. Such soil moisture data are increasingly available and are not currently being used in the context of wildfire preparedness.

- Increasing availability of soil moisture data makes its inclusion in wildfire danger assessments more feasible, and our results can guide wildfire managers on how to use this information when assessing wildfire danger. We recommend that concurrent and lagged soil moisture be included in wildfire danger assessments in Oklahoma and other regions with similar climates and vegetation types.

- Severe drought can change the spatial scale at which fuel heterogeneity occurs in landscapes that are burned and grazed. Fire managers using heterogeneity as the basis for grassland conservation should be ready to adapt in the face of more frequently occurring climatic extremes expected in future decades. Establishing ways to adapt in order to enhance landscape-level heterogeneity in the face of environmental extremes has received little research or management attention.

- Fire managers and meteorologists should consider using technologies that can provide rapid and accurate assessments of grassland fuels at an appropriate spatial resolution. Great Plains grassland managers have a long history of using grassland biomass and moisture content as the primary properties to consider in prescribed fire planning and for some wildfire danger models. Interactions among fuel components appear to be as important, or more important, as grasses cure.

- As grass curing progresses, especially in the growing season and in extreme drought conditions, managers should prepare for non-linear change in fire behavior in grassland fuels. For example, as grass curing becomes abruptly pronounced in severe drought, fire intensity and rate of spread can increase exponentially.

- Achieving natural resource management objectives with fire will often require a broader range of fuel conditions than currently outlined in fire prescriptions for rangelands. Our recently completed multiple experimental investigations show socially imposed constraints on fire behavior limit fire from causing mortality of both resprouting and non-resprouting woody plants, thereby facilitating the expansion of woody plants even in areas that are burned frequently.

Relationship to Other Recent Findings and Ongoing Work on This Topic

While our work has been favorably received among the wildfire community in general, one question left unanswered from our results was how the relationships between measured soil moisture (FAW) and wildfires compare to wildfire relationships with the more commonly used Keetch-Byram drought index (KBDI), a surrogate for soil moisture. Despite the strong link between FAW and wildfires that we found, and the intrinsic strengths of a drought index based on measured soil moisture (FAW) compared with one that is derived from weather (KBDI), wildfire managers may prefer the more familiar KBDI when assessing wildfire danger. In the absence of soil moisture data, the reliance on KBDI is understandable. However, our group is currently conducting research, with the manuscript in draft form, aimed at addressing the question whether the continued use of KBDI is justifiable when high quality soil moisture data are available (Krueger et al. draft manuscript). The work on this paper was made possible with funding from the Department of Interior South Central Climate Science Center (SCCSC)

Building on this JFSP grant, Krueger and Ochsner, along with Steven Quiring from The Ohio State University, have been awarded a grant through the SCCSC evaluate soil moisture-based drought indicators for the southern Great Plains.

We also aim to finish our evaluation of the relationship between soil moisture and live fuel moisture. Data collection is completed and the analysis is ongoing and expected to be completed within one year.

J. D. Carlson plans to author a technical note that explains in detail the constituent differential method that was used to estimate live and dead fuel loads in the project. He also will explore the relationships between the measured/calculated grassland fuelbed variables and spectral indices calculated from the patch-averaged Landsat and MODIS satellite data and how the relationships correspond with the relationships using data from the hand-held radiometer. A similar approach will be used with respect to the eastern redcedar foliage moisture data. The effect of soil moisture (concurrent and various lag times) on measured/calculated variables will be investigated for both the grassland fuelbed and the eastern redcedar moisture data.

Dirac Twidwell is conducting multiple studies that explore social-ecological responses to manipulations of fire regimes. His ongoing studies push beyond traditional fire prescriptions to quantify thresholds, resilience and the adaptive capacity of rangelands and forests. He is currently using thermal imaging technology to map fine-scale spatial variation in fire behavior across landscapes and corresponding changes in grass-tree dominance.

Future Work Needed

Based on the promising performance of FAW as an indicator of wildfire in danger in Oklahoma, and the questions raised by our findings, we have identified several key areas for future work.

