

A BURNING QUESTION: HOW MUCH DROUGHT
CAUSES INCREASED FLAMMABILITY IN EASTERN
REDCEDAR?

By

JEFF DUDEK

Bachelor of Science in Marine and Environmental

Biology and Policy

Monmouth University

West Long Branch, New Jersey

2018

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December, 2020

A BURNING QUESTION: HOW MUCH DROUGHT
CAUSES INCREASED FLAMMABILITY IN EASTERN
REDCEDAR?

Thesis Approved:

Dr. Henry D. Adams

Thesis Adviser

Dr. Mark Fishbein

Dr. Bryan Murray

Dr. Sam Fuhlendorf

ACKNOWLEDGEMENTS

I thank Dr. Mark Fishbein, Dr. Bryan Murray, Dr. Sam Fuhlendorf, Dr. Rod Will, and, most especially, Dr. Henry Adams for their advice, encouragement, and guidance throughout my time at Oklahoma State University. I also thank my lab mates and friends Alex Thompson, Kaitlyn McNeil, Luke Wilson, and especially Bill Hammond for all their support in research and life. Finally, I thank my partner Jenna Corso, along with my parents Susan and Michael Dudek for their undying support throughout this research.

Name: Jeff Dudek

Date of Degree: DECEMBER, 2020

Title of Study: A BURNING QUESTION: HOW MUCH DROUGHT CAUSES
INCREASED FLAMMABILITY IN EASTERN REDCEDAR

Major Field: PLANT BIOLOGY, ECOLOGY, AND EVOLUTION

Abstract: Encroachment of eastern redcedar, *Juniperus virginiana*, due to fire suppression, is one of the greatest contributors to the degradation of North American grasslands. Mature trees are unlikely to burn during wet periods. However, during extended dry periods when live foliar moisture (LFM) approaches 80% they become more easily ignited and combustible. Currently, the amount of drought that is necessary to cause such reductions in LFM is unknown. To identify factors that contribute to wildfire risk I examined the relationship between leaf water potential and LFM in eastern redcedar. I used a dual greenhouse/field approach to link field conditions with changes in LFM and water potential. In the greenhouse, I designed a drought experiment to track LFM and leaf water potential in eastern redcedar. The field study was designed to relate greenhouse results to realistic field conditions. I chose 3 sites in Oklahoma with different levels of annual precipitation: Woodward (dry), Marena (moderate), and Cookson (wet). I measured LFM, water potential, and soil moisture in the field through a range of seasonal variation in climate. I used the Oklahoma Mesonet to identify other meteorological factors which contribute to changes in LFM. I found that leaf water potential can be used to predict LFM accurately and that relationship does not fluctuate based on site or previous drought conditions. Specifically, I observed a decline in LFM in two phases, a more rapid initial decline followed by a less rapid decline that is consistent with the onset of stomatal regulation in this species. Additionally, I identified a physiologically based model using metrics of soil water potential and vapor pressure data that I calculated from data available from the Oklahoma Mesonet to predict fire risk in eastern redcedar. Ultimately, my model can be used to predict LFM in populations of eastern redcedar across the state which can be used to improve fire risk predictions in Oklahoma.

TABLE OF CONTENTS

Chapter	Page
I. LITERATURE REVIEW	1
Literature Cited	7
II. A BURNING QUESTION: HOW MUCH DROUGHT CAUSES INCREASED FLAMMABILITY IN EASTERN REDCEDAR.....	13
Abstract	13
Introduction.....	14
Methods.....	18
Results.....	22
Discussion.....	25
Acknowledgements.....	30
Literature Cited	31
Tables	41
Figures.....	42

LIST OF TABLES

Table	Page
Table 1. AIC scores for all models considered for how eastern redcedar LFM is affected by drought.	41

LIST OF FIGURES

Figure	Page
<p>Figure 1. The relationship between live fuel moisture and leaf water potential at all 3 sites and in the greenhouse. Solid lines show the segmented regression is fit separately to each site and greenhouse data. R-squared values were 0.59, 0.49, 0.64, and 0.89 for the Cookson, Marena, Woodward, and Greenhouse data, respectively ($p < 0.01$). Dashed lines indicate 95% confidence interval for each segmented regression.....</p>	42
<p>Figure 2. The relationship between live fuel moisture and leaf water potential in eastern redcedar during the final drought of greenhouse experiment 2 for three treatments, previous exposure to moderate, severe, or no drought. Relationships for each treatment are fit with a negative exponential regression. Confidence intervals for each represent the standard error around the regression line.....</p>	43
<p>Figure 3. The relationship between live fuel moisture (LFM) and two spectral indices, the normalized difference vegetation index (NDVI) and the normalized difference water index (NDWI). Grey shading indicates the 95% confidence intervals for each regression line. The relationship between LFM and NDWI had a steeper slope than the relationship between LFM and NDVI ($p < 0.01$).....</p>	44
<p>Figure 4. A comparison of daily water potential of eastern redcedar for each site and the greenhouse data when live fuel moisture (LFM) was within $\pm 5\%$ of 80%. Boxplots show the range from 25% to 75% as solid boxes, whiskers are one standard error, and outliers beyond this are shown as points. There was no significant difference among the 3 sites and greenhouse data in Ψ_{plant} at $80 \pm 5\%$ LFM (Kruskall-Wallis, $p > 0.05$).....</p>	45
<p>Figure 5. The relationship between xylem tension and live fuel moisture (LFM) fitted with a single segmented regression for all data ($R^2 = 0.644$, $p < 0.01$; a), and the relationship between soil moisture and LFM (b) in eastern redcedar. Data in (a) are from 3 sites across Oklahoma and the greenhouse experiments; data in (b) are from the field sites only. The dashed lines around the regression line in panel a represents the 95% confidence interval.....</p>	46
<p>Figure 6. Individual linear regression analyses using Ψ_{soil} and vapor pressure deficit (VPD) to predict (LFM). Ψ_{soil} can explain 31% of variation while VPD can explain 39.5% of variation in LFM. Combined as a multiple regression model to predict LFM from Ψ_{soil} and VPD, the accuracy is improved ($R^2 = 0.613$, $p < 0.05$).....</p>	47

Figure 7. A validation of the multiple regression model used to predict live fuel moisture in eastern redcedar across three field sites. The training set consisted of 80% of all collected data at each site while the test set consisted of a randomly chosen 20% of the data at each site. Points shown are the daily mean values for all trees sampled on each day at each site. Error bars are standard in the observed mean. The 1:1 line is shown in black, and the linear regression between observed and predicted values is shown in blue, with the standard error of the regression shown in grey. Data validation for each site separately is shown in Figure 10.....48

Figure 8. A validation of the multiple regression model used to predict live fuel moisture in eastern redcedar across three field sites separately, for Cookson (a), Marena (b), and Woodward (c). The training set consisted of 80% of all collected data at each site while the test set consisted of a randomly chosen 20% of the data at each site. Points shown are the daily mean values for all trees sampled on each day at each site. Error bars are standard in the observed mean. The 1:1 line is shown in black, and the linear regression between observed and predicted values is shown in blue, with standard error of the regression shown in grey49

Figure 9. Time series of My model predictions and measured observations for live fuel moisture (LFM) in eastern redcedar at the Woodward site. Predictions were calculated on a daily basis from the Woodward, OK Mesonet station and then averaged to give a monthly LFM estimate. Observed are the Monthly LFM estimates are shown in (a) and daily LFM estimates are shown in (b). The period during which the Rhea and Complex 34 fires were burning near the Woodward site is highlighted in red.....50

Figure 10. Mean percent of stations that are below the 80% live fuel moisture threshold for increased wildfire risk shown monthly averaged over the entire history of the Oklahoma Mesonet for all 120 stations. Error bars are 95% confidence intervals51

Figure 11. A validation of the multiple regression model used to predict live fuel moisture in eastern redcedar across three field sites separately, for Cookson (a), Marena (b), and Woodward (c). The training set consisted of 80% of all collected data at each site while the test set consisted of a randomly chosen 20% of the data at each site. Points shown are the daily mean values for all trees sampled on each day at each site. Error bars are standard in the observed mean. The 1:1 line is shown in black, and the linear regression between observed and predicted values is shown in blue, with standard error of the regression shown in grey52

Figure 12. The relationship between Keetch-Byram Drought Index as calculated from the Oklahoma Mesonet and live fuel moisture in eastern redcedar. Each point represents a mean daily average from day of sampling LFM53

CHAPTER I

LITERATURE REVIEW

Woody plant encroachment into grasslands is a phenomenon that has been observed in systems across the world, including savannas in South America (Rosan et al., 2019), Africa (Stevens et al., 2017), and North America (Jackson et al. 2002). This process can have dramatic effects on regional and global biogeochemical and hydrological cycles (Archer et al., 2001; Schimel et al., 2001; Huxman et al., 2005) but has also been shown to cause more local environmental effects such as the loss of productive grassland area and increases in soil erosion (Grover and Musick, 1990). These environmental impacts are particularly important because most of the agricultural production of livestock worldwide occurs in grassland and savanna systems (Scholes and Archer 1997).

Widespread encroachment of eastern redcedar (*Juniperus virginiana*) and other juniper species into native plant communities in the Great Plains and western United States has received increased attention due to the associated economic and ecological impacts (Bidwell et al., 1996; Meneguzzo & Liknes, 2015). Among these impacts are the accelerated depletion of groundwater (Wine & Hendrickx, 2013; Zou et al., 2018), reduction in grassland biodiversity (Briggs et al., 2002), decrease in forage for livestock and wildlife (Knapp et al., 2008), and an increase in wildfire potential. Prior to European-American settlement, eastern redcedar had been excluded

from spreading throughout Oklahoma due to the prevalence of wildfire in the region (Briggs et al., 2002; Hallgren et al., 2012). However, wildfire suppression following Euro-American settlement has since allowed the expansion of eastern redcedar westward through Oklahoma (Briggs et al. 2002; DeSantis et al., 2011; Wang et al., 2017).

Historically, wildfire studies in the Great Plains have focused on using drought indices and the relationship between heat fluxes and dead fuels (Bidwell et al. 1996; Briggs et al. 2002). Generally, this method of wildfire prediction works fairly well, as it has been shown that dead fuels respond very quickly to temperature changes (Ruffault et al. 2018) and that dryness of dead fuels can often be the first indicator of the potential of widespread wildfire (Nolan et al. 2016). However, it was recently shown that the effects of life fuel moisture (LFM) on the rate of wildfire spread has most likely been underestimated in older wildfire models (Rossa & Fernandes, 2017; Pimont et al., 2019). This discovery has led to a recent push in wildfire science to embrace more complete models for prediction of wildfire occurrence (Yedinak et al., 2018). Recently, the concept of pyro-ecophysiology has emerged from this area of wildfire science (Jolly & Johnson, 2018), which posits that when modeling wildfire in complex ecosystems, physiological response to drought of living plants needs to be considered. Specifically, Jolly and Johnson (2018) outline four types of physiological processes that could potentially affect the flammability of living plants. These processes are the fine leaf/branch flammability, interior water flow, canopy structure, and chemical composition (Behm et al. 2004; Page et al. 2012). Fine leaf/branch flammability is determined by processes such as transpiration, plant water potential (Ψ_{plant}), and soil water absorption.

Ψ_{plant} is a measurement of the water tension inside the xylem of living plants which is driven by atmospheric demand for moisture. Inside a plant, water moves through a pathway from soil through the plant and into the atmosphere, along a gradient of tension, the inverse of which is quantified as water potential. The lower water potential of the atmosphere, and relatively higher

water potential inside the plant, leads to a diffusion gradient across the stomata of foliage, drawing water out of the leaves as vapor. Water lost at the stomata is replaced by water from the xylem, which due to the cohesion-tension properties of water in the xylem of plants, pulls additional water molecules through the xylem from the roots toward the leaf. (Passioura 1982). Essentially, when soil water is low or atmospheric demand is high, tension inside the plant rises. The relationship between Ψ_{plant} and plant moisture content is non-linear, such that as water content declines more rapidly below a wilting point in Ψ_{plant} , also termed the turgor loss point (Bartlett et al. 2012).

Weir and Scasta (2014) examined the relationship between four components of flammability and LFM in eastern redcedar. These were ignitability (time to flaming combustion), sustainability (duration of sustained flaming), combustibility (flame height), and consumability (percentage of leaf mass that was consumed). They measured these components at different LFM values after drying each sample in a microwave. They showed that there was little variation in flammability in wetter foliage, specifically when LFM was greater than 80%. However, when LFM dropped below 80%, there was consistent increase in flame height and quicker combustion as LFM declined.

McCaw et al. (2018) found a similar threshold of around 80% LFM beyond which moderate intensity crown fire becomes much more likely in Ashe Juniper (*Juniperus ashei*), a congener of eastern redcedar. Additionally, large stands of Ashe juniper were found to be much more easily ignited when LFM was low, and a threshold of around 80% has since been established as a benchmark for the increasing the likelihood of a large crown fire (Twidwell et al., 2009; Twidwell et al., 2013). Conversely, when LFM is high in these species, prescribed fires become less effective at causing mortality in large stands, which indicates that the foliage of these trees is less flammable when LFM is high (Ortmann et al. 1998; Twidwell et al. 2013). In fact, similar findings of dynamic flammability, where the flammability of juniper trees is dependent

upon physiological status of foliage, were demonstrated by showing that lower levels of LFM were a useful predictor of crown fire in *Juniperus pinchotii* (Bunting et al., 1983).

Demonstrations of LFM thresholds leading to larger crown fires have also been shown in shrubby species, in chaparral communities in California (Dennison et al. 2008), heathlands in the United Kingdom (Davies & Legg, 2011), and in southeastern Australia (Nolan et al. 2016).

Typically, LFM modeling studies have focused on correlating seasonal changes in LFM with meteorological drought indices, with mixed success. Pellizzaro et al. (2007) showed that Drought Code, a numeric rating of the average moisture content of deep, compact organic soil layers from the Canadian Forest Fire Weather Index System, could be used to predict LFM in several Mediterranean shrubland species. However, it only worked for species that were particularly sensitive to rapid weather changes. They also showed that a number of commonly used drought indices, including the Keetch–Byram Drought Index (KBDI), had no relationship with the LFM of any of the plant populations they studied. KBDI, an index derived to simulate the balance between evapotranspiration and precipitation, uses daily precipitation and daily temperature relative to the running average of those measurements from the previous two weeks (Keetch & Byram, 1968).

Additionally, Nolan et al. (2018) showed that predawn Ψ_{plant} was the strongest predictor of LFM in Mediterranean plants, as it outperformed all meteorological drought indices that were measured. Generally, recent research has shown that this pattern, where Ψ_{plant} predicts LFM better than any meteorological drought index, holds across many different systems globally. Research has identified very clearly defined critical LFM thresholds in California shrublands, which can be used to accurately predict the occurrence of larger wildfires (Dennison et al., 2008). Additionally, Nolan et al. (2016) showed that inclusion of LFM in wildfire models in Australia could have more accurately predicted the large Australian wildfires of 2013 and 2000 even though differences in LFM relative to typical conditions were relatively small.

