AN ABSTRACT FOR THE THESIS OF

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Title: *Lespedeza cuneata*: How an Invasive Legume is Altering Fire Ecology in Tallgrass Prairie

Abstract Approved: ______________________________

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Biodiversity within the tallgrass prairies of Flint Hills in Kansas is being threatened by an invasive legume, sericea lespedeza (*Lespedeza cuneata*). Management techniques, like herbicide applications and grazing, can be expensive and ineffective if not correctly targeted. The primary treatment for sericea lespedeza is annual spring prescribed burns. Fire can be an effective tool to manage invasives in vulnerable periods during their life-cycle (e.g. during seed set), especially in fire-adapted ecosystems such as tallgrass prairie. However, annual spring burns increase rates of germination and productivity for sericea lespedeza. I investigated how sericea lespedeza affects fire and how fire affects sericea lespedeza productivity. My main objectives were to determine 1) flammability characteristics of sericea lespedeza and the affect sericea lespedeza has on fire, 2) spring fires in conjunction with secondary treatments impact on sericea lespedeza, and 3) fall fires in conjunction with secondary treatments impact on sericea lespedeza. Flammability characteristics were conducted at Humboldt State University, and seasonal prescribed burns, in conjunction with secondary treatments, were conducted at Marais

des Cygnes National Wildlife Refuge. Sericea lespedeza drastically decreases flammability characteristics as a result of decreased oxygen availability and increased moisture retention. Reduction in flammability characteristics can reduce fire intensity that result in adverse effects for tallgrass prairie ecosystems that lead to increased germination rates of sericea lespedeza seeds. Prescribed burns in the fall, in conjunction with secondary management techniques target sericea lespedeza, and increases seed mortality, compared to spring burns. The true test for land owners treating for sericea lespedeza results in two questions: How much time do they have, and how much money are they willing to invest in the treatment for sericea lespedeza?

LESPEDEZA CUNEATA: HOW AN INVASIVE LEGUME

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PREFACE

This thesis is divided into two chapters. The chapters describe the research conducted within this study and will be submitted to and follow the format guidelines for the *Journal of Rangeland Management* and *Ecosphere*.

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CHAPTER 1

Flammability Characteristics of *Lespedeza cuneata*

Introduction

Fire and grazing are two of the most common global disturbances that maintain and promote many grassland ecosystems worldwide (Bond and Van Wilgen 1996; Fuhlendorf and Engle 2001; van Langevelde et al. 2003; Bond and Keeley 2005; Anderson 2006). Approximately 80% of global fires occur in grassland ecosystems and these fires are critical to native grasses productivity, prevention of woody vegetation encroachment, and management of invasive species (Bragg 1982; Knapp 1984; Knapp 1985; Engle et al. 1998; Engle and Bidwell 2001; Mouillot and Field 2005; Towne and Kemp 2008; Leys et al. 2018). Unfortunately, fire suppression can result in a rapid transition from grassland to forest or shrubland ecosystems and create conditions that favor native and non-native invasive species (Scasta et al. 2016; Leys et al. 2018).

In addition to fire suppression, the presence of non-native, invasive plant species can alter fire regimes through changes in fuel properties that affect native vegetation in many ecosystems and are a leading threat to global biodiversity and ecosystem function (Chapin et al. 2000; Brooks et al. 2004; Clavero and Garcia-Berthou 2005). In many instances, non-native invasive species increase flammability in grasslands due to increases in fuel load, fire intensity, and frequency (Smith and Tunison 1992; Brooks 1999; Rossiter et al. 2003; Brooks et al. 2004). In tropical savannas of northern Australia, Yellowsedge bluestem (*Andropogon virginicus*; Linnaeus) increased fuel loads leading to increased fire intensity and frequency (Rossiter et al. 2003). However, in some instances non-native species can decrease flammability due to higher moisture content, changes in packing ratios, and decreased fuel loads (van Wilgen and Richardson 1985; Keeley 2001; Brooks et al. 2004). In South African grasslands, an invasive shrub, *Hakea sericea* Schrad. (Richardson et al. 1987), increased fine fuel loads by 60% and inhibited combustion and the spread of fire due to densely packed fuel beds (van Wilgen and Richardson 1985). Another fire reduction mechanism is increased fuel moisture content as is seen with tall fescue (*Festuca arundinacea* Shreber). Tall fescue, a cool season (C_3) grass, decreases fire intensity and spread due to higher fuel moisture content than native grasses during the fire season (McGranahan et al. 2013; Livingston and Varner 2016). These examples show the influence of non-native invasive species on flammability in grasslands is driven by the fuel characteristics of invasive species.

One of North America's grasslands, the tallgrass prairie, once covered large tracts of the continental United States, but it has seen the greatest reduction of any North American ecosystem with less than 1% remaining intact due to expanded non-grazing agricultural use in the nineteenth and twentieth centuries (Samson and Knopf 1994; Harr et al. 2014). Pre-European settlement fires, primarily caused by anthropogenic and lightening ignitions, minimized woody plant encroachment. During much of the twentieth century, fire exclusion policies contributed to degradation of tallgrass prairies through woody plant encroachment and invasive plant species establishment (Harr et al. 2014). The largest remaining tracts of native tallgrass prairie are located in the Flint Hills of east central Kansas to north central Oklahoma (Cully et al. 2003; Anderson 2006). Approximately 23% of the 2,223 species of vascular plants documented in Kansas are non-native with 29% of the non-native species considered invasive (Delisle et al. 2012).

One of the most common non-native plant species threatening tallgrass prairie is sericea lespedeza (*Lespedeza cuneata*) [Dum. Cours.] G. Don.; Cummings et al. 2007).