- **Education.** While soil moisture may be a familiar concept to wildfire scientists, wildfire managers, and the general public, the representation of soil moisture as fraction of available water capacity (FAW) likely is not. For our work to be most useful to these stakeholders, there is a need to provide education on soil moisture in general, and specifically on concepts of plant available water (PAW) as a quantity and as a proportion of its maximum (FAW). It is also vital that those familiar with the more commonly used KBDI are aware of the strengths and weaknesses of and differences between FAW and KBDI.
- **Assessment of soil moisture-wildfire relationships in forested areas:** The wildfires in our study occurred across a suite of vegetation types, but wildfire in Oklahoma occurs primarily in herbaceous fuels. Therefore, our results apply mainly to regions of similar vegetation, such as neighboring states. There is a critical need, however, to assess soil moisture-wildfire relationships in regions dominated by shrublands and forests to make possible FAW's broader application.
- **Develop methods to incorporate soil moisture into existing wildfire models:** While it is possible to immediately deploy FAW as a standalone assessment of wildfire potential in Oklahoma, used in much the same way as KBDI in OK-FIRE, strategies to incorporate FAW into wildfire danger models are currently lacking. For example, KBDI is currently used to increase fuel loading under conditions of drought in the National Fire Danger Rating System (NFDRS). Based on the promising performance of FAW in our study, a similar application of FAW may be possible.

We aim to test our models of live herbaceous fuel moisture content on experimental fuelbeds at this same research location and at other locations. Our collaborator John Weir, research associate at Oklahoma State University, is using the constituent differential method to assess mass and water content of live herbaceous fuels in the growing season in experimental burn plots that he studies (manuscript under review in Fire Ecology). Those estimates, together with his measurements of canopy reflectance from a hand-held radiometer, will then be used to later validate models utilizing local spectral reflectance of the fuelbed.

Fundamental research is needed that explores the link between variable fuels (this project), variable fire behavior (both experimental and in modeling), and the first-order and second-order effects of fire in grasslands.

Dissemination to the public.

To disseminate the research to other scientists, team members have presented oral papers and poster papers at scientific conferences, we have published three journal articles, and we are writing more papers for submission to refereed journals.

Within Oklahoma, 40-cm FAW will become an important variable to be displayed in various venues in the next iteration of the current OK-FIRE website (http://okfire.mesonet.org), which should be publically available in early 2017 as an OK-FIRE module on the Oklahoma Mesonet website (http://mesonet.org). In particular, 40-cm % PAW (Plant Available Water) will be used, which is simply 100*(40-cm FAW). Current values at all Mesonet stations will be available, as well as past daily values which will be displayable as time series on charts and tables. In addition, a custom, color-coded map will be developed that will be updated daily and which will be capable of animation over past time periods.

After the next-generation OK-FIRE website becomes available in early 2017, a series of statewide full-day workshops will begin for wildland fire managers in use of the new OK-FIRE. Since the original OK-FIRE website became available in 2006, over 1000 fire managers have been trained on the system. The new workshops will integrate the new soil moisture products (40-cm % Plant Available Water) and feature instruction on their importance and utility, particularly as indicators of large wildfire potential during the growing season.

In addition to future training sessions for Oklahomans, we will be presenting this at conferences to inform the fire science community and users that our approach can be adapted for similar fuels and climates elsewhere in the U.S.

Our team has worked with the Great Plains Fire Science Exchange to disseminate our research. We are also engaged with state and regional landowner prescribed burning cooperatives. These groups apply more fire in the Great Plains than any other demographic group or natural resource agency.

The deliverables crosswalk table

Deliverable type	Description	Delivery status
FY 2012 annual report	Report on project progress	All reports, through 2015 were delivered
FY 2013 annual report	Report on project progress	Delivered
Meeting presentations	Three presentations at scientific conferences (one symposium on grass fuelbeds)	Delivered
FY 2014 annual report	Report on project progress	Delivered
Dissertations/theses	Dissertations/theses submitted to graduate college	M.S. thesis scheduled to be submitted in December 2016; PhD dissertation to be submitted May 2017
Dynamic models	Dynamic grassland models evaluated and finalized	In progress: (M.S. thesis, PhD dissertation, and Carlson's research).
Manuscripts	Manuscripts submitted to refereed scientific journals	In progress: M.S. thesis: field study of fuel moisture and fuel loading in response to time since fuel treatment (C. Bielski) PhD dissertation: model construction using hand-held radiometer and soil moisture Carlson: model construction using hand-held radiometer, soil moisture, and satellite data across spatial scales (S. Sharma)
Final JFSP report	Final report submitted to JFSP	Submitted Sep 2016
Additional deliverables not listed in the proposal		
Meeting presentations	14 presentations at conferences	Delivered
Manuscripts	Manuscripts submitted to refereed scientific journals	Delivered. Three submitted and published; two in draft form, one to be submitted within the next month.
Datasets	3 data sets in the proposal and two additional data sets	Five data sets have been constructed, subjected to quality control, and are being analyzed
Website	Soil moisture products for next-generation fire danger website (OK-FIRE)	Website being constructed; draft map product is constructed
Training	Soil moisture in next-generation fire danger website (OK-FIRE)	To be developed, implemented into training protocol that has been used for many years

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