When meteorological drought indices, such as the Keetch-Byram Drought Index (KBDI; (Keetch & Byram, 1968) and Drought Code perform well, they likely do so as a proxy for water status within the plant, suggesting that direct measurements of plant water status can further improve the ability to predict flammability. LFM dynamics are likely a result of both water content and changes in dry mass. So, a better approach to modeling LFM might be to evaluate the effects of these two variables independently (Jolly et al. 2018). In addition, key ecophysiological drivers of these physiological responses can be evaluated to more thoroughly understand how wildfire dynamics might change in a given system due to differences in LFM response to these variables across species (Jolly and Johnson 2018). A recent study of woody plant species in California chaparral communities found that while LFM varied greatly between species and seasons, Ψ_{plant} was always able to accurately predict the LFM of each species such that as Ψ_{plant} was more negative, water content of live foliage was always lower (Pivovarovoff et al., 2019). The same study found a distinct inflection point in the correlation between LFM and Ψ_{plant} for all 11 species (from 6 different families) that were studied, which corresponded to the turgor loss point of each species. This relationship indicates that drought adaptation strategies across different species might have an effect on the potential flammability of individuals of the species.

Specifically, the water potential at which leaves wilted (turgor loss point) was associated with a switch in rate of foliage water loss (Pivovarovoff et al., 2019). As plants began to dry, LFM declined rapidly with small changes in Ψ until reaching the turgor loss point, when changes in LFM became much less sensitive to changes in Ψ_{plant} . This finding, that plant physiological tolerances influence the rate of decline in LFM, could potentially provide a mechanistic explanation for the finding that wildfire area tends to vary nonlinearly with change in climactic variables (Schoenberg et al., 2003).

Ultimately, it has been shown that variations in LFM can lead to changes in the flammability of individual trees. These changes might impact the rate of wildfire spread in the

Great Plains where eastern redcedar has encroached rapidly in the last century. Currently, wildfire models mostly utilize metrics which account only for changes in weather over time. This method of wildfire potential prediction misses the impact that LFM dynamics can have on wildfire spread. Currently, LFM dynamics in eastern redcedar are yet to be described and it is unknown how physiological drought status in eastern redcedar can contribute to LFM dynamics. Previous research in global ecosystems have shown that Ψ_{plant} can be used to predict LFM in species with similar stomatal control mechanisms and tolerance to more negative Ψ_{plant} . Soil moisture measurements may be able to predict Ψ_{plant} in eastern redcedar, and in turn LFM, improving wildfire risk forecasting in Oklahoma.

Literature Cited

- Archer, S., Boutton, T. W., & Hibbard, K. A. (2001). Trees in grasslands: biogeochemical consequences of woody plant expansion. *Global Biogeochemical Cycles in the Climate System*, January 2001, 115–137. <https://doi.org/http://dx.doi.org/10.1016/B978-012631260-7/50011-X>
- Behm, A. L., Duryea, M. L., Long, A. J., & Zipperer, W. C. (2004). Flammability of native understory species in pine flatwood and hardwood hammock ecosystems and implications for the wildland-urban interface. *International Journal of Wildland Fire*, 13(3), 355–365. <https://doi.org/10.1071/WF03075>
- Bidwell, T. G., Engle, D. M., & Moseley, M. E. (1996). Invasion of Oklahoma rangelands and forests by eastern redcedar and ashe juniper. *Circular E*, 10.
- Briggs, J. M., Knapp, A. K., & Brock, B. L. (2002). Expansion of woody plants in tallgrass prairie: A fifteen-year study of fire and fire-grazing interactions. *American Midland Naturalist*, 147(2), 287–294. [https://doi.org/10.1674/0003-0031\(2002\)147\[0287:EOWPIT\]2.0.CO;2](https://doi.org/10.1674/0003-0031(2002)147[0287:EOWPIT]2.0.CO;2)
- Bunting, S. C., Wright, H. A., & Wallace, W. H. (1983). Seasonal Variation in the Ignition Time of Redberry Juniper in West Texas. *Journal of Range Management*, 36(2), 169. <https://doi.org/10.2307/3898155>
- Davies, G. M., & Legg, C. J. (2011). Fuel Moisture Thresholds in the Flammability of *Calluna vulgaris*. *Fire Technology*, 47(2), 421–436. <https://doi.org/10.1007/s10694-010-0162-0>

- Dennison, P. E., Moritz, M. A., & Taylor, R. (2008). Evaluating predictive models of critical live fuel moisture in the Santa Monica Mountains , California. *International Journal Of Wildland Fire*, 18–27.
- DeSantis, R. D., Hallgren, S. W., & Stahle, D. W. (2011). Drought and fire suppression lead to rapid forest composition change in a forest-prairie ecotone. *Forest Ecology and Management*, 261(11), 1833–1840. <https://doi.org/10.1016/j.foreco.2011.02.006>
- Hallgren, S. W., Desantis, R. D., & Burton, J. A. (2012). Fire and Vegetation Dynamics in the Cross Timber Forests of South-Central North America. *Proceedings of the 4th Fire in Eastern Oak Forests Conference*, Stallings, 52–66. <https://www.nrs.fs.fed.us/pubs/gtr/gtr-nrs-p-102papers/04hallgren-p-102.pdf>
- Huxman, T. E., Wilcox, B. P., Breshears, D. D., Scott, R. L., Snyder, K. A., Small, E. E., Hultine, K., Pockman, W. T., & Jackson, R. B. (2005). Ecohydrological implications of woody plant encroachment. *Ecology*, 86(2), 308–319. <https://doi.org/10.1890/03-0583>
- Jolly, W., & Johnson, D. (2018). Pyro-Ecophysiology: Shifting the Paradigm of Live Wildland Fuel Research. *Fire*, 1(1), 8. <https://doi.org/10.3390/fire1010008>
- Knapp, A. K., Briggs, J. M., Collins, S. L., Archer, S. R., Bret-Harte, M. S., Ewers, B. E., Peters, D. P., Young, D. R., Shaver, G. R., Pendall, E., & Cleary, M. B. (2008). Shrub encroachment in North American grasslands: Shifts in growth form dominance rapidly alters control of ecosystem carbon inputs. *Global Change Biology*, 14(3), 615–623. <https://doi.org/10.1111/j.1365-2486.2007.01512.x>
- Jolly, W., Hintz, J., Linn, R. L., Kropp, R. C., Conrad, E. T., Parsons, R. A., & Winterkamp, J. (2016). Seasonal variations in red pine (*Pinus resinosa*) and jack pine (*Pinus banksiana*)

foliar physio-chemistry and their potential influence on stand-scale wildland fire behavior. *Forest Ecology and Management*, 373, 167–178.
<https://doi.org/10.1016/j.foreco.2016.04.005>

McCaw, W. M., Grobert, D. M., Brown, S. B., Strickland, S., Thompson, G. A., Gillman, G., Ball, L. M., & Robinson, C. D. (2018). Seasonal Patterns and Drivers of Ashe Juniper Foliar Live Fuel Moisture and Relevance to Fire Planning. *Fire Ecology*, 14(1), 50–64.
<https://doi.org/10.4996/fireecology.140150064>

Meneguzzo, D. M., & Liknes, G. C. (2015). Status and trends of eastern redcedar (*Juniperus virginiana*) in the central united states: Analyses and observations based on forest inventory and analysis data. *Journal of Forestry*, 113(3), 325–334.
<https://doi.org/10.5849/jof.14-093>

Nolan, R. H., Boer, M. M., Resco De Dios, V., Caccamo, G., & Bradstock, R. A. (2016). Large-scale, dynamic transformations in fuel moisture drive wildfire activity across southeastern Australia. *Geophysical Research Letters*.
<https://doi.org/10.1002/2016GL068614>

Nolan, Rachael H., Sugai, T., Resco de Dios, V., Hedo, J., & Arteaga, C. (2018). Physiological drought responses improve predictions of live fuel moisture dynamics in a Mediterranean forest. *Agricultural and Forest Meteorology*.
<https://doi.org/10.1016/j.agrformet.2018.09.011>

Page, W. G., Jenkins, M. J., & Runyon, J. B. (2012). Mountain pine beetle attack alters the chemistry and flammability of lodgepole pine foliage. *Canadian Journal of Forest Research*, 42(8), 1631–1647. <https://doi.org/10.1139/X2012-094>

- Passioura J.B. (1982) Water in the Soil-Plant-Atmosphere Continuum. In: Lange O.L., Nobel P.S., Osmond C.B., Ziegler H. (eds) *Physiological Plant Ecology II. Encyclopedia of Plant Physiology (New Series)*, vol 12 / B. Springer, Berlin, Heidelberg.
https://doi.org/10.1007/978-3-642-68150-9_2
- Pellizzaro, G., Cesaraccio, C., Duce, P., Ventura, A., & Zara, P. (2007). Relationships between seasonal patterns of live fuel moisture and meteorological drought indices for Mediterranean shrubland species. *International Journal of Wildland Fire*.
<https://doi.org/10.1071/WF06081>
- Pimont, F., Ruffault, J., Martin-Stpaul, N. K., & Dupuy, J. L. (2019). A cautionary note regarding the use of cumulative burnt areas for the determination of fire danger index breakpoints. *International Journal of Wildland Fire*, 28(3), 254–258. <https://doi.org/10.1071/WF18056>
- Pivovarov, A. L., Emery, N., Sharifi, M. R., Witter, M., Keeley, J. E., & Rundel, P. W. (2019). The Effect of Ecophysiological Traits on Live Fuel Moisture Content. *Fire*, 2(2), 28.
<https://doi.org/10.3390/fire2020028>
- Rosan, T. M., Aragão, L. E. O. C., Oliveras, I., Phillips, O. L., Malhi, Y., Gloor, E., & Wagner, F. H. (2019). Extensive 21st-Century Woody Encroachment in South America's Savanna. *Geophysical Research Letters*, 46(12), 6594–6603.
<https://doi.org/10.1029/2019GL082327>
- Rossa, C. G., & Fernandes, P. M. (2017). On the effect of live fuel moisture content on fire rate of spread. *Forest Systems*, 26(3), 2013–2017. <https://doi.org/10.5424/fs/2017263-12019>
- Schimel, D. S., House, J. I., Hibbard, K. A., Bousquet, P., Ciais, P., Peylin, P., Braswell, B. H., Apps, M. J., Baker, D., Bondeau, A., Canadell, J., Churkina, G., Cramer, W., Denning, A. S., Field, C. B., Friedlingstein, P., Goodale, C., Heimann, M., Houghton, R. A., ...

- Wirth, C. (2001). Recent patterns and mechanisms of carbon exchange by terrestrial ecosystems. *Nature*, 414(6860), 169–172. <https://doi.org/10.1038/35102500>
- Schoenberg, F. P., Peng, R., Huang, Z., & Rundel, P. (2003). Detection of non-linearities in the dependence of burn area on fuel age and climatic variables. *International Journal of Wildland Fire*, 12(1), 1–6. <https://doi.org/10.1071/WF02053>
- Stevens, N., Lehmann, C. E. R., Murphy, B. P., & Durigan, G. (2017). Savanna woody encroachment is widespread across three continents. *Global Change Biology*, 23(1), 235–244. <https://doi.org/10.1111/gcb.13409>
- Twidwell, D., Fuhlendorf, S. D., Engle, D. M., & Taylor, C. A. (2009). Surface fuel sampling strategies: Linking fuel measurements and fire effects. *Rangeland Ecology and Management*, 62(3), 223–229. <https://doi.org/10.2111/08-124R2.1>
- Twidwell, D., Rogers, W. E., Fuhlendorf, S. D., Wonkka, C. L., Engle, D. M., Weir, J. R., Kreuter, U. P., & Taylor, C. A. (2013). The rising Great Plains fire campaign: Citizens' response to woody plant encroachment. *Frontiers in Ecology and the Environment*, 11(SUPPL. 1). <https://doi.org/10.1890/130015>
- Wang, J., Xiao, X., Qin, Y., Dong, J., Geissler, G., Zhang, G., Cejda, N., Alikhani, B., & Doughty, R. B. (2017). Mapping the dynamics of eastern redcedar encroachment into grasslands during 1984–2010 through PALSAR and time series Landsat images. *Remote Sensing of Environment*, 190, 233–246. <https://doi.org/10.1016/j.rse.2016.12.025>
- Wine, M. L., & Hendrickx, J. M. H. (2013). Biohydrologic effects of eastern redcedar encroachment into grassland, Oklahoma, USA. *Biologia (Poland)*, 68(6), 1132–1135. <https://doi.org/10.2478/s11756-013-0252-9>

Yedinak, K., Strand, E., Hiers, J., & Varner, J. (2018). Embracing Complexity to Advance the Science of Wildland Fire Behavior. *Fire*, 1(2), 20. <https://doi.org/10.3390/fire1020020>

Zou, C. B., Twidwell, D., Bielski, C. H., Fogarty, D. T., Mittelstet, A. R., Starks, P. J., Will, R. E., Zhong, Y., & Acharya, B. S. (2018). Impact of Eastern redcedar proliferation on water resources in the great plains USA- current state of knowledge. *Water (Switzerland)*, 10(12). <https://doi.org/10.3390/w1012176>

CHAPTER II

A BURNING QUESTION: HOW MUCH DROUGHT CAUSES INCREASED FLAMMABILITY IN EASTERN REDCEDAR?

Abstract

Encroachment of eastern redcedar, *Juniperus virginiana*, due to fire suppression, is one of the greatest contributors to the degradation of North American grasslands. Mature trees are unlikely to burn during wet periods. However, during extended dry periods when live foliar moisture (LFM) approaches 80% they become more easily ignited and combustible. Currently, the amount of drought that is necessary to cause such reductions in LFM is unknown. To identify factors that contribute to wildfire risk I examined the relationship between Ψ_{plant} and LFM in eastern redcedar. I used a dual greenhouse/field approach to link field conditions with changes in LFM and water potential.

In the greenhouse, I conducted a drought experiment to track LFM and Ψ_{plant} in eastern redcedar. The field study was designed to relate greenhouse results to realistic field conditions. I chose three sites in Oklahoma with different levels of annual precipitation: Woodward (dry), Marena (moderate), and Cookson (wet). I measured LFM, water potential, and soil moisture in the field across seasons. I used the Oklahoma Mesonet to identify other meteorological factors that contribute to changes in LFM.

I found that Ψ_{plant} can be used to predict LFM accurately and that the relationship does not vary based on site or previous drought conditions. Specifically, I observed a decline in LFM in two phases, a more rapid initial decline followed by a reduced decline that is consistent with the onset of stomatal regulation in this species. Additionally, I developed a physiologically based model using metrics of Ψ_{soil} and vapor pressure that I calculated from Mesonet data to predict fire risk in eastern redcedar. My model can be used to predict LFM in populations of eastern redcedar across the state, which can be used to improve fire risk predictions in Oklahoma.