Sericea lespedeza has been declared a noxious weed in Kansas (Eddy et al. 2003). Its expansion has been due in part to its ability to rapidly colonize areas by producing five-times more seed than native tallgrass prairie species, and because that seed can remain viable in the soil for many years (Ohlenbusch et al. 2001; Woods et al. 2009). In 2009, the Kansas Department of Agriculture determined that over 250,900 ha in Kansas and 8,090 ha in the Flint Hills were infested with sericea lespedeza (Kansas Department of Agriculture 2014). Early growth of sericea lespedeza is highly nutritious and palatable; however, as the plant matures, grazers avoid the plant because of increased tannin concentration (Clarke et al. 1939; Donnelly 1954). Avoidance of consumption by grazing animals increases the productivity and density of sericea lespedeza thereby leading to a homogeneic landscape comprised of only sericea lespedeza. Management strategies to reduce sericea lespedeza have had mixed results and the solution to eradicate it is unknown.

Sericea lespedeza management can be expensive, time consuming, and has had limited success. Management techniques to control sericea lespedeza include herbicide applications, grazing/mowing, and prescribed burns. For many land owners, the cost of herbicide applications can be cost prohibitive and ineffective if not correctly targeted. Silliman and Maccarone (2005) estimated costs for treating sericea lespedeza ranged from \$0.15-\$40.45 per ha. A less expensive potential alternative to control sericea lespedeza is prescribed burning.

Annual spring prescribed burns are a common management practice to increase forage production and manage woody plant encroachment in the Flint Hills of Kansas (Towne and Owensby 1984; Parmenter 2008; Towne and Kemp 2008). Prescribed burns are relatively inexpensive to conduct, but annual spring burns have not been successful in eradicating sericea lespedeza (Cummings et al. 2007). Seed mortality of sericea lespedeza occurs at 250°C with 2 minute exposure; however, annual spring burns are unlikely to reach this temperature for a duration long enough to cause mortality (Young 2000; Bell 2012). Annual spring burns have been found to scarify seeds, increasing germination rates and spread of sericea lespedeza (Segelquist 1971). In addition, by the time spring burns occur, most seed has been incorporated into the soil seed bank which is well insulated from fire. However, previous research has not identified sericea lespedeza fuel characteristics (e.g. moisture content, packing ratio, etc.) that could reduce its flammability. Sericea lespedeza's leaves are individually small with a large total surface area per plant, and we suspect that high total surface area increases fuel moisture content and decreases oxygen availability for fire through dense packing ratios. The net result is sericea lespedeza biomass does not burn thoroughly and rarely does the fire burning through dense sericea lespedeza infestations reach sufficient temperatures to make seeds inviable.

The goal of this research was to examine the influence of the non-native, sericea lespedeza, on fuelbed structure, moisture, and flammability within native grassland fuels. Our objectives were to: (1) examine changes in flammability between grass and sericea lespedeza litter with increasing fuel loads, (2) examine the effect of composition and drying times (a proxy for fuel moisture) on grass and sericea lespedeza litterbeds, and (3) examine the influence of fuel load, drying time and composition of native grass and sericea fuelbeds on maximum fire temperature.

We hypothesized that: (1) flammability would be lower in sericea lespedeza than grass litter, but that both litter types would increase flammability with increased fuel load, (2) increasing moisture and proportion of sericea lespedeza would decrease flammability, (3) as increased sericea lespedeza fuel loads would result in lower maximum temperatures, and (4) as drying time increases and proportion of sericea lespedeza decreases, maximum fire temperature will increase. This research will provide information about the mechanisms and effects of the non-native sericea lespedeza on litter flammability in tallgrass prairie ecosystems. Results of our research can advise managers that are interested in using prescribed fire to improve or restore tallgrass prairie.

Materials and Methods

Study Site and Sample Collection

Native grass litter used in our study was collected from six native, tallgrass prairie pastures in Lyon, Greenwood, and Chase counties in Kansas during the spring of 2018. The four most common tallgrass species at the site are: switchgrass (*Panicum virgatum* L.; Vogel et al. 2011), indiangrass (*Sorghastrum nuans* [L.] Nash; Moser and Vogel 1995), big bluestem (*Andropogon gerardii* Vitman; Moser and Vogel 1995), and little bluestem (*Schizachyrium scoparium* [Michx.] Nash; Pfeiffer and Hartnett 1995), all of which are adapted to fire and grazing disturbances. Native grass litter was collected from three patch-burn grazed and three annual-burn grazed pastures to account for variation of native grass fuels. Sericea lespedeza litter was collected from Marais des Cygnes National Wildlife Refuge (NWR) in Lynn County, Kansas during the fall of 2017, as part of another study examining the effect of fire season on sericea lespedeza.

Fuel loading and drying time values used in this study were partially informed by samples collected at the previously described sites prior to prescribed burns. We conducted drying trials in the laboratory that looked at drying rates and these rates, in conjunction with field observations, were used to determine laboratory drying times. Fuel load samples in native tallgrass prairie were collected every 10 meters along two 150 m transects. Fuel load samples were clipped from a 0.1 m^2 quadrat, placed in paper bags first and then placed in a sealable plastic bag to retain moisture. Samples were returned to the lab and weighed to obtain wet fuel load weight. The plastic bag was removed from all samples and were dried at 70°C for 24-48 h, and weighed to calculate dry fuel load and moisture content. The distribution of fuel loads and moisture content for native tallgrass prairies were obtained from data collected each spring from 2016 to 2018, within one hour prior to prescribed burns at each site. Two fuel load samples were collected at each point on the transect and averaged for fuel load and moisture content at that sample point. In native tallgrass prairie pastures, approximately 90% or more of fuel load and moisture samples collected were comprised of native grass. Mean fuel loading was 527 g m^{-2} (SE=7.8, n=1010) and mean fuel moisture content was 20% (SE=4.5, n=1010).

The most abundant species at the Marais des Cygnes NWR research site was sericea lespedeza. The site contained 8 plots (50 m x 50 m) receiving fire treatments, and each plot had 16 different fuel load sampling locations. Samples were collected annually from 2015-2017. Sericea lespedeza fuel loads were collected in plots prior to prescribed burns and were clipped and processed in the same manner as described for native grass litter. Mean fuel loading for sericea lespedeza was 310 g m^{-2} (SE=2.3, n=183) and mean fuel moisture content was 46% (SE=2.7, n=183).

Experimental Design

For the first experiment, we examined the role of fuel loading on flammability for sericea lespedeza and native grass litter, separately across 40 fuel beds (n=20 native grass only and n=20 sericea lespedeza only). Fuel loading was categorized as 20 g, 35 g, 50 g, 65 g, and 85 g of native grass or sericea lespedeza independently. Each fuel loading category was replicated four times for each of the two fuel types. All fuels were burned under equilibrium moisture content (EMC) because we wanted to observe how native grasses and sericea lespedeza impacted fire without the influence of fuel moisture content. Equilibrium moisture content was attained by prolonged exposure to stable atmospheric conditions (Blackmarr 1971). Burning trial and flammability measurement methods are described in detail below.

For the second experiment, we examined the effect of moisture and composition on native grass and sericea lespedeza litter flammability. All litter was initially oven-dried at 60°C for 24 h and weighed. Composition categories consisted of 100%, 75%, 50%, 25%, and 0% of sericea lespedeza by mass and all fuel beds had a total of 50 g, based on oven-dry weight. To vary moisture content of the fuels, we used three drying times, 24 h, 36 h, and 48 h (i.e., EMC) after saturation, following the similar methods as Kreye et al. (2018). We submerged each of the fuel beds in a pan of water for 24 h to reach saturation moisture content and then dried for either 24 h, 36 h, or 48 h (EMC) in a drying chamber under relatively controlled conditions. Drying chamber temperatures ranged from 17.7°C to 27.8°C ($\bar{x}$=23.1°C, SD=1.9) and relative humidity ranged from 29.6% to 56.8% ($\bar{x}$=37.9%, SD=5.6). Each combination of composition category (5) and each drying time categories (3) were burned four times resulting in 60 fuel beds.

All burning trials were conducted at the Humboldt State University Wildland Fire Science Laboratory in Arcata, California, USA. Fuel beds for both experiments were burned in a randomized block experimental design using well-established methods (e.g., Fonda et al. 1998; Kane et al. 2008; and Kreye et al. 2018). For each burn trial, litter was placed on a cross pattern of xylene-soaked cotton strings laid out in a 35 × 35 cm grid, with the majority of the litter located within the interior 20 × 20 cm portion. Fuel bed depth measurements were taken at four locations, approximately 7 cm diagonally from each corner. Xylene-soaked strings were ignited around the perimeter to provide a uniform ignition source. Laboratory conditions during burns ranged from 14.9°C to 25.8°C ($\bar{x}$=21.2°C, SD=2.0) and 33.9% to 57.9% relative humidity ($\bar{x}$=44.3%, SD=4.5).

During each burn trial, we measured maximum flame height (cm), flaming time (s), smoldering time (s), temperature (°C), and consumption (%). Maximum flame height was visually estimated using a large ruler placed just behind the fuel bed. Flaming time was measured as the time between flame contact with the fuel bed and flame extinction. Smoldering time was measured as the time between flame extinction and when embers were no longer visible. Percent consumption was calculated by preburn weight and the difference of change in mass divided by preburn weight multiplied by 100. We used seven type-K thermocouples, constructed from 10 m plastic coated, double stranded wire leads (model CASS-14U-60-NHX, ungrounded, 6.35-mm sheath, Omega Engineering, Stamford, CT, USA), positioned at 0, 10, 20, 30, 50, 75, and 100 cm above the base of the fuel bed to measure temperature in 1 s intervals. A Campbell Scientific CR1000 data logger (Campbell Scientific Instruments, Logan, UT, US) was used to record fire temperatures and was calibrated prior to use. We report the average maximum temperature for each height position above the fuel bed.

Statistical Analyses

Since flammability metrics are often correlated (see supplemental information), we conducted a principal components analysis (PCA), similar to Kane et al. (2008), Engber and Varner (2012), and Kreye et al. (2018), to reduce the dimensionality of the observed flammability metrics. PCA was used to test for differences in flammability between fuel types (native grasses and sericea lespedeza) and their fuel load levels (20 cm, 35 cm, 50 cm, 65 cm, and 80 cm). A second principal component analysis was used to test for differences in flammability between drying times (24 h, 36 h, and EMC) and proportion of sericea (0%, 25%, 50%, 75%, and 100%). Principal components analyses were compared with standardized values (mean=0, standard deviation=1) for each of the five flammability metrics. Dependent variables included in the PCA consisted of max flame height (cm), flame time (s), smolder time (s), maximum temperature (°C), and percent consumption (%). Temperatures were highly correlated among varying heights and we only included temperature data at 50 cm above the fuel bed to avoid overrepresentation of temperature variables in the PCA ordination.

We only considered axes that resulted in >65% of the cumulative variation explained. Scores were log-transformed and standardized for maximum flame height, flame time, smolder time, percent consumption, and temperatures at 50 cm. Results of the scores were used in analyses of drying time and fuel loadings. Factor scores were compared across moisture, composition categories, and fuel loading using PERMANOVA to test for main effects and interactions.

We conducted a general linear regression to examine the relationship of temperatures and fuel load by species, and in a separate analysis for drying time and composition (proportion of sericea). Fuel load and species content were used to examine their relationship with maximum temperatures at 0 cm, 10 cm, 20 cm, 30 cm, 50 cm, 75 cm, and 100 cm above the fuel bed. We also performed a general linear model analysis of the relationship between height and maximum temperature. We tested fuel load and species composition (without interaction term) into the model for maximum temperatures. Visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity or normality. We used the Pillai's test to examine differences in factors. P-values were obtained by likelihood ratio tests of the full model with the effect in question against the model without the effect in question. Significance level was set at $\alpha=0.05$.

Influence of drying time and proportion of sericea lespedeza on maximum fire temperatures were examined using general linear regression analysis. Drying time and proportion of sericea lespedeza (without interaction term) were independent variables in the model. Visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity or normality. P-values were obtained by likelihood ratio tests of the full model with the effect in question against the model without the effect in question. Three temperature observations were deleted due to unrealistic values in the fuel load and species composition experiment as well as the dry times and proportion of sericea lespedeza. All analyses were conducted using R v 3.5.2 (Vienna, Austria).