Introduction

Woody encroachment of eastern redcedar (*Juniperus virginiana*) occurs in many North American grasslands and is of particular concern across the Midwest and Great Plains. It has been estimated that nearly 300,000 acres of grassland are invaded by eastern redcedar every year (Bidwell et al. 1996). Eastern redcedar invasion is known to be responsible for a wide range of ecological impacts including the reduction of prairie plant species diversity and productivity through the replacement of native grasses (Briggs et al. 2002), reduction in forage for wildlife and livestock (Starks et al. 2011), and altered hydrologic cycles (Wine et al., 2012; Limb et al., 2019). Notably, it has also been shown to promote wildfire through increasing the dead fuel load (Wang et al. 2017; Hoff et al., 2018).

Eastern redcedar has a dynamic relationship with fire. Before Euro-American settlement, eastern redcedar establishment in Oklahoma grasslands was limited to riparian areas and steep slopes, where it was able to avoid the characteristic fire of grasslands (Bidwell et al. 1996). Fire suppression following Euro-American settlement has allowed its encroachment into the plains (Engle et al., 2008), and mature eastern redcedar are unlikely to burn under conditions that are considered safe for prescribed fire (Ortmann et al., 2006). During wet seasons, large stands of eastern redcedar can act as a fuel break and individual trees are often able to survive prescribed fire. One study showed that a spring burn, when moisture was high, killed only 10% of trees taller than 3 meters (Ortmann et al., 2007). However, during drought, eastern redcedar has been shown to exacerbate the spread and intensity of wildfires throughout the Great Plains (Stambaugh et al., 2009, 2013) and drought intensity is expected to increase in the next century (Cook et al. 2015).

Close relatives of eastern redcedar are similarly flexible in their response to wildfire. Dynamic flammability, the property of having variability in combustability or ignitability in plant species which depends on physiological processes in the plant, is also observed in Ashe juniper (*Juniperus ashei*). This congener of eastern redcedar showed a major rise in mortality due to fire

in central Texas coinciding with a rare period of low foliar moisture (Twidwell et al. 2009). However, during wet periods, when foliar moisture in the canopy of these stands is high, Ashe juniper was resilient to controlled burns (Twidwell et al. 2009). For eastern redcedar, Weir and Scasta (2014) examined the relationship between four components of flammability and live fuel moisture (LFM), which is a measure of the proportion of a plant's water content to its dry biomass, at different fire temperatures. These were ignitability (time to flaming combustion), sustainability (duration of sustained flaming), combustibility (flame height), and consumability (percentage of leaf mass that was consumed). They measured the four variables at different LFM values after microwaving each sample for predetermined amounts of time. They showed that when live fuel moisture was above 80% there was little variation in flammability. However, after foliage, including leaves and fine branches, reached between 80% - 60% LFM, flame height gradually increased, while the time to flaming combustion gradually decreased (Weir & Scasta, 2014). Research in other regions, including the Mediterranean, Australia, and California, has shown that other species respond similarly to changes in live fuel moisture and fire danger in many mixed vegetation stands is considered high when live fuel moisture falls below 60%-80% (Pellizzarro et al. 2007; Dennison et al. 2008; Nolan et al. 2018).

Eastern redcedar is known for its very high tolerance of extreme drought because it can maintain conductivity and resist embolism in its xylem under extreme tensions that occur when soil moisture is low (Axmann & Knapp, 1993). One study showed that eastern redcedar lost 50% of its xylem conductivity at a tension of 4.5 MPa, and its resistance to embolism is much greater than the species with which it co-occurs across North America (Maherali et al. 2006, Choat et al., 2012). Sperry and Tyree (1990) showed it can maintain 10% of its xylem conductivity at a xylem tension of 9 MPa. Similarly, it can tolerate extraordinary variation across different branches simultaneously in its foliar moisture content when experiencing drought events (Bahari et al., 1985), consistent with the mechanism of stomatal control typical in Cupressaceae

species, where stomatal closure is passively driven by local tissue desiccation, rather than through active hormonal upregulation of abscisic acid (Brodribb et al. 2014). Therefore, eastern redcedar may have foliage at varying degrees of flammability while experiencing little physiological stress. Thus, a better understanding of the relationship between drought tolerance and LFM in eastern redcedar is critical for understanding the occurrence and severity of wildfire in stands of eastern redcedar. However, there is currently a surprising lack of specific knowledge on the relationship between eastern redcedar's physiological response to drought and its variation in LFM.

Current projections of drought in the central United States show that the later 21st century will be much drier than recent history, and even drier than the driest centuries of the last 1000 years (Cook et al., 2015). In fact, Cook et al. (2015) predicted that there is a greater than 80% chance of a multidecadal drought spanning 35 years under a future high emissions scenario of continued warming. Prolonged droughts are well-known to be positively associated with the occurrence of large-scale wildfires, including in the Great Plains (Westerling et al. 2006; Dimitrakopoulos et al., 2011; Williams et al. 2013; Krueger et al., 2015).

Oklahoma benefits from an advanced fire prediction model, the Oklahoma Fire Danger Model (OKFDM; Carlson et al., 2001), which was adapted from the USDA Forest Service's National Fire Danger Rating System. This model uses hourly weather data collected by the Oklahoma Mesonet, a network of over 100 meteorological stations across the state, to calculate fire risk at a 1 km resolution. Model predictions are available to the public and fire managers (<http://okfire.mesonet.org>). Inputs into the OKFDM include hourly weather measurements, dead fuel load estimates using the Keetch-Byram Drought Index (KBDI; (Keetch & Byram, 1968), and dead fuel moisture, estimated through temperature, humidity and solar radiation. Additionally, the OKFDM uses NDVI, the Normalized Difference Vegetation Index, to estimate live fuel moisture's effect on fire risk. NDVI is calculated from spectral reflectance bands in the visible

red region and in the near infrared to estimate vegetation “greenness” (Huete et al. 2002). It is calculated from the relative spectral reflectance in the red (wavelength = 0.66 μm) compared to the near infrared (NIR; wavelength = 0.86 μm). An alternative metric, the Normalized Difference Water Index (NDWI) is a remote sensing index designed for detecting water in vegetation (Gao, 1996) and has been shown to improve some wildfire prediction models (Krofcheck et al., 2016). NDWI is calculated from the relative spectral reflectance in the short-wave infrared (SWIR; wavelength = 0.86 μm) compared to the near infrared (NIR; wavelength = 1.61 μm).

The NDVI approach is effective for many plant species, including prairie grasses (Burgan & Hartford, 1993). However, due to junipers’ ability to withstand extreme variation in foliar moisture without outwardly displaying stress (Bahari et al., 1985; Willson et al. 2008; McCulloh et al., 2018), this approach may be ineffective for predicting eastern redcedar flammability risk. Stimson et al. (2005) showed that variation in NDVI could explain only 33% of variation in live juniper foliar moisture.

In Oklahoma, LFM in eastern redcedar is strongly influenced by drought. Invasion by eastern redcedar has increased the fuel loads throughout the plains (Hoff et al., 2018). However, current wildfire risk prediction models using remotely sensed vegetation greenness may be ineffective for predicting eastern redcedar’s contribution to wildfire risk. My research set out to accomplish two primary objectives:

1. Determine how eastern redcedar’s physiological response to drought affects variation in foliar moisture content.
2. Develop a model to determine the contribution of eastern redcedar to wildfire risk by relating the variation in the species’ foliar moisture content to environmental conditions (weather and soil water availability).

Determining this risk is becoming increasingly important as eastern redcedar invasion increases and future climate scenarios project higher levels of drought than Oklahoma has seen in recent history.

Methods

Study sites

Field sampling in the study occurred at three sites across Oklahoma across its gradient of mean annual precipitation. These sites were the Cookson Hills Wildlife Management Area (116 cm mean annual precipitation from 1995 - 2019), Marena (94 cm; Oklahoma State University's Cross Timbers Experimental Range), and Woodward (66 cm, Boiling Springs State Park). These sites were chosen to balance between being typical of areas encroached by eastern redcedar in the region of the state in which each site was located, and to capture a wide range of environments across the state. Cookson Hills is a naturally forested area within the Ozark highlands consisting of oak-hickory forest, my site was a narrow, wooded area on the edge between two managed grasslands. Marena is an encroached Cross Timbers woodland, dominated by oaks (*Quercus stellata* and *Q. marilandica*). Woodward is a hilly site with a stand dominated entirely by eastern redcedar. All sampling sites were located within a 1 km radius of an Oklahoma Mesonet station. Simultaneously, I ran two separate greenhouse experiments using a greenhouse in Stillwater, Oklahoma, not far from the Marena site. This allowed me to impose severe drought that was not encountered during the field study, and to control for any differences that might have occurred based on patterns in seasonal weather.

Field Experiment

At each field site I sampled LFM on 50 randomly selected adult trees as the percent of dry mass relative to water mass following complete desiccation in a drying oven for at least 72 hours at 65°C using the formula: $LFM = [(Mass_{wet} - Mass_{dry})/Mass_{dry}]$. Of the 50 sampled trees, I

used the first 10 to measure plant water potential (Ψ_{plant}) using a Scholander pressure chamber (Scholander et al., 1965). Additionally, I measured shallow soil moisture from the edge of the canopy using a Hydrosense (20 cm) soil-water sensor. I made measurements periodically over the course of 18 months (from August 2017 to December 2019), sampling opportunistically to obtain data from sites across a range of moisture conditions for each. All sites were sampled approximately monthly during the 2 growing seasons or twice a month during late summer and early fall when the sites experienced longer droughts. I also used data collected retrospectively from the Oklahoma Mesonet station located near each site to further examine relationships between eastern redcedar physiology and environmental factors.

Greenhouse experiment 1

In order to determine the relationship between live fuel moisture and Ψ_{plant} in eastern redcedar, my first drought experiment used eastern redcedar saplings in a greenhouse. I used 25 saplings from Cedar Valley Nursery in Ada, Oklahoma that had been grown in 11.4 liter pots. Saplings were 1 m tall on average and approximately 2 years old. At the start of the experiment I watered all saplings to field capacity and then ceased watering 20 of these, leaving the remaining five as a watered control. I measured all saplings twice weekly for LFM, Ψ_{plant} and soil moisture. Live fuel moisture was measured as described for the field experiment. Plant water potential was measured pre-dawn, when it relates most strongly to soil moisture, as described for the field experiment (Scholander, et al. 1965).

Greenhouse Experiment 2

The second greenhouse experiment aimed to quantify the antecedent effects of previous droughts by tracking recovery following various degrees of drought. For this experiment, I obtained 35 eastern redcedar saplings from Cedar Valley Nursery in Ada, Oklahoma. At the beginning of this experiment I watered all 35 to field capacity then ceased watering all of them

until three predetermined thresholds were reached. Drought treatments were determined through measuring each tree's Ψ_{plant} . For the most severe drought treatment plants were re-watered when Ψ_{plant} reached -8 MPa, for the moderate drought treatment plants were re-watered when Ψ_{plant} reached -4 MPa, and for the least severe treatment plants were watered when Ψ_{plant} reached -1.5 MPa.

Following the completion of the most severe drought treatment, I watered all treatments to field capacity and tracked how live fuel moisture and Ψ_{plant} recovered. Following this, I applied the severe drought treatment to all plants. Again, I measured live fuel moisture, Ψ_{plant} to track how previous treatment history affected drought response. Additionally, during the final drought I measured spectral reflectance of the control trees using a Malvern Panalytical ASD FieldSpec spectroradiometer. Using these data, I calculated two commonly used spectral indices for vegetation, the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Water Index (NDWI). NDVI is a commonly used remote sensing index for determining vegetation greenness (Huete et al. 2002). It is calculated from the relative spectral reflectance in the red (wavelength = 0.66 μm) compared to the near infrared (NIR; wavelength = 0.86 μm) using the formula:

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

NDWI is a remote sensing index designed for detecting water in vegetation (Gao, 1996) and has been shown to improve some wildfire prediction models (Krofcheck et al., 2016). NDWI is calculated from the relative spectral reflectance in the short-wave infrared (SWIR; wavelength = 0.61 μm) compared to the near infrared (NIR; wavelength = 0.86 μm) using the formula:

$$NDWI = \frac{NIR - SWIR}{NIR + SWIR}$$

Data Analysis

I considered multiple models of linear regression to best fit the relationship between Ψ_{plant} and LFM. Among these were exponential, logarithmic, and segmented regressions. Exponential and logarithmic both could've been used to fit the data, but implementation of such models for inclusion in fire danger model would require complex data transformations. Ultimately, I used segmented regression on the relationship between Ψ_{plant} (independent variable) and LFM (dependent variable) using the *r* package “segmented” which creates multiple breakpoint estimates and then decides which of these breakpoints best fits the data (Muggeo, 2003). I used segmented regression because I expected to find two distinct relationships before and after stomatal closure, where the slope of the line would be much steeper before stomatal closure (Pivovarov et al. 2019). Additionally, segmented regression shows two distinct relationships which do not require data transformation and can be easily compared using R^2 to characterize variation of the models and to assess the goodness of fit. Making the models less mathematically intense is advantageous for the purpose of implementation into wildfire models. I then used a standardized major axis regression to test for common slope (Wharton et al. 2012) to determine if there were differences in the relationship between these two variables across sites. Additionally, I used Kruskal-Wallis ANOVA on the Ψ_{plant} (dependent) that corresponds to an 80% (+/-5) LFM (independent) across all 3 sites and in the greenhouse. This method offers an alternative way to assess the point of drought stress which coincides with an increased risk of fire in eastern redcedar foliage while allowing me to test for differences in that point without relying upon a linear model.

For the second greenhouse experiment, I used linear regression on the relationship between log-transformed LFM and Ψ_{plant} to compare the effects of prior drought treatments on the relationship between LFM and Ψ_{plant} . I chose this method instead of segmented regression because the sample size was too small to confidently estimate a breakpoint. After log-

transforming the LFM data, I used standardized major axis regression to test for common slope (Wharton et al. 2012) to test for the effects of the site differences. Additionally, I used linear regression to estimate the relationships between the spectral indices NDVI and NDWI with LFM.

For model selection using Mesonet data, I built multiple regression models using factors that are commonly used in fire risk prediction models, including soil moisture, wind speed, temperature and, vapor pressure deficit to build a mechanistic model for how meteorological variables can impact LFM in eastern redcedar. I then used AIC to determine which of these models was strongest (Table 1). Ultimately, I used multiple regression to fit a model that predicts live fuel moisture using two variables (Ψ_{soil} and vapor pressure deficit) obtained from the Oklahoma Mesonet. I validated the model by leaving out a randomly selected 20% of field data from each site when fitting the model for testing the relationship between predicted and observed data. Additionally, I validated the model using a site to site comparison. For each site, I formed a training set consisting of all days sampled at the other two sites and built a model using the same two variables from those two sites to predict all the days at the third site.