Results

Increased fuel loads of native grass increased flammability characteristics; however, sericea lespedeza decreased flammability characteristics. Increased native grass litter fuel loads increased percent consumption, flaming time, and smoldering time 25%, 24%, and 57%, respectively (Table 1-1). Conversely, increased sericea lespedeza fuel loads decreased percent consumption, flaming time, and smoldering time 69%, 14%, and 60%, respectively.

Results from our PERMANOVA showed significant differences for flammability metrics in species, fuel loads, and their interaction (P<0.001; Fig. 1-1). Increased flammability characteristics included taller flames, higher temperatures, longer flame and smolder time, and higher percent consumption. Examined flammability metrics were correlated and combined using PCA. The PCA resulted in one factor (Flam1) that explained 81% of the variability in the dataset, with an eigenvalue of 4.05. Flam1 scores with negative loadings increased flammability characteristics and positive loadings decreased flammability characteristics. Native grass flammability characteristics significantly increased as a result of increased fuel loads, conversely, sericea lespedeza flammability characteristics decreased as fuel loads increased.

Sericea lespedeza mean fuel bed depth was significantly lower compared to native grasses (P<0.001; Fig. 1-2). Sericea lespedeza and native grass mean fuel bed depth increased significantly as fuel loads increased by 79% and 80%, respectively. However, an increase in fuel bed depth did not increase flammability characteristics. Sericea lespedeza flammability characteristics decrease as a result of the small, dense, fuel bed created by litter. Sericea lespedeza leaf structure has a high surface area and as a result create a high packing ratio. The high packing ratio of sericea lespedeza litter decreases oxygen availability and results in lower flammability characteristics.

Decreased drying times and increased proportion of sericea lespedeza significantly decreased flammability characteristics, supporting our hypothesis. Decreased drying times and increased proportions of sericea lespedeza decreased average flaming time, smoldering time, and percent consumption 44%, 80%, and 83%, respectively (Table 1-2).

Results from our PERMANOVA showed significant differences in flammability for drying time (P<0.004), proportions of sericea lespedeza (P<0.001), and their interaction (P<0.013; Fig. 1-3). Examined flammability metrics were correlated and combined using PCA. The PCA resulted in one factor (Flam1) that explained 69% of the variability in the dataset, with an eigenvalue of 3.46. Decreased drying times and increased proportions of sericea lespedeza decreased flammability characteristics. Increased flammability characteristics included taller flames, higher temperatures, longer flame and smolder time, and higher percent consumption.

Fuel bed depth has a significant relationship to drying times and proportions of sericea lespedeza (P<0.001; Fig. 1-4). Fuel bed depth was significantly less in 24 h drying times compared to 36 h and 48 h (P<0.001; Table 1-2). Increased proportions of sericea lespedeza and decreased drying times decrease fuel bed depths and flammability characteristics through increased moisture retention and dense packing. The synergistic effect of increased moisture retention and dense packing ratio, represented by a thin fuel bed depth, is effective at decreasing flammability characteristics and independently of each other.

Maximum fire temperatures increase significantly with increased fuel loads, supporting our hypothesis. Maximum fire temperatures were significantly different for species composition, fuel load, and their interaction (P<0.001; Fig. 1-5). Native grass significantly increased maximum fire temperatures, as fuel loads increased; however, sericea lespedeza does not significantly increase maximum fire temperature. Sericea lespedeza maximum fire temperature was 84% lower than native grasses, regardless of fuel load. Conversely, maximum fire temperatures increased 69% as fuel load increased, regardless of species composition. Native grass maximum fire temperatures significantly increased 66%, as fuel load increased (P<0.001). Sericea lespedeza maximum fire temperatures increased 13%, as fuel load increased. The significant difference in maximum fire temperatures for species composition in conjunction with fuel loads are a result of varied native grass maximum fire temperatures. Sericea lespedeza maximum fire temperatures did not significantly increase as fuel load increased (P=0.358).

Maximum fire temperatures increased significantly with increased drying times and decreased proportions of sericea lespedeza, supporting our hypothesis. Maximum fire temperatures were significantly different for drying times (P<0.001), proportions of sericea lespedeza (P<0.001), and their interaction (P=0.003; Fig. 1-6). Maximum fire temperatures increased 47% with increased drying times and decreased 76% as a result of increased proportions of sericea lespedeza. Drying time of 24 h in conjunction with all proportions of sericea lespedeza significantly decreased maximum fire temperatures. Proportions of sericea lespedeza ≥ 50% negatively affect maximum fire temperatures for drying times of 36 h and 48 h.

Discussion

Sericea lespedeza poses a major threat to tallgrass prairies in the United States by decreasing flammability characteristics through increased moisture retention and decreased oxygen availability and as a result dampens fire intensity. Decreased oxygen availability and increased fuel moisture content are a result of densely packed sericea lespedeza fuel loads that decrease ignition and combustion. Reducing fire intensity can have adverse effects for tallgrass prairie ecosystems that can lead to increased germination rates of sericea lespedeza seeds (Qui et al. 1995; Kalburtji et al. 2007).

We expected the rate of consumption to increase with increasing sericea lespedeza fuel loads. Unexpectedly, percent consumption of litter decreased 71% between the lowest and highest fuel loading (Table 1). This result highlighted sericea lespedeza's strong ability to halt fire progression regardless of moisture content. Similar patterns were seen when drying times and proportion of sericea lespedeza were analyzed. Fuel load consumption dropped as drying times decreased and proportions of sericea lespedeza increased. Decreases in percent consumption were most pronounced with proportions of $\geq$ 50% sericea lespedeza at all drying times (Table 1-2). This reinforces Mooers and Ogden (1935) research that stated fire progression in pure stands of sericea lespedeza may be halted.

Similar to Mooers and Ogden (1935), our results show sericea lespedeza's ability to decrease flammability characteristics by its dense packing ratio and ability to retain moisture (Fig. 1-2; Fig. 1-4). Previous studies have observed litterbed structure and leaf structure of other invasive species and have noted similar findings (Scarff and Westoby 2006; Kane et al. 2008; Cromwell et al. 2015; Kreye et al. 2018). Sericea lespedeza leaves are small and flat and settle close together creating a large surface area which is able to retain moisture and decrease oxygen availability creating a damp and oxygen deprived fuel bed. Fuel bed structure for sericea lespedeza alters fire behavior and lowers flammability characteristics in grassland ecosystems. Conversely, large leaves with lower surface area create less compact litter which burns more rapidly with intense fires, similar to what we see in native grasses (Cromwell et al. 2015).

Fire intensity is important in management of mortality of sericea lespedeza seeds. Temperatures that reach 250°C for 120 s can cause mortality in sericea lespedeza seeds (Bell 2012). If these results are similar to field based fire temperatures, this can be problematic for land owners who use prescribed burns as the only control for sericea lespedeza. Prescribed burns that do not reach sufficient fire intensities to cause mortality to sericea lespedeza seeds can scarify the coat which promotes germination and may cause increased productivity of sericea lespedeza (Segelquist 1971).

A number of studies have investigated how invasive plant species have pyrophytic characteristics that can increase fire frequencies, intensities, or dampen ecosystems (Smith and Tunison 1992; Rossiter et al. 2003; Brooks et al. 2004), but few studies have addressed how non-native invasive species exhibit mesophytic characteristics that can dampen fire in pyrophytic tallgrass prairie ecosystems. Furthermore, the majority of research looking at flammability characteristics, in a laboratory setting, has investigated flammability characteristics in forest ecosystems (Kane et al. 2008; Kreye et al. 2013; Kreye et al. 2018). However, to our knowledge, this study was the first controlled setting to analyze flammability characteristics of a non-native invasive species, invading grassland systems. In controlled experimental burns, sericea lespedeza's effect on flammability characteristics can be evaluated without confounding variables like aspect, slope, and other ecological variables.

One of the current largest threats to tallgrass prairie is encroachment and invasion of mesophytic native and non-native invasive species. Mesophytic invasive species can dampen fire behavior through incorporation of less flammable or fire-impeding litter. Sericea lespedeza directly influences grassland structure and function by increases in density, greater shade, increased moisture content, and reduced grass productivity; congruently, this results in a shift from fire tolerant ecosystems to a fire-sensitive ecosystem (Nowacki and Abrams 2009; Stambaugh et al. 2015).

This information can be useful to land owners when deciding to use prescribed burns for removal of non-native invasive species, like sericea lespedeza. In order to increase flammability characteristics use of prescribed burns is suggested at drying times of 36 h, proportions of sericea lespedeza are less than 50%. Nonetheless, if dense stands of sericea lespedeza exist, alternative management techniques may be required. Maintenance and restoration of grassland systems will require a multifaceted approach to management for land owners that require the use of various tools like intense patch-burn grazing, herbicide applications, and mow treatments. Prescribed burns should be incorporated with other management techniques to treat sericea lespedeza and support fire in tallgrass prairie.

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Table 1-1. Mean values of fuel bed depth (FBD), maximum flame height (Max Ht), flaming time (FT), smoldering time (ST), percent consumption (Cons.), and the average temperature at 50 cm by fuel loading and type. Values in parentheses are standard error.

Fuel Type	Fuel Load (g)	FBD (cm)	Max Ht (cm)	FT (s)	ST (s)	Cons. (%)	T_{50} (°C)
Native Grass							
	20	2.3 (0.2)	40.0 (7.0)	74 (3)	135 (39)	62 (2)	44 (6)
	35	5.1 (0.3)	86.5 (4.5)	102 (6)	194 (39)	77 (3)	62 (6)
	50	8.2 (0.4)	93.0 (7.3)	100 (17)	228 (36)	78.1 (4)	49 (5)
	65	10.8 (0.4)	124.8 (2.1)	118 (14)	271 (9)	80.6 (1)	59 (2)
	80	11.8 (0.5)	116.8 (6.2)	98 (16)	313 (39)	83.1 (1)	75 (6)
L. cuneata							
	20	0.4 (0.0)	4.5 (0.9)	62 (10)	27 (2)	5.9 (0)	36 (2)
	35	0.7 (0.1)	5.5 (1.0)	58 (5)	45 (15)	4.2 (1)	34 (1)
	50	1.0 (0.1)	7.0 (0.6)	65 (7)	19 (3)	3.2 (0)	36 (3)
	65	1.4 (0.0)	7.5 (0.9)	60 (8)	37 (14)	2.3 (0)	35 (2)
	80	1.8 (0.1)	10.0 (1.4)	53 (5)	11 (2)	1.8 (0)	39 (3)

Table 1-2. Mean values of fuel bed depth (FBD), maximum flame height (Max Ht), flaming time (FT), smoldering time (ST), percent consumption (Cons), and the average temperature at 50 cm by fuel loading and type. Values in parentheses are standard error.

Dry Time	Proportion of Sericea	FBD (cm)	Max Ht (cm)	FT (s)	ST (s)	Cons (%)	T_{50} (°C)
24-h							
	0%	3.2 (0.1)	41.5 (5.6)	92 (20)	76 (21)	29 (10)	44 (2)
	25%	2.7 (0.1)	38.3 (6.6)	60 (12)	75 (17)	19 (6)	40 (3)
	50%	2.3 (0.1)	23.0 (3.0)	66 (6)	44 (9)	11 (2)	40 (4)
	75%	2.0 (0.1)	15.5 (2.3)	50 (6)	50 (3)	8 (1)	35 (1)
	100%	1.4 (0.1)	11.3 (1.1)	51 (10)	29 (11)	12 (5)	34 (1)
36-h							
	0%	7.6 (0.4)	97.3 (3.2)	123 (10)	149 (8)	74 (3)	50 (9)
	25%	5.8 (0.6)	74.3 (11.6)	140 (11)	140 (24)	56 (6)	48 (3)
	50%	4.6 (0.3)	34.5 (6.8)	86 (13)	64 (26)	27 (7)	46 (2)
	75%	2.2 (0.3)	27.3 (11.6)	68 (15)	50 (25)	11 (4)	36 (2)
	100%	1.3 (0.1)	9.5 (1.0)	60 (7)	21 (3)	4 (0)	39 (3)
48-h							
	0%	8.2 (0.4)	93.0 (7.3)	100 (17)	228 (36)	78 (4)	50 (5)
	25%	7.2 (0.5)	72.8 (14.1)	120 (13)	173 (72)	54 (6)	49 (4)
	50%	4.2 (0.7)	40.8 (13.5)	93 (10)	118 (54)	30 (6)	44 (4)
	75%	2.6 (0.3)	20.0 (4.2)	91 (20)	40 (10)	17 (2)	43 (6)
	100%	1.0 (0.1)	7.0 (0.6)	65 (7)	19 (3)	3 (0)	35 (3)