Results

In the first greenhouse experiment, I found a strong, non-linear decline in eastern redcedar LFM with reduced Ψ_{plant} under increasing drought stress ($R^2 = 0.894$, $p < 0.01$, $df = 687$; Fig 1) with a break point estimated at $\Psi_{\text{plant}} = -3.197$ (± 0.124). This relationship was best described with a segmented regression with a breakpoint that occurs around the point of stomatal closure in eastern redcedar, which has been shown to be approximately -3.5 MPa (Torquato et al. 2020). The wet end of the relationship can be described as $LFM = -27.76 (\Psi_{\text{plant}}) + 146.55$. The dry end of the relationship can be described as $LFM = -8.997 (\Psi_{\text{plant}}) + 131.97$.

In the second greenhouse experiment I found no observable antecedent effects of drought on the relationship between LFM and Ψ_{plant} ($p > 0.05$, $df = 232$; Fig 2). Exposing trees to repeated

drought followed by re-watering, with different thresholds of -1.5, -4, and -8 MPa had no effect on the shape of the relationship between LFM and Ψ_{plant} in a subsequent complete dry down ($p > .05$, Fig 2). Confidence intervals for the curves fit to these treatments were overlapping, and a test for common slope using a standardized major axis regression of the log-transformed data showed no significant difference ($p > .05$). Additionally, I found that both NDVI ($R^2=.859$, $p<.05$, $df=48$) and NDWI ($R^2= .813$, $p<.05$, $df=48$) can be used to predict live fuel moisture at the individual plant level during the initial drought ($p < 0.05$, Fig 3). However, the slope of the NDWI line (127.48) is less steep than that of the NDVI line (411.51) which should make NDWI a more sensitive predictor of LFM at finer changes in water status.

Similar to the greenhouse results, I found that LFM of eastern redcedar at three field sites declined with Ψ_{plant} in negative segmented regressions (Fig 1). The amount of variance explained by the regressions at Woodward, Marena, and Cookson, were $R^2 = 0.638$, 0.489 , and 0.587 , respectively. The relationship did not differ across sites, as the test for a common slope was not rejected, and there was no significant difference in the intercepts ($p > 0.05$). In addition, analysis of Ψ_{plant} (dependent) at 80% LFM (+/-5%) among three sites was not significantly different using a Kruskal-Wallis one-way analysis of variance ($p > .05$; Fig 4). This method allowed me to show that Ψ_{plant} around the point of increased flammability was the same across all 3 sites and in the greenhouse. Given these results I calculated a combined relationship by pooling the data from the three field sites and greenhouse experiment 1 for the relationship between LFM and Ψ_{plant} . This curve is again represented by a segmented regression. The wet end can be described as: $\text{LFM} = -33.33(\Psi_{\text{plant}}) + 151.33$, while the dry end can be described as: $\text{LFM} = -2.87(\Psi_{\text{plant}}) + 70.62$ (Fig. 5a).

Using data from the Oklahoma Mesonet, I built models using metrics that are commonly associated with wildfire spread including daily vapor pressure deficit (VPD), daily high temperature, relative humidity, average daily wind speed, soil moisture (averaged over 3 soil

depths including 5 cm, 25 cm and, 50 cm to capture moisture that would be available at all layers of the rooting zone), and Ψ_{soil} . I then used stepwise regression to eliminate model factors with strong collinearity. Using AIC, I determined that the model that included Ψ_{soil} and VPD without considering their interaction had the best fit (Table 1). On their own, Ψ_{soil} and VPD can be used to weakly predict LFM with R^2 values of 0.311 and 0.395 respectively. However, when combined into a multiple regression model they show a strong negative relationship between LFM and the combination of VPD and Ψ_{soil} (Fig 6). The multiple regression is described as $\text{LFM} = 113.5667 - 1.8759(\text{VPD}) - 9.5155(\Psi_{\text{soil}})$ yielding an R^2 value of 0.613 with a standard error of 5.23 for LFM.

I performed cross validation on a subset of data that was withheld from the data set, which consisted of 20% of sampling days from each site. The relationship between observed LFM and predicted LFM had a slope of 0.9559 with an R^2 value of 0.60 (Fig 7). When broken down by site, the validation performs strongly at Cookson ($R^2 = 0.60$, slope = .985) and Woodward ($R^2=0.78$, slope = 1.12) but is less strong at Marena ($R^2 = 0.50$, slope =0.421; Fig 8). My site to site validation confirmed that the relationship between Ψ_{psoil} and VPD could be used to predict LFM (Fig 9). This method of validation again performs strongly at Cookson ($R^2 = 0.48$, slope = 0.89) and Woodward($R^2=0.45$, slope = 0.96), but is less strong at Marena ($R^2=0.39$, slope = 0.88).

Using the multiple regression model, I retroactively estimated monthly and daily LFM during past years, including for the 2018 fire season at the Woodward site during the period of the Rhea and Complex 34 fires (Fig 10.) The model estimates and observations show a drop in LFM in the weeks before and after the fire. Daily estimates show a precipitous drop in LFM in the days immediately leading up to the fire.

Using predicted LFM for each Mesonet site in the state using the multiple regression model, I estimated eastern redcedar fire risk across Oklahoma by determining when LFM at each

site was predicted to dip below 80%. The model predicts a distinct peak of eastern redcedar fire risk potential, as 40% of Mesonet sites were predicted to be below the 80% LFM threshold in the months of July and August (Fig 11). Using data from the Oklahoma Mesonet, I confirmed that KBDI is not predictive of foliar water content in Oklahoma ($p > .05$, $df=30$, Fig 12).

Discussion

Despite their importance in predicting wildfire risk, the environmental factors influencing Live Fuel Moisture (LFM) dynamics are not well studied (Jolly and Johnson 2018). Commonly used drought indices, such as Keetch-Byram Drought Index (KBDI) do a poor job of predicting variation in LFM in many plant populations (Dimitrakopoulos and Bemmerzouk 2003), even though these indices are often useful for predicting other components of wildfire risk (Carlson et al. 2007). While these types of indices have been shown to successfully predict mean spread rate, they have also been shown to miss the variability around fire intensity and ignition, which limits the ability of wildfire models to predict variability in systems with complex wildfire dynamics (Taylor et al. 2004; Cruz et al. 2013; Yedinak et al 2018). Overall, my research was not designed to rewrite wildfire models, but to help strengthen the ability of wildfire models to capture some of this variation. My results for LFM point to a need to better understand how drought affects physiological function related to vegetation water content which is consistent with previous findings (Soler Martin et al., 2017; Ruffault et al., 2018). Physiological response to drought has been shown to be tightly correlated to LFM dynamics (Easterday et al., 2019; Nolan et al., 2018; Nolan et al., 2020). My results show that Ψ_{plant} , a measure of xylem tension, is a strong predictor of LFM dynamics in Oklahoma populations of eastern redcedar (Fig. 1). This study adds to the growing body of literature that shows that an eco-physiological approach to understanding tree responses to drought can help to improve forest flammability predictions (Jolly et al. 2016; Nolan et al. 2020; Martin-StPaul et al. 2020), while also providing a convenient method for estimating wildfire risk assessment through a simple empirical model. Plant water potential is strongly influenced by soil moisture availability and atmospheric demand for

moisture, which are represented in the model with Ψ_{soil} and VPD, and predicts ~60% of the variability in redcedar LFM. Additionally, I found the superiority of considering LFM over drought indices in greenhouse studies, which indicate that there is no antecedent effect of drought on the water potential-LFM relationship, suggesting that LFM can be predicted across a broad range of climates in Oklahoma.

Plant Physiology

My results indicate that eastern redcedar LFM is strongly correlated with physiological response. Ψ_{plant} predicts LFM as expected, since there is a well-established relationship between Ψ_{plant} and plant water content (Tyree & Hammel, 1972; Martinez-Vilalta et al. 2019). Ψ_{plant} is a function of the combined effects of Ψ_{soil} and atmospheric demand for water, as mediated by stomatal control (Hinckley et al. 1978). This is a mechanistic basis for why LFM can be predicted by Ψ_{plant} and for why this might be more useful than drought indices, which do not account for plant physiological function.

Usage of VPD to predict large-scale wildfires has increased in recent years because of the drying effect that elevated VPD has on dead fuels in fire-prone regions (Williams et al., 2019; Mueller et al., 2020). However, there has been some debate over the efficacy of using physical drivers, such as VPD, alone for predicting wildfire spread (Martin St. Paul et al. 2020), because doing so ignores the physiological response of individual plants and fails to capture variation in LFM within those plants (Soler Martin et al., 2017; Ruffault et al., 2018). I found that VPD explains 39.5% of the variability in LFM in eastern redcedar (Fig 6). However, when the effects of VPD are combined with the effects of Ψ_{soil} , a metric of soil water availability which should closely reflect Ψ_{leaf} , in a multiple regression model, together they can explain 61.3% of variation in LFM. This increase we saw is consistent with observations that drought stress in forest systems depends on both soil moisture supply and atmospheric moisture demand (Breshears et al., 2013,

Novick et al., 2016, Williams et al., 2013). My model demonstrates a method for utilizing the predicted response of individual trees to changes in VPD to improve species-specific wildfire models.

Antecedent Effects

I found no antecedent effect of prior drought on the relationship between LFM and Ψ_{plant} in greenhouse-grown eastern redcedar. This is reflected in the field experiment, which showed that there were not significant differences in this relationship across sites, even though the sites often varied in the timing and sequence of dry conditions. Previous research on the antecedent effects of drought on eastern redcedar is relatively sparse. However, antecedent rainfall events in Ashe juniper did not affect plant water status (Heilman et al., 2009). Additionally, Dennison and Moritz (2009) found that LFM in the current fire season in California chaparral plants did not change based on precipitation in prior fire seasons. While the time scale of that study is larger than mine, the key message, that LFM is unaffected by previous drought, was consistent with my results.

Spectral Reflectance

Many studies have confirmed the efficacy of predicting moisture status in plants using NDVI (Gu et al., 2008; Whitney et al., 2018; Easterday et al., 2019); however, to my knowledge none directly test the relationship in eastern redcedar, although other juniper species have been studied. Eitel et al. (2011) showed that NDVI was ineffective for predicting change in water stress in pinyon-juniper woodlands where the junipers are predominantly *Juniperus monosperma*. Stimson et al. (2005) showed that NDVI was very weakly related to water content in *J. monosperma*. Krofcheck et al. (2015) showed that models of productivity in pinyon-juniper woodlands could be improved by using NDWI, which quantifies reflectance in bands that directly respond to changes in the presence of water, instead of NDVI.

I found that both NDVI and NDWI were strong predictors of LFM in greenhouse experiment 2 (Fig 3). Although the R^2 for these relationships were similar (0.859 for NDVI, 0.813 for NDWI), the relationships differed in their slope. From 45% to 120% LFM, NDVI only varied by 0.06, while NDWI varied by 0.49 across the same range (Fig 3). This difference in slope should allow for more fine scale predictability of LFM during progressing droughts using NDWI. My assessment was based on a greenhouse experiment that minimized confounding factors, but further studies should aim to validate this result in the field. I acknowledge that fine-scale, remotely sensed NDVI data are much more readily available to fire managers than NDWI.

Frequency of Occurrence

The multiple regression model developed here provides a quantitative basis for predicting how drought conditions promote flammability in eastern redcedar. The model predicted a very steep drop in LFM in the early days of the Rhea fire, which was one of the largest wildfires in recent years in Oklahoma. Additionally, when validated with my sampled data my models performed very well, getting very close to matching the observed data especially during dry periods at the Woodward site which coincided with the Rhea wildfire (Fig. 8).

Using the mean LFM estimated for all Mesonet stations from 1994 to 2020, I predicted seasonal changes in fire risk due to eastern redcedar across Oklahoma (Fig 9). In early summer, the proportion of sites with high fire risk due to predicted LFM below the 80% threshold increases and peaks in the middle of summer, before declining through the fall. Based on these predictions, 45% of Mesonet sites across the state would be below the 80% LFM threshold throughout the entire summer (Fig 9).

Improving Wildfire Models

Pyro-ecophysiological models should aim to predict drought responses tailored to specific areas and specific vegetation types. Yedinak et al. (2018) showed that removing broad

assumptions that do not hold true across vastly different ecological systems can vastly improve wildfire models. At the least, empirical wildfire models created for one vegetation type should be validated when used to predict wildfire risk in different vegetation. For example, my approach, which utilizes Ψ_{soil} , will likely work well in other juniper populations because Ψ_{plant} frequently closely follows Ψ_{soil} in other juniper species, even under intense drought (Linton et al. 1998; West et al., 2007; Breshears et al., 2009). A similar approach might be useful in predicting LFM in trees that exhibit similar behavior in other fire-prone regions, such as other species of Cupressaceae, including western redcedar (McCulloh et al., 2014), Mediterranean cypress (Klein, 2020), as well as sclerophyllous shrubs of southern California (Pivovarov et al., 2019). However, in fire-prone regions that are dominated by pines, in which Ψ_{soil} and Ψ_{plant} may vary independently under drought (McDowell et al. 2008), a different approach might be more useful.

My results provide one example of how physiological response to drought can be used to improve wildfire models with inputs that can be tailored to specific areas. A model based on physiological processes accounts for one aspect of flammability, but other aspects could be important as well. For example, foliar chemistry has been shown to change as a response to drought (Orians et al., 2019; Trowbridge et al., 2019) and can greatly impact the flammability of certain tree species (Jolly et al. 2016). However, there are aspects of flammability that might change based on environmental factors as well. For example, elevated VPD has been shown to increase the size of burned areas due to its impact on the moisture of dead fuels (Williams et al. 2013). Additionally, it is well known that strong winds can exacerbate the spread of crown fires, though there is debate over whether wind or fuel loads are more important for spreading large wildfires in certain systems (Keeley & Syphard, 2019). Of course, direct anthropogenic influence cannot be ignored either, as Nagy et al. (2018) showed that large wildfires were much more likely to be started by accidental human ignition than the naturally occurring lightning strikes.

Acknowledgements

This research was funded by the Oklahoma Center for the Advancement of Science and Technology Plant Basic Research Program (PS17-006). J.D. was also supported by the Oklahoma State University Department of Plant Biology, Ecology, and Evolution's McPherson fund. W.M.H. was supported by the NSF Graduate Research Fellowship program (#1-653428). H.D.A. was supported by the NSF Division of Integrative Organismal Systems, Integrative Ecological Physiology Program (IOS-1755345). I thank Kaitlyn McNeil and DeAndre Garrett for field assistance, and Mark Fishbein, Sam Fuhlendorf, Rod Will, and Chris Zou for advice and feedback on the direction of research.