Fig. 1-1. The relationship between fuel load and flammability (FLAM 1) by fuel type. Native grasses are represented as blue diamonds and sericea lespedeza are represented as red hexagons.

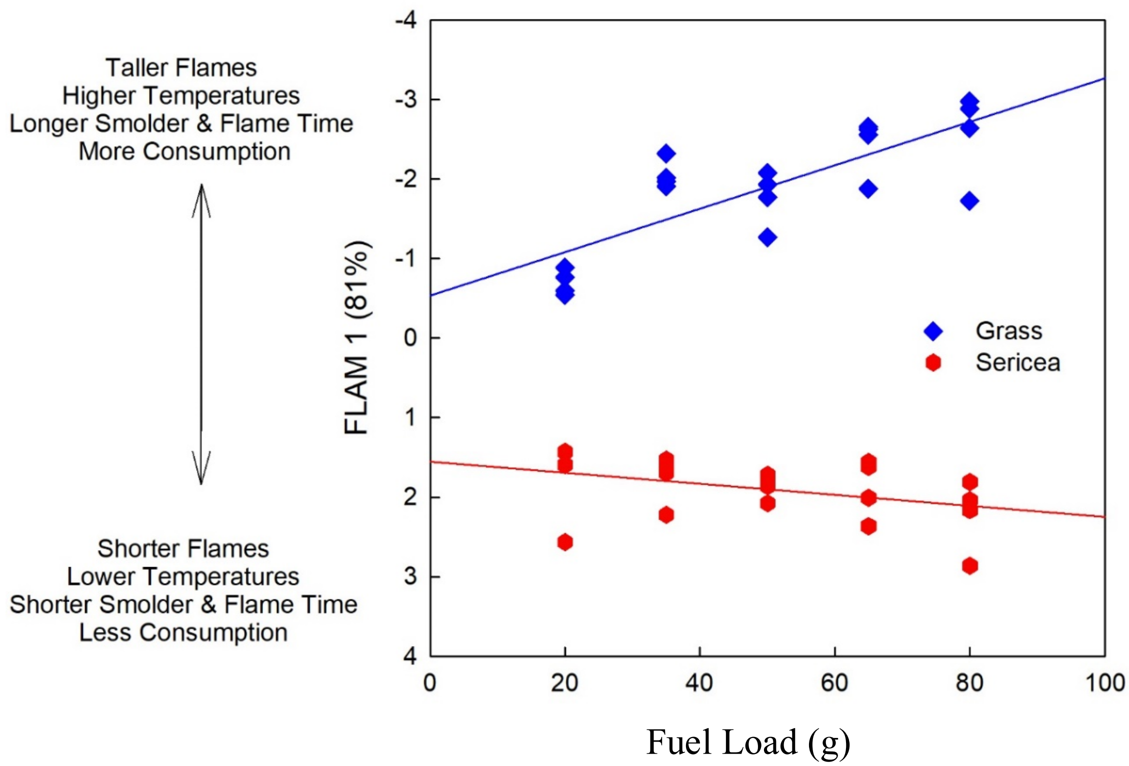

Taller Flames
Higher Temperatures
Longer Smolder & Flame Time
More Consumption
Shorter Flames
Lower Temperatures
Shorter Smolder & Flame Time
Less Consumption
FLAM 1 (81%)
-4
-3
-2
-1
0
1
2
3
4
0
20
40
60
80
100
Grass
Sericea
Fuel Load (g)

Fig. 1-2. Flammability characteristics combined through PCA across different fuel loads with varying amounts (native grass or sericea) of fuel load (20, 35, 50, 65, and 80 g). Native grasses are diamonds and sericea lespedeza are circles. Fuel loads are designated by their respective color. Species (native grass and sericea lespedeza), fuel loads, and their interaction were all significantly different ($P<0.001$).

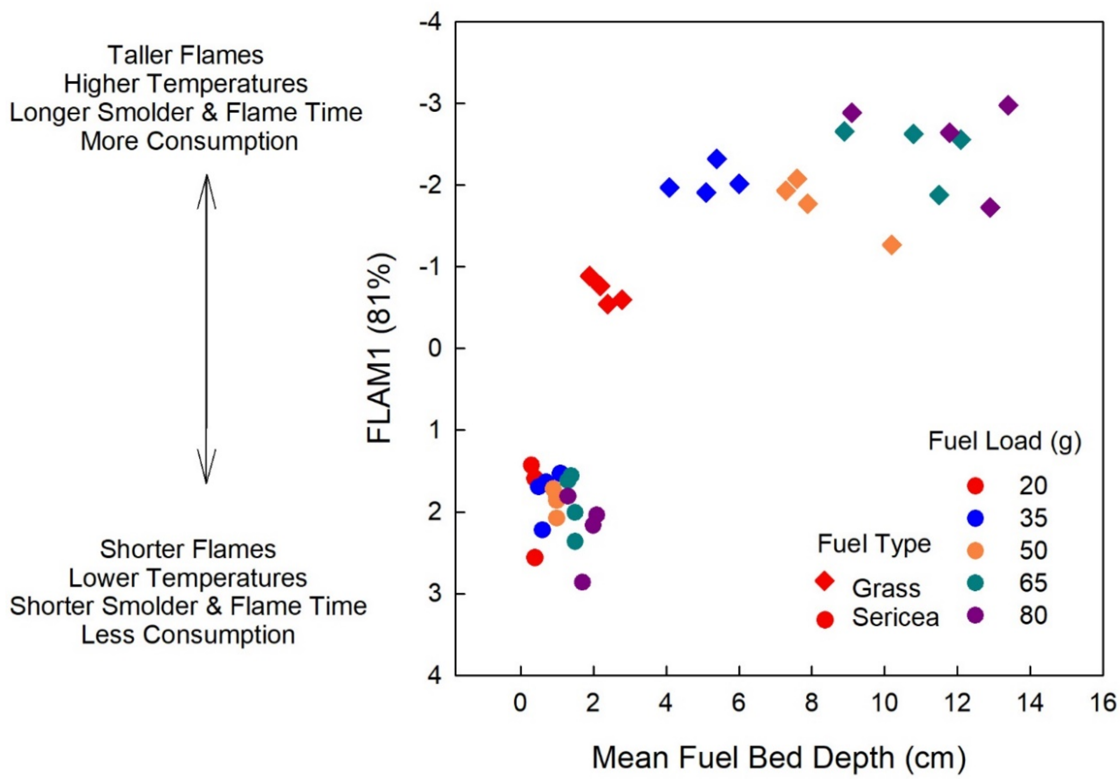

Taller Flames
Higher Temperatures
Longer Smolder & Flame Time
More Consumption
Shorter Flames
Lower Temperatures
Shorter Smolder & Flame Time
Less Consumption
FLAM1 (81%)
-4
-3
-2
-1
0
1
2
3
4
0
2
4
6
8
10
12
14
16
Mean Fuel Bed Depth (cm)
Fuel Load (g)
20
35
50
65
80
Fuel Type
Grass
Sericea

Fig. 1-3. The relationship between proportion of sericea lespedeza and flammability metrics in PCA as a function of dry time and proportion of sericea in fuelbed. 24 h dry time is a blue triangle, 36 h dry time is a green circle, and 48 h (EMC) is a red square.

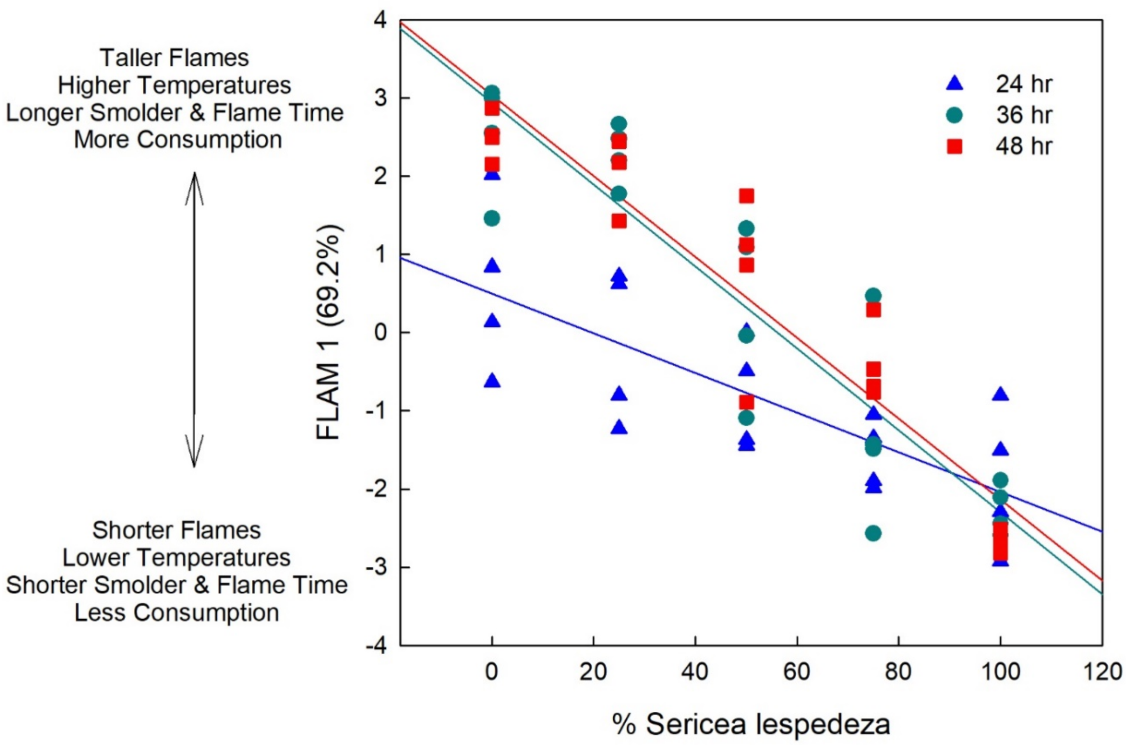

Taller Flames
Higher Temperatures
Longer Smolder & Flame Time
More Consumption
Shorter Flames
Lower Temperatures
Shorter Smolder & Flame Time
Less Consumption
24 hr
36 hr
48 hr
FLAM 1 (69.2%)
% Sericea lespedeza
4
3
2
1
0
-1
-2
-3
-4
0
20
40
60
80
100
120

Fig. 1-4. Flammability characteristics combined through principal component analysis across different litter compositions with varying amounts of mesophytic species after 24, 36, and 48 h of drying, following saturation at EMC. 24 h is a triangle, 36 h is a circle, 48 h (EMC) is a square; percents of sericea is designated by color. Flammability characteristics were significantly different in dry time (P<0.004), proportion of sericea (P<0.001), and the interaction (P<0.013).