Literature Cited

- Adams, H. D., Guardiola-Claramonte, M., Barron-Gafford, G. A., Villegas, J. C., Breshears, D. D., Zou, C. B., Troch, P. A., & Huxman, T. E. (2009). Temperature sensitivity of drought-induced tree mortality portends increased regional die-off under global-change-type drought. *Proceedings of the National Academy of Sciences of the United States of America*, 106(17), 7063–7066.
<https://doi.org/10.1073/pnas.0901438106>
- Bahari, Z. A., Pallardy, S. G., & Parker, W. C. (1985). Photosynthesis, water relations, and drought adaptation in six woody species of oak- hickory forests in central Missouri. *Forest Science*, 31(3), 557–569.
- Breshears, D. D., Adams, H. D., Eamus, D., McDowell, N. G., Law, D. J., Will, R. E., Williams, A. P., & Zou, C. B. (2013). The critical amplifying role of increasing atmospheric moisture demand on tree mortality and associated regional die-off. *Frontiers in Plant Science*, 4(AUG), 2–5.
<https://doi.org/10.3389/fpls.2013.00266>
- Breshears, D. D., Myers, O. B., Meyer, C. W., Barnes, F. J., Zou, C. B., Allen, C. D., McDowell, N. G., & Pockman, W. T. (2009). Tree die-off in response to global change-type drought: Mortality insights from a decade of plant water potential measurements. *Frontiers in Ecology and the Environment*, 7(4), 185–189. <https://doi.org/10.1890/080016>
- Brodribb, T.J., McAdam, S. A. M., Jordan, G. J., & Martins, S. C. V. (2014). Conifer species adapt to low-rainfall climates by following one of two divergent pathways. *Proceedings of the National Academy of Sciences of the United States* 111(40), 14489-14493.

- Burgan, R. E., & Hartford, R. a. (1993). Monitoring vegetation greenness with satellite data. *Forest Service*, May, 13.
- Carlson, J. d., Burgan, R., Engle, D., & Greenfield, J. (2001). of Wildland Fire. *International Journal Of Wildland Fire*, 10(4), 405–413. <https://doi.org/10.1071/WF01038>
- Carlson, J.D., L.S. Bradshaw, R.M. Nelson, Jr., R.R. Bensch, and R. Jabrzemski, 2007. Application of the Nelson model to four timelag fuel classes using Oklahoma field observations: Model evaluation and comparison with National Fire Danger Rating System algorithms. *International Journal of Wildland Fire*, 16:204-216.
- Chelsea Nagy, R., Fusco, E., Bradley, B., Abatzoglou, J. T., & Balch, J. (2018). Human-related ignitions increase the number of large wildfires across U.S. Ecoregions. *Fire*, 1(1), 1–14. <https://doi.org/10.3390/fire1010004>
- Choat, B., Jansen, S., Brodribb, T. J., Cochard, H., Delzon, S., Bhaskar, R., Bucci, S. J., Feild, T. S., Gleason, S. M., Hacke, U. G., Jacobsen, A. L., Lens, F., Maherali, H., Martínez-Vilalta, J., Mayr, S., Mencuccini, M., Mitchell, P. J., Nardini, A., Pittermann, J., ... Zanne, A. E. (2012). Global convergence in the vulnerability of forests to drought. *Nature*, 491(7426), 752–755. <https://doi.org/10.1038/nature11688>
- Cook, B. I., Ault, T. R., & Smerdon, J. E. (2015). Unprecedented 21st century drought risk in the American Southwest and Central Plains. *Science Advances*, 1(1), e1400082. <https://doi.org/10.1126/sciadv.1400082>
- Cruz, M.G.; Alexander, M.E. Uncertainty associated with model predictions of surface and crown fire rates of spread. *Environ. Model. Softw.* 2013, 47, 16–28.

- Dennison, P. E., & Moritz, M. A. (2009). Critical live fuel moisture in chaparral ecosystems: A threshold for fire activity and its relationship to antecedent precipitation. *International Journal of Wildland Fire*, 18(8), 1021–1027. <https://doi.org/10.1071/WF08055>
- Dimitrakopoulos, A. P., Vlahou, M., Anagnostopoulou, C. G., & Mitsopoulos, I. D. (2011). Impact of drought on wildland fires in Greece: Implications of climatic change? *Climatic Change*, 109(3–4), 331–347. <https://doi.org/10.1007/s10584-011-0026-8>
- Easterday, K., Kislik, C., Dawson, T. E., Hogan, S., & Kelly, M. (2019). Remotely sensed water limitation in vegetation: Insights from an experiment with unmanned aerial vehicles (UAVs). *Remote Sensing*, 11(16), 1–18. <https://doi.org/10.3390/rs11161853>
- Engle, D. M., Coppedge, B. R., & Fuhlendorf, S. D. (2008). From the Dust Bowl to the Green Glacier: Human Activity and Environmental Change in Great Plains Grasslands. 253–271. https://doi.org/10.1007/978-0-387-34003-6_14
- Gao, B. (1996). <NDWI—A normalized difference water index for r.pdf>. 266(April), 257–266. [https://doi.org/10.1016/S0034-4257\(96\)00067-3](https://doi.org/10.1016/S0034-4257(96)00067-3)
- Gu, Y., Hunt, E., Wardlow, B., Basara, J. B., Brown, J. F., & Verdin, J. P. (2008). Evaluation of MODIS NDVI and NDWI for vegetation drought monitoring using Oklahoma Mesonet soil moisture data. *Geophysical Research Letters*, 35(22), 1–5. <https://doi.org/10.1029/2008GL035772>
- Heilman, J. L., McInnes, K. J., Kjelgaard, J. F., Keith Owens, M., & Schwinning, S. (2009). Energy balance and water use in a subtropical karst woodland on the Edwards Plateau, Texas. *Journal of Hydrology*, 373(3–4), 426–435. <https://doi.org/10.1016/j.jhydrol.2009.05.007>
- Hoff, D. L., Will, R. E., Zou, C. B., & Lillie, N. D. (2018). Encroachment dynamics of *Juniperus virginiana* L. and mesic hardwood species into cross timbers forests of north-central Oklahoma, USA. *Forests*, 9(2). <https://doi.org/10.3390/f9020075>

- Kaur, R., Joshi, O., & Will, R. E. (2020). The ecological and economic determinants of eastern redcedar (*Juniperus virginiana*) encroachment in grassland and forested ecosystems: A case study from Oklahoma. *Journal of Environmental Management*, 254(July 2019), 109815.
<https://doi.org/10.1016/j.jenvman.2019.109815>
- Keeley, J. E., & Syphard, A. D. (2019). Twenty-first century California , USA , wildfires : fuel-dominated vs. wind-dominated fires.
- Keetch, J. J. J. J., & Byram, G. M. G. M. (1968). A drought index for forest fire control. *Notes*, E-38. Ashe, 35. <https://doi.org/10.1016/j.accpm.2015.04.007>
- Klein, T. (2020). A race to the unknown: Contemporary research on tree and forest drought resistance, an Israeli perspective. *Journal of Arid Environments*, 172(March 2019), 104045.
<https://doi.org/10.1016/j.jaridenv.2019.104045>
- Krofcheck, D. J., Eitel, J. U. H., Lippitt, C. D., Vierling, L. A., Schulthess, U., & Litvak, M. E. (2016). Remote sensing based simple models of GPP in both disturbed and undisturbed piñon-juniper woodlands in the southwestern U.S. *Remote Sensing*, 8(1). <https://doi.org/10.3390/rs8010020>
- Krueger, E. S., Ochsner, T. E., Engle, D. M., Carlson, J. D., Twidwell, D., & Fuhlendorf, S. D. (2015). Soil Moisture Affects Growing-Season Wildfire Size in the Southern Great Plains. *Soil Science Society of America Journal*, 79(6), 1567. <https://doi.org/10.2136/sssaj2015.01.0041>
- Limb, R. F., Engle, D. M., Alford, A. L., & Hellgren, E. C. (2019). Society for Range Management Tallgrass Prairie Plant Community Dynamics Along a Canopy Cover Gradient of Eastern Redcedar (*Juniperus virginiana* L.) Author (s): Ryan F . Limb , David M . Engle , Aaron L . Alford and Eric C . Hellgren Published by : Soc. 63(6), 638–644.

- Linton, M. J., Sperry, J. S., & Williams, D. G. (1998). Limits to water transport in *Juniperus osteosperma* and *Pinus edulis*: Implications for drought tolerance and regulation of transpiration. *Functional Ecology*, 12(6), 906–911. <https://doi.org/10.1046/j.1365-2435.1998.00275.x>
- Maherali H., Moura C.F., Caldeira M.C., Willson C.J., Jackson R.B. (2006) Functional coordination between leaf gas exchange and vulnerability to xylem cavitation in temperate forest trees. *Plant, Cell, and Environment* 29, 571-583.
- Martin-StPaul N , Ruffault J , Blackmann C , Cochard H , De Cáceres M , Delzon S , Dupuy JL , Fargeon H , Lamarque L , Moreno M, Parsell R, Pimont F, Ourcival JM, Torres-Ruiz J, L. J. (2020). Modelling live fuel moisture content at leaf and canopy scale under extreme drought using a lumped plant hydraulic model. *BioArxiv*. <https://doi.org/10.1101/2020.06.03.127167>
- Matt Jolly, W., Hintz, J., Linn, R. L., Kropp, R. C., Conrad, E. T., Parsons, R. A., & Winterkamp, J. (2016). Seasonal variations in red pine (*Pinus resinosa*) and jack pine (*Pinus banksiana*) foliar physio-chemistry and their potential influence on stand-scale wildland fire behavior. *Forest Ecology and Management*, 373, 167–178. <https://doi.org/10.1016/j.foreco.2016.04.005>
- McCulloh, K. A., Domec, J.-C., Smith, D. D., Johnson, D. M., Baker, K. v., & Berry, Z. C. (2018). Leaf hydraulic parameters are more plastic in species that experience a wider range of leaf water potentials. *Functional Ecology*, 32(4), 894–903. <https://doi.org/10.1111/1365-2435.13049>
- McCulloh, K. A., Johnson, D. M., Meinzer, F. C., & Woodruff, D. R. (2014). The dynamic pipeline: Hydraulic capacitance and xylem hydraulic safety in four tall conifer species. *Plant, Cell and Environment*, 37(5), 1171–1183. <https://doi.org/10.1111/pce.12225>
- McDowell, N., Pockman, W. T., Allen, C. D., Breshears, D. D., Cobb, N., Kolb, T., Plaut, J., Sperry, J., West, A., Williams, D. G., & Yezzer, E. A. (2008). Mechanisms of plant survival and mortality

- during drought: Why do some plants survive while others succumb to drought? *New Phytologist*, 178(4), 719–739. <https://doi.org/10.1111/j.1469-8137.2008.02436.x>
- Mueller, S. E., Thode, A. E., Margolis, E. Q., Yocom, L. L., Young, J. D., & Iniguez, J. M. (2020). Climate relationships with increasing wildfire in the southwestern US from 1984 to 2015. *Forest Ecology and Management*, 460(July 2019), 117861. <https://doi.org/10.1016/j.foreco.2019.117861>
- Muggeo, V. M. R. (2003). Estimating regression models with unknown break-points. *Statistics in Medicine*, 22(19), 3055–3071. <https://doi.org/10.1002/sim.1545>
- Nolan, R. H., Blackman, C. J., de Dios, V. R., Choat, B., Medlyn, B. E., Li, X., Bradstock, R. A., & Boer, M. M. (2020). Linking forest flammability and plant vulnerability to drought. *Forests*, 11(7), 1–16. <https://doi.org/10.3390/F11070779>
- Novick, K. A., Ficklin, D. L., Stoy, P. C., Williams, C. A., Bohrer, G., Oishi, A. C., Papuga, S. A., Blanken, P. D., Noormets, A., Sulman, B. N., Scott, R. L., Wang, L., & Phillips, R. P. (2016). The increasing importance of atmospheric demand for ecosystem water and carbon fluxes. *Nature Climate Change*, 6(11), 1023–1027. <https://doi.org/10.1038/nclimate3114>
- Orians, C. M., Schweiger, R., Dukes, J. S., Scott, E. R., & Müller, C. (2019). Combined impacts of prolonged drought and warming on plant size and foliar chemistry. *Annals of Botany*, 124(1), 41–52. <https://doi.org/10.1093/aob/mcz004>
- Ortmann, J., Stubbendieck, J., Masters, R. A., Pfeiffer, G. H., & Bragg, T. B. (2007). Efficacy and Costs of Controlling Eastern Redcedar. *Journal of Range Management*, 51(2), 158. <https://doi.org/10.2307/4003201>
- Ortmann, J., Stubbendieck, J., Masters, R. A., Pfeiffer, G. H., Bragg, T. B., Journal, S., Mar, N., Management, R., & Manage, J. R. (2006). Society for Range Management Efficacy and Costs of Controlling Eastern Redcedar Published by : Society for Range Management Stable URL :

<http://www.jstor.org/stable/4003201> Linked references are available on JSTOR for this article :

You may need to log in. *Rangeland Ecol Manage*, 51(2), 158–163.

Pivovarovff, A. L., Emery, N., Sharifi, M. R., Witter, M., Keeley, J. E., & Rundel, P. W. (2019). The Effect of Ecophysiological Traits on Live Fuel Moisture Content. *Fire*, 2(2), 28.

<https://doi.org/10.3390/fire2020028>

Ruffault, J., Curt, T., Martin-Stpaul, N. K., Moron, V., & Trigo, R. M. (2018). Extreme wildfire events are linked to global-change-type droughts in the northern Mediterranean. *Natural Hazards and Earth System Sciences*, 18(3), 847–856. <https://doi.org/10.5194/nhess-18-847-2018>

Schoenberg, F. P., Peng, R., Huang, Z., & Rundel, P. (2003). Detection of non-linearities in the dependence of burn area on fuel age and climatic variables. *International Journal of Wildland Fire*, 12(1), 1–6. <https://doi.org/10.1071/WF02053>

Scholander, P. F., Hammel, H. T., Bradstreet, E. D., & Hemmingen, E. A. (1965). Sap Pressure in Vascular Plants Published by : American Association for the Advancement of Science Linked references are available on JSTOR for this article : Sap Pressure in Vascular Plants Negative hydrostatic pressure can be measured in plants . *Science*, 148(3668), 339–346.

Soler Martin, M., Bonet, J. A., Martínez De Aragón, J., Voltas, J., Coll, L., & Resco De Dios, V. (2017). Crown bulk density and fuel moisture dynamics in *Pinus pinaster* stands are neither modified by thinning nor captured by the Forest Fire Weather Index. *Annals of Forest Science*.

<https://doi.org/10.1007/s13595-017-0650-1>

SPERRY, J., & TYREE, M. (1990). Water-stress-induced xylem embolism in three species of conifers. *Plant, Cell & Environment*, 13, 427–436.

Stambaugh, M. C., Guyette, R. P., Godfrey, R., McMurry, E. R., & Marschall, J. M. (2009). Stambaugh et al.: Fire, drought, and human history of the Wichita Mountains. In *Fire Ecology* (Vol. 5, Issue 2).

- Stambaugh, M. C., Guyette, R. P., & Marschall, J. (2013). Fire History in the Cherokee Nation of Oklahoma. *Human Ecology*. <https://doi.org/10.1007/s10745-013-9571-2>
- Stimson, H. C., Breshears, D. D., Ustin, S. L., & Kefauver, S. C. (2005). Spectral sensing of foliar water conditions in two co-occurring conifer species: *Pinus edulis* and *Juniperus monosperma*. *Remote Sensing of Environment*, 96(1), 108–118. <https://doi.org/10.1016/j.rse.2004.12.007>
- Taylor, S.W.; Wotton, B.M.; Alexander, M.E.; Dalrymple, G.N. Variation in wind and crown fire behaviour in a northern jack pine-black spruce forest. *Can. J. For. Res.* 2004, 34, 1561–1576
- Torquato PR, Zou CB, Adhikari A, Adams HD and Will RE (2020) Drought Tolerance and Competition in Eastern Redcedar (*Juniperus virginiana*) Encroachment of the Oak-Dominated Cross Timbers. *Front. Plant Sci.* 11:59. doi: 10.3389/fpls.2020.00059
- Trowbridge, A. M., Stoy, P. C., Adams, H. D., Law, D. J., Breshears, D. D., Helmig, D., & Monson, R. K. (2019). Drought supersedes warming in determining volatile and tissue defenses of piñon pine (*Pinus edulis*). *Environmental Research Letters*, 14(6). <https://doi.org/10.1088/1748-9326/ab1493>
- Twidwell, D., Fuhlendorf, S. D., Engle, D. M., & Taylor, C. A. (2009). Surface fuel sampling strategies: Linking fuel measurements and fire effects. *Rangeland Ecology and Management*, 62(3), 223–229. <https://doi.org/10.2111/08-124R2.1>
- Tyree, M. T., & Hammel, H. T. (1972). The measurement of the turgor pressure and the water relations of plants by the pressure-bomb technique. *Journal of Experimental Botany*, 23(1), 267–282. <https://doi.org/10.1093/jxb/23.1.267>
- Wang, J., Xiao, X., Qin, Y., Dong, J., Geissler, G., Zhang, G., Cejda, N., Alikhani, B., & Doughty, R. B. (2017). Mapping the dynamics of eastern redcedar encroachment into grasslands during 1984–2010 through PALSAR and time series Landsat images. *Remote Sensing of Environment*, 190, 233–246. <https://doi.org/10.1016/j.rse.2016.12.025>

- West, A. G., Hultine, K. R., Jackson, T. L., & Ehleringer, J. R. (2007). Differential summer water use by *Pinus edulis* and *Juniperus osteosperma* reflects contrasting hydraulic characteristics. *Tree Physiology*, 27(12), 1711–1720. <https://doi.org/10.1093/treephys/27.12.1711>
- Westerling, A. L., Hidalgo, H. G., Cayan, D. R., & Swetnam, T. W. (2006). Warming and earlier spring increase Western U.S. forest wildfire activity. *Science*, 313(5789), 940–943. <https://doi.org/10.1126/science.1128834>
- Whitney, K., Kim, S. H., Jia, S., & Kafatos, M. (2018). Estimation of the relationship between satellite-derived vegetation indices and live fuel moisture towards wildfire risk in Southern California. 2018 7th International Conference on Agro-Geoinformatics, *Agro-Geoinformatics 2018*, 1–6. <https://doi.org/10.1109/Agro-Geoinformatics.2018.8476038>
- Williams, A. P., Abatzoglou, J. T., Gershunov, A., Guzman - Morales, J., Bishop, D. A., Balch, J. K., & Lettenmaier, D. P. (2019). Observed Impacts of Anthropogenic Climate Change on Wildfire in California. *Earth's Future*. <https://doi.org/10.1029/2019ef001210>
- Williams, A. P., Allen, C. D., Macalady, A. K., Griffin, D., Woodhouse, C. A., Meko, D. M., Swetnam, T. W., Rauscher, S. A., Seager, R., Grissino-Mayer, H. D., Dean, J. S., Cook, E. R., Gangodagamage, C., Cai, M., & Mcdowell, N. G. (2013). Temperature as a potent driver of regional forest drought stress and tree mortality. *Nature Climate Change*, 3(3), 292–297. <https://doi.org/10.1038/nclimate1693>
- Willson, C. J., Manos, P. S., & Jackson, R. B. (2008). Hydraulic traits are influenced by phylogenetic history in the drought-resistant, invasive genus *Juniperus* (Cupressaceae). *American Journal of Botany*, 95(3), 299–314. <https://doi.org/10.3732/ajb.95.3.299>

Wine, M. L., Ochsner, T. E., Sutradhar, A., & Pepin, R. (2012). Effects of eastern redcedar encroachment on soil hydraulic properties along Oklahoma's grassland-forest ecotone. *Hydrological Processes*, 26(11), 1720–1728. <https://doi.org/10.1002/hyp.8306>

Tables

Table 1. AIC scores for all models considered for how eastern redcedar LFM is affected by drought factors.

MODELS	AIC	DELTA AIC	D.F.	WEIGHT
LFM ~ VPD + Soil Y	208.4	0.0	3	.55592
LFM ~ Avg Temp + VPD + Soil Y	209.7	1.3	5	.2964
LFM ~ Avg Temp * VPD + Soil Y	211.2	2.8	6	.1399
LFM ~ VPD	218.7	10.3	3	.0032
LFM ~ Avg Temp + Soil Y	219.6	11.2	4	.0021
LFM ~ Avg Temp + VPD + Avg Hum	355.4	147	5	<.001
LFM ~ Avg Temp * VPD + Soil Moisture	358.5	150.1	4	<.001
LFM ~ Soil Y	360.6	152.2	3	<.001
LFM = null	368.5	160.1	3	<.001
LFM ~ Avg Temp	368.9	160.5	3	<.001

Figures

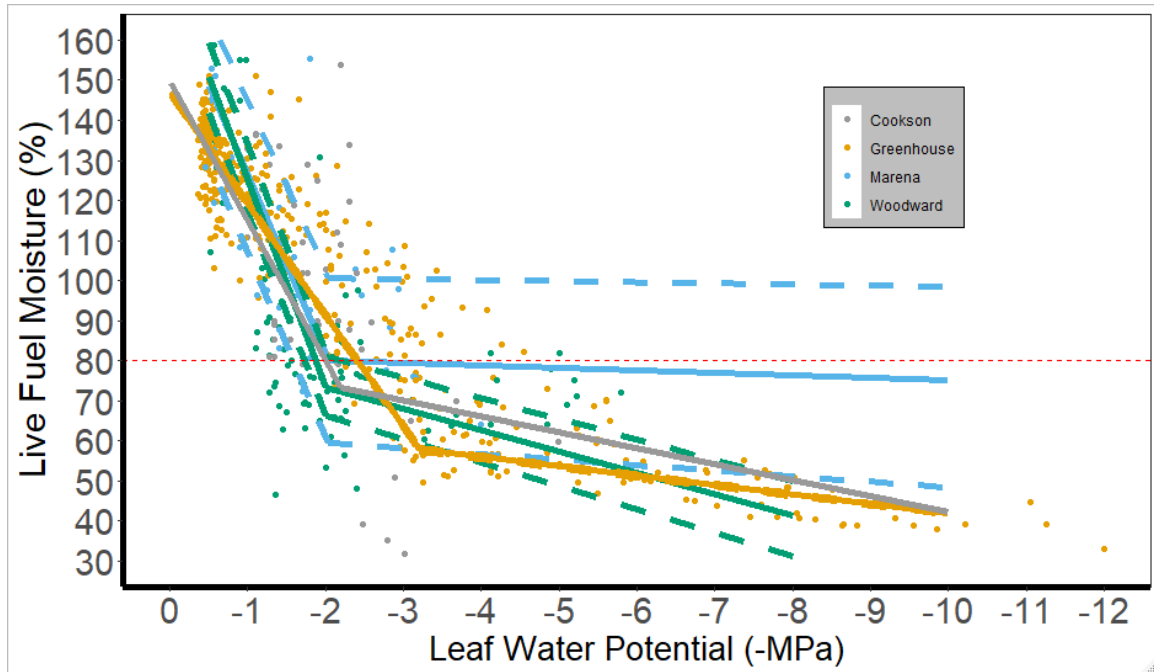


Figure 1. The relationship between live fuel moisture and leaf water potential at all 3 sites and in the greenhouse. Solid lines show the segmented regression is fit separately to each site and greenhouse data. R-squared values were .59, .49, .64, and .89 for the Cookson, Marena, Woodward, and Greenhouse data, respectively ($p < 0.01$). Dashed lines indicate 95% confidence interval for each segmented regression.

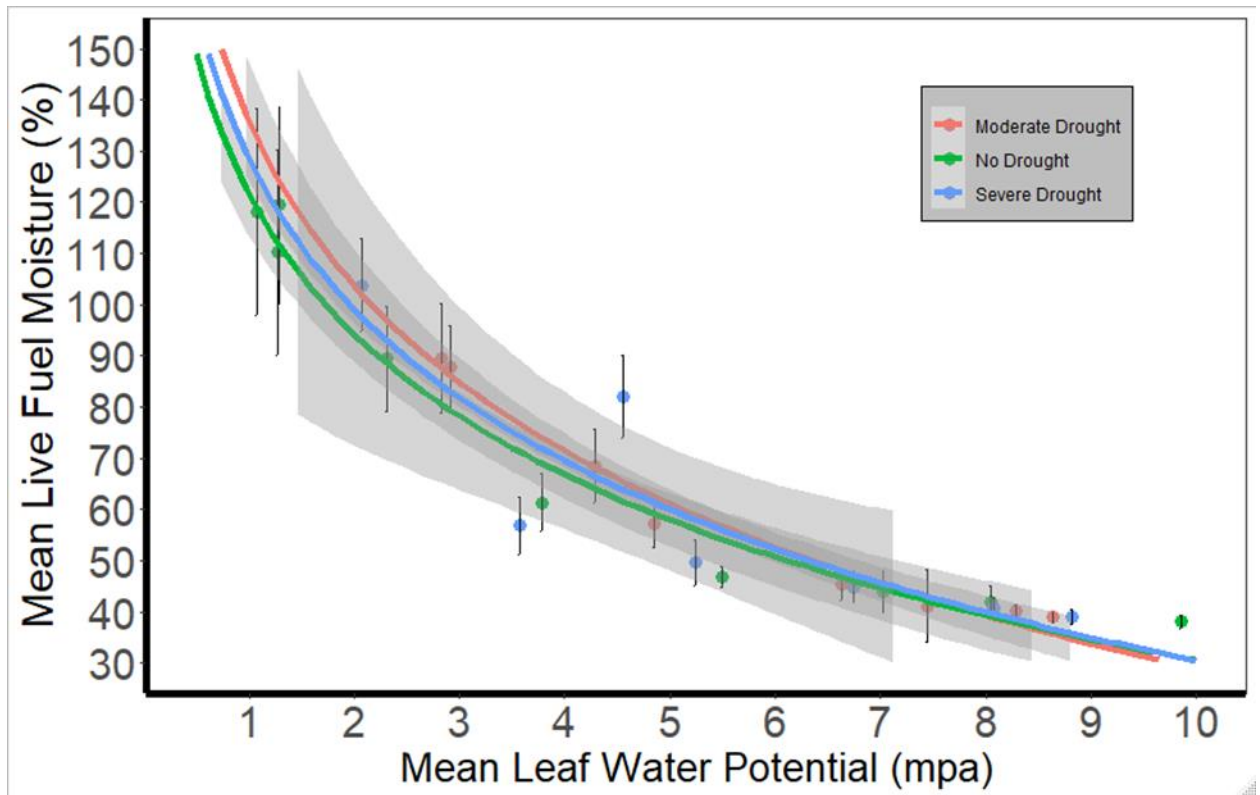


Figure 2. The relationship between live fuel moisture and leaf water potential in eastern redcedar during the final drought of greenhouse experiment 2 for three treatments, previous exposure to moderate, severe, or no drought. Relationships for each treatment are fit with a negative exponential regression. Confidence intervals for each represent the standard error around the regression line.

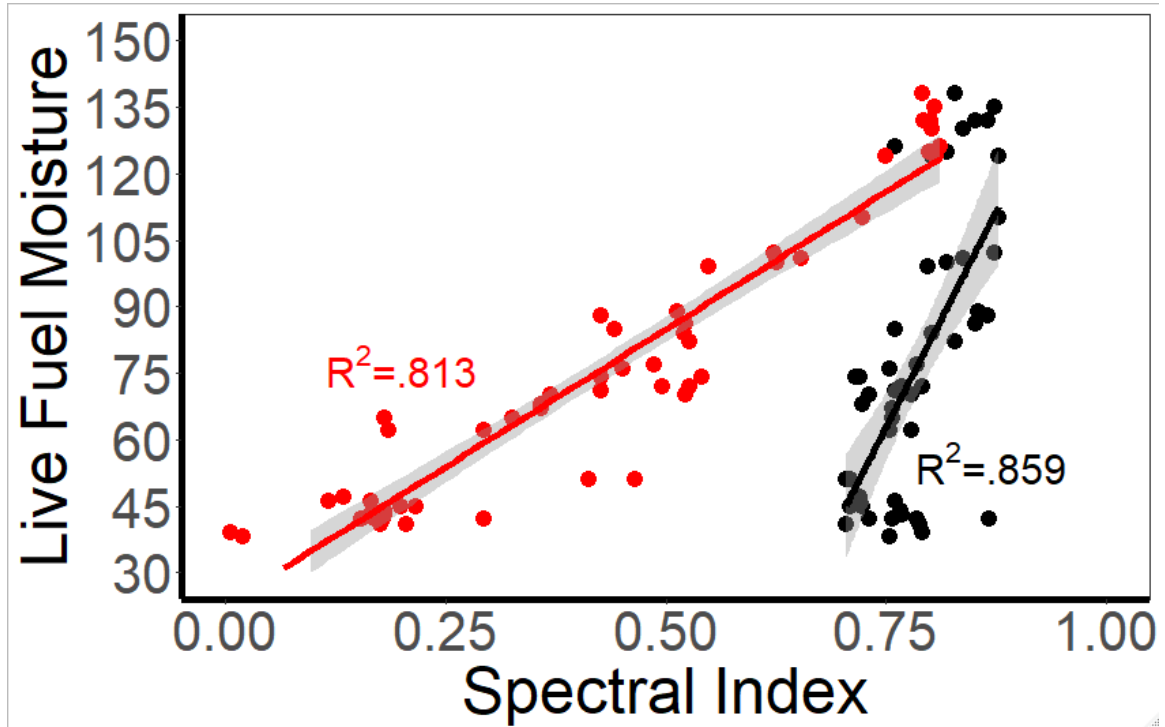


Figure 3. The relationship between live fuel moisture (LFM) and two spectral indices, the normalized difference vegetation index (NDVI) and the normalized difference water index (NDWI). Grey shading indicates the 95% confidence intervals for each regression line. The relationship between LFM and NDWI had a steeper slope than the relationship between LFM and NDVI ($p < 0.01$).