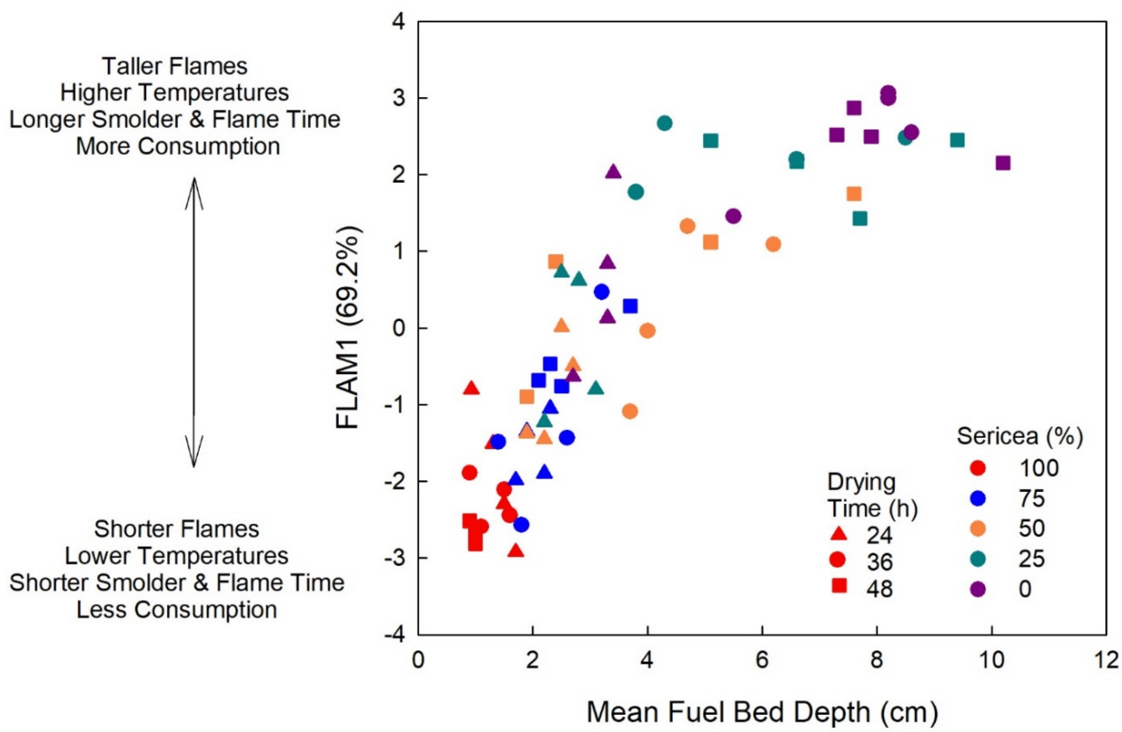

Taller Flames
Higher Temperatures
Longer Smolder & Flame Time
More Consumption
Shorter Flames
Lower Temperatures
Shorter Smolder & Flame Time
Less Consumption
FLAM1 (69.2%)
Mean Fuel Bed Depth (cm)
Drying Time (h)
24
36
48
Sericea (%)
100
75
50
25
0
4
3
2
1
0
-1
-2
-3
-4
0
2
4
6
8
10
12

Fig. 1-5. Average maximum temperature at EMC for fuel load (20 g, 35 g, 50 g, 65 g, and 80 g) and species (sericea lespedeza and native grasses) in relation to measured height above the fuel bed (0 cm, 10 cm, 20 cm, 30 cm, 50 cm, 75 cm, and 100 cm).

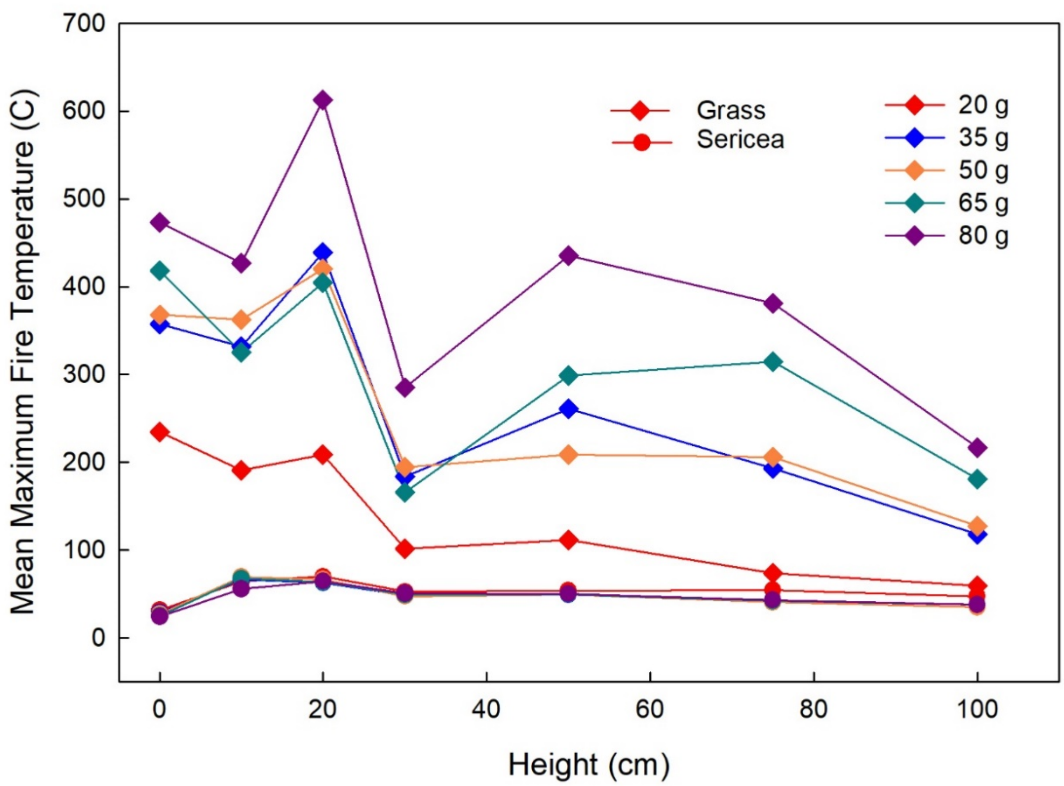