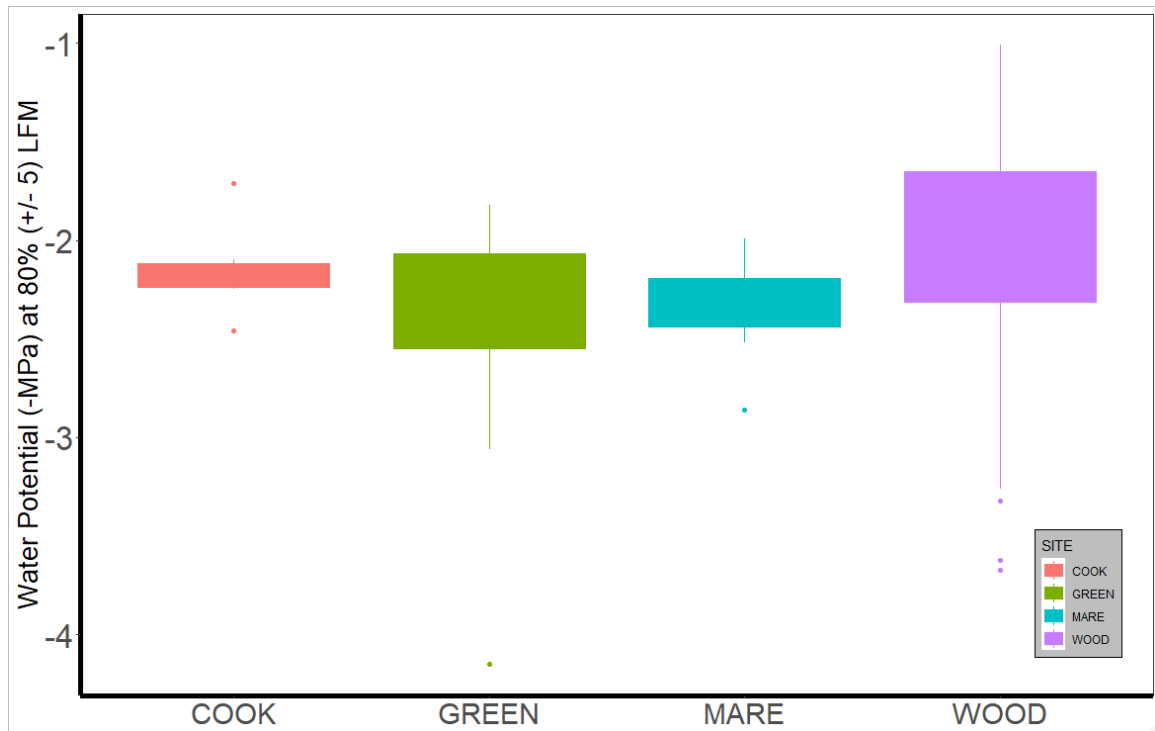


Figure 4. A comparison of daily plant water potential of eastern redcedar for each site and the greenhouse data when live fuel moisture (LFM) was within $\pm 5\%$ of 80%. Boxplots show the range from 25% to 75% as solid boxes, whiskers are one standard error, and outliers beyond this are shown as points. There was no significant difference among the 3 sites and greenhouse data in Ψ_{plant} at $80 \pm 5\%$ LFM (Kruskal-Wallis, $p > 0.05$).

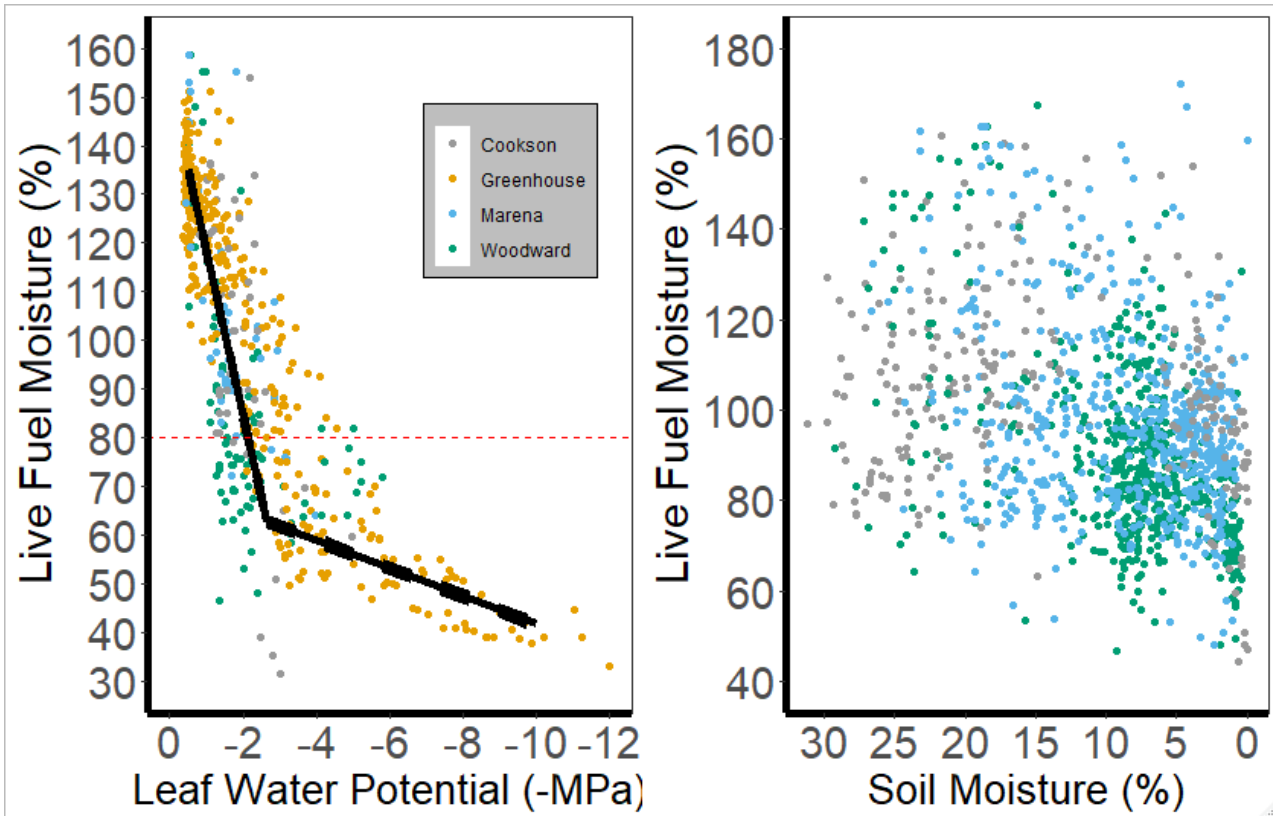


Figure 5. The relationship between xylem tension and live fuel moisture (LFM) fitted with a single segmented regression for all data ($R^2 = 0.644$, $p < 0.01$; a), and the relationship between soil moisture and LFM (b) in eastern redcedar. Data in (a) are from 3 sites across Oklahoma and the greenhouse experiments; data in (b) are from the field sites only. The dashed lines around the regression line in panel a represents the 95% confidence interval.

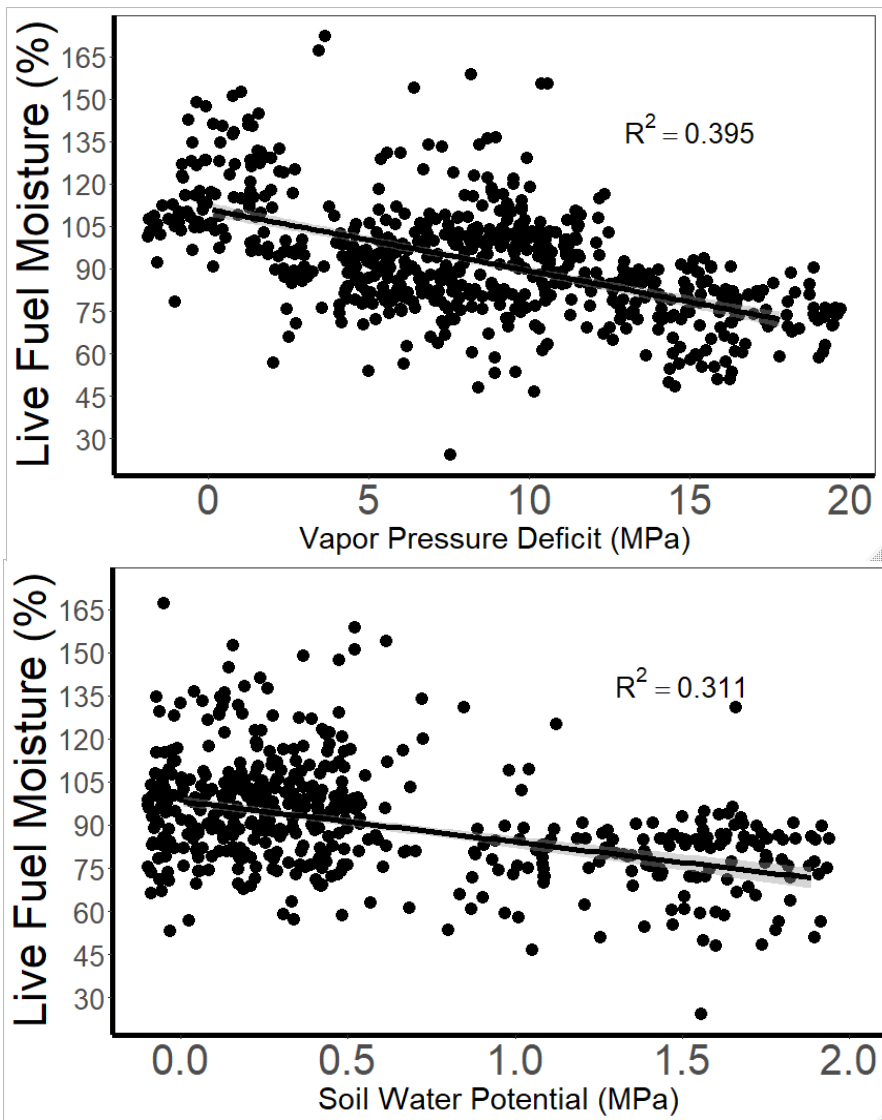


Figure 6. Individual linear regression analyses using Ψ_{soil} and vapor pressure deficit (VPD) to predict (LFM). Ψ_{soil} can explain 31% of variation while VPD can explain 39.5% of variation in LFM. Combined as a multiple regression model to predict LFM from Ψ_{soil} and VPD, the accuracy is improved ($R^2 = 0.613$, $p < 0.05$).

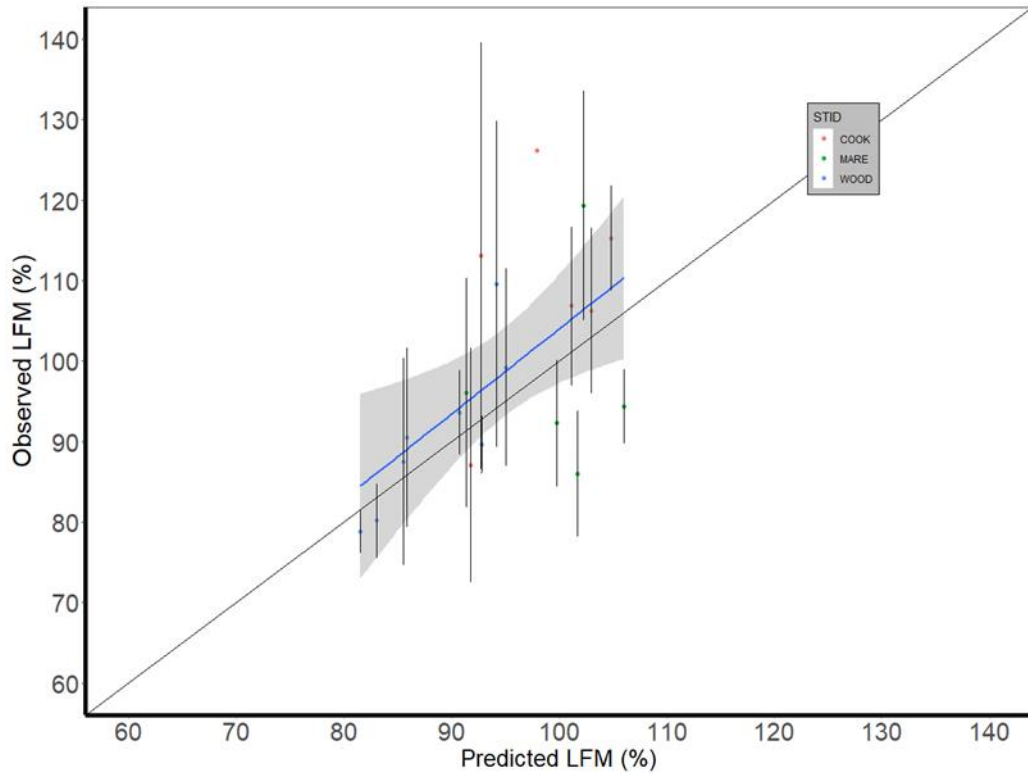


Figure 7. A validation of the multiple regression model used to predict live fuel moisture in eastern redcedar across three field sites. The training set consisted of 80% of all collected data at each site while the test set consisted of a randomly chosen 20% of the data at each site. Points shown are the daily mean values for all trees sampled on each day at each site. Error bars are standard in the observed mean. The black line is The 1:1 line is shown in black, and the linear regression between observed and predicted values is shown in blue, with the standard error of the regression shown in grey. Data validation for each site separately is shown in Figure 10.

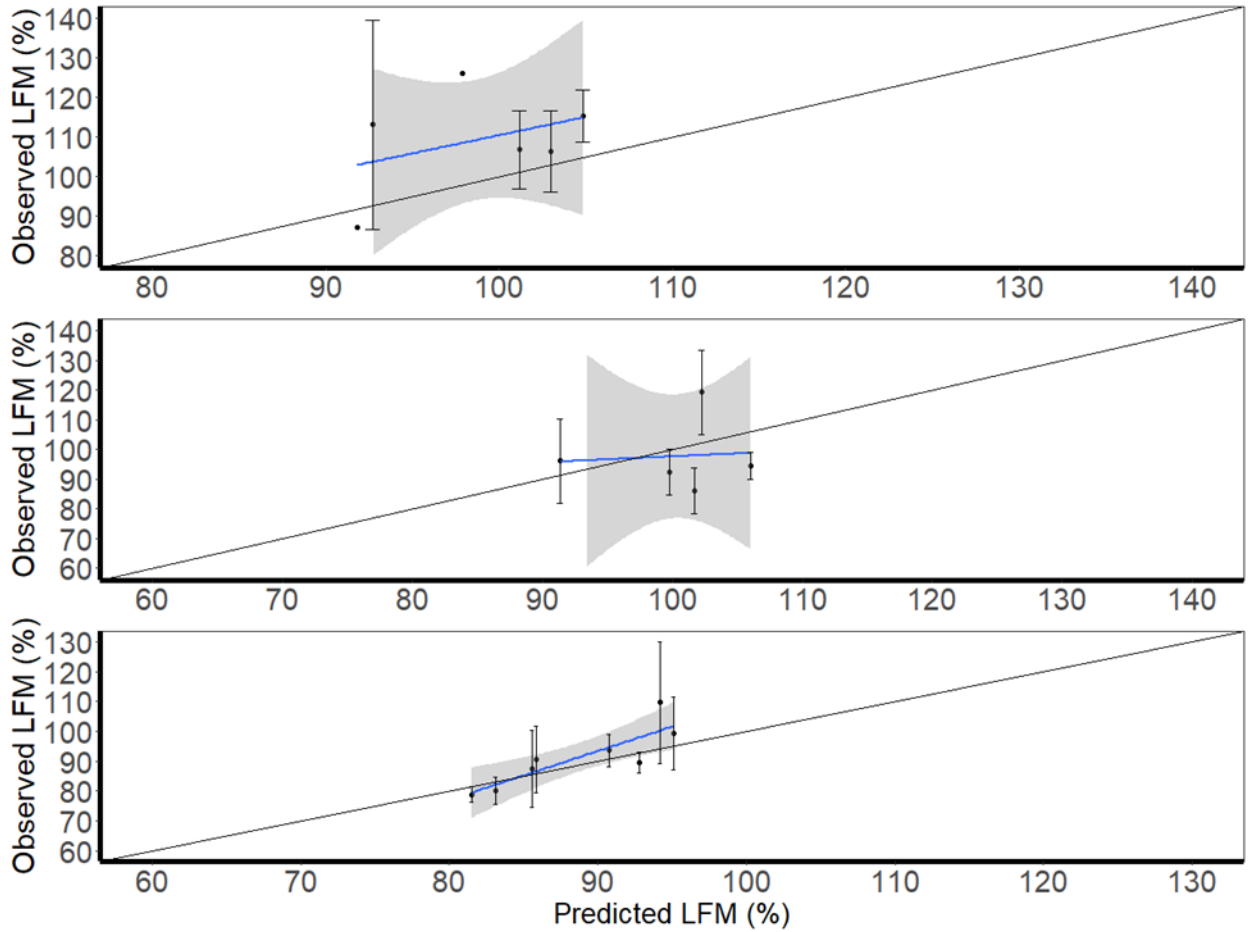


Figure 8. A validation of the multiple regression model used to predict live fuel moisture in eastern redcedar across three field sites separately, for Cookson (a), Marena (b), and Woodward (c). The training set consisted of 80% of all collected data at each site while the test set consisted of a randomly chosen 20% of the data at each site. Points shown are the daily mean values for all trees sampled on each day at each site. Error bars are standard in the observed mean. The 1:1 line is shown in black, and the linear regression between observed and predicted values is shown in blue, with standard error of the regression shown in grey.

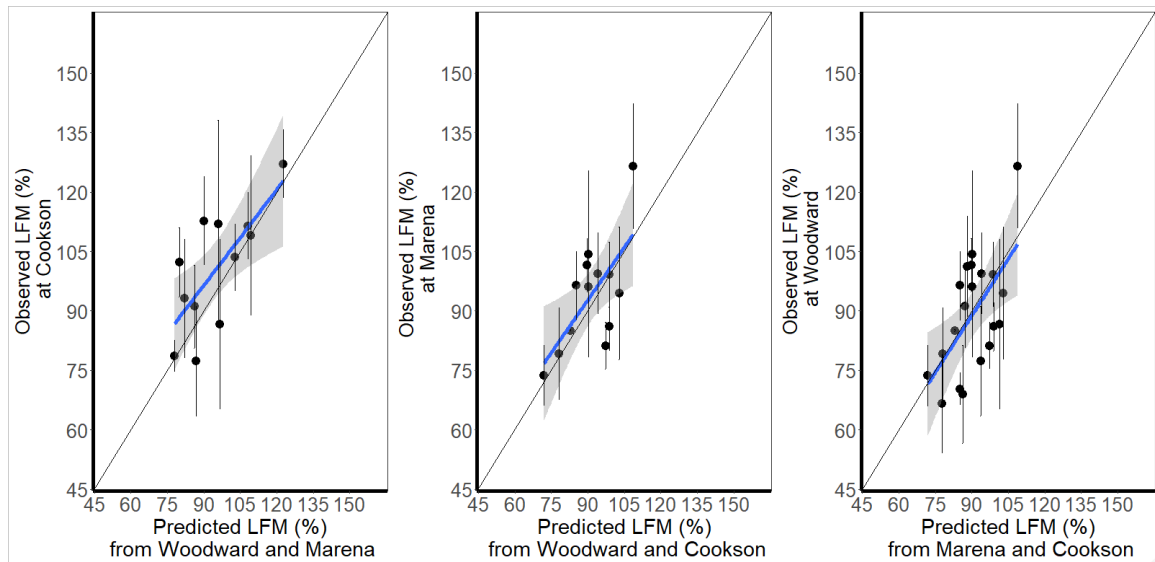


Figure 9. A validation of the multiple regression model used to predict live fuel moisture in eastern redcedar across three field sites separately, for Cookson (a), Marena (b), and Woodward (c). The training set consisted of all collected data at 2 of the 3 sites while the test set consisted of all of the collected data at the final site. Points shown are the daily mean values for all trees sampled on each day at each site. Error bars are standard in the observed mean. The 1:1 line is shown in black, and the linear regression between observed and predicted values is shown in blue, with standard error of the regression shown in grey.

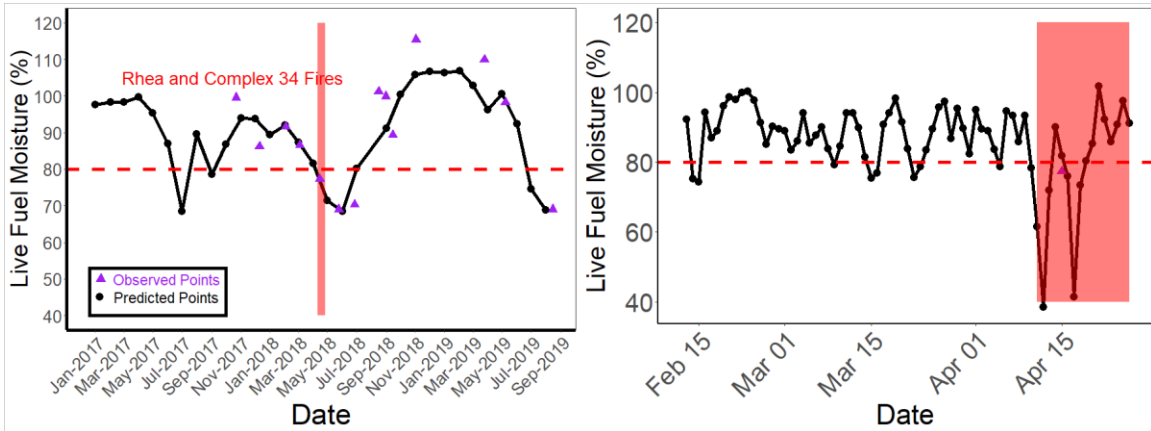


Figure 10. Time series of model predictions and measured observations for live fuel moisture (LFM) in eastern redcedar at the Woodward site. Predictions were calculated on a daily basis from the Woodward, OK Mesonet station and then averaged to give a monthly LFM estimate. Observations and the monthly LFM estimates are shown in (a) and daily LFM estimates are shown in (b). The period during which the Rhea and Complex 34 fires were burning near the Woodward site is highlighted in red.

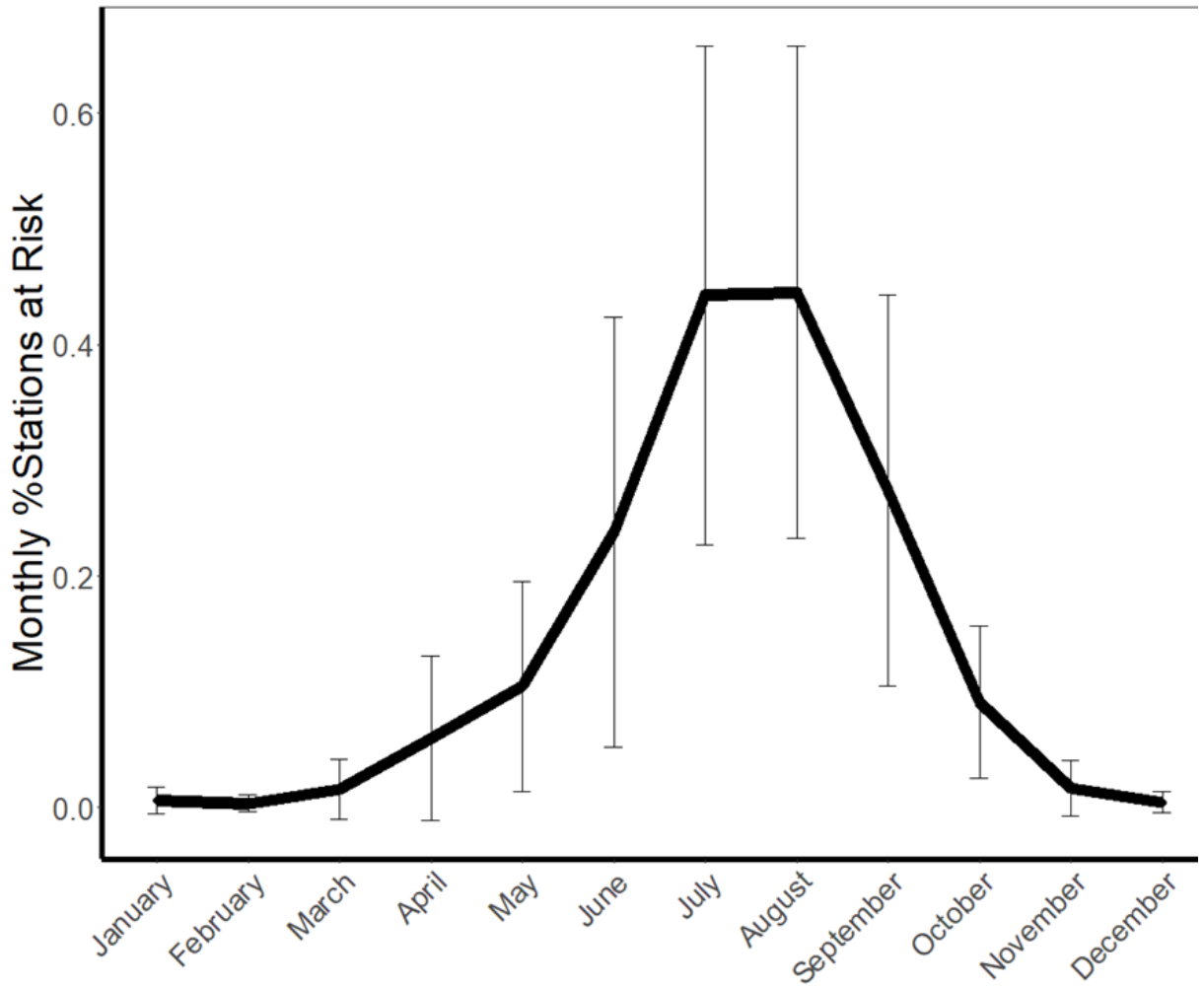


Figure 11. Mean percent of stations that are below the 80% live fuel moisture threshold for increased wildfire risk shown monthly averaged over the entire history of the Oklahoma Mesonet for all 120 stations. Error bars are 95% confidence intervals.

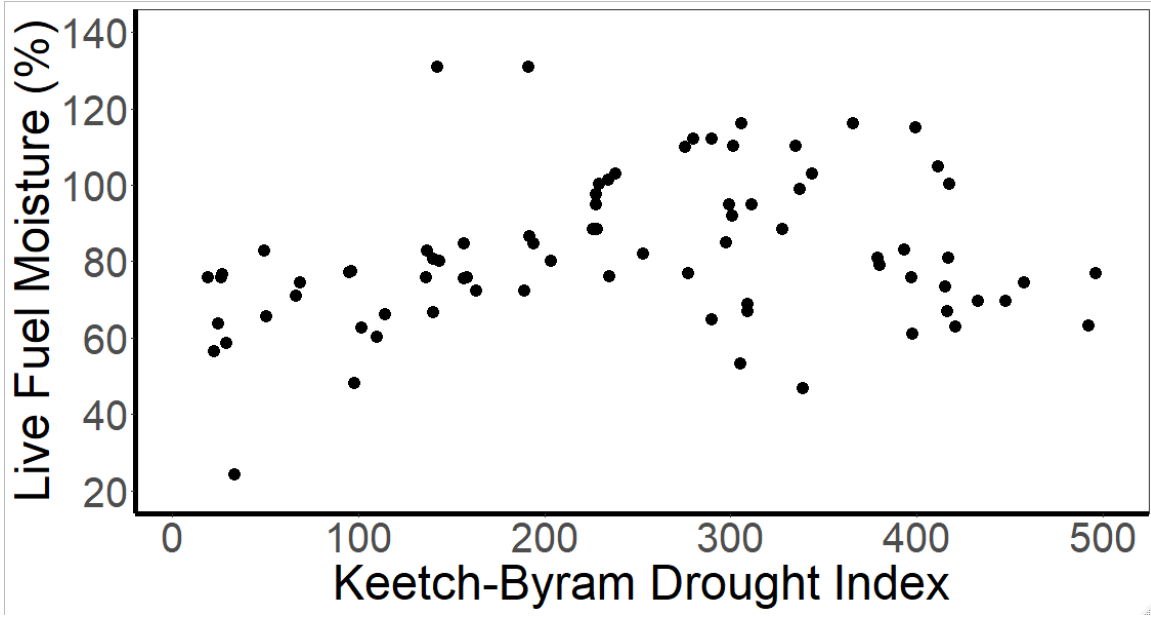


Figure 12. The relationship between Keetch-Byram Drought Index as calculated from the Oklahoma Mesonet and live fuel moisture in eastern redcedar. Each point represents a mean daily average from day of sampling LFM.

VITA

Jeffrey Dudek

Candidate for the Degree of

Master of Science

Thesis: A BURNING QUESTION: HOW MUCH DROUGHT CAUSES INCREASED
FLAMMABILITY IN EASTERN REDCEDAR?

Major Field: Plant Biology, Ecology, and Evolution

Biographical:

Education:

Completed the requirements for the Master of Science in your Plant Biology,
Ecology, and Evolution at Oklahoma State University, Stillwater, Oklahoma in
December, 2020.

Completed the requirements for the Bachelor of Science in Marine and
Environmental Biology and Policy at Monmouth University, West Long
Branch, New Jersey in 2018.

Experience:

Teaching Assistant in Oklahoma State University from 2018-2020 for General
Ecology and Plant Biology.

Professional Memberships:

BGSO Secretary 2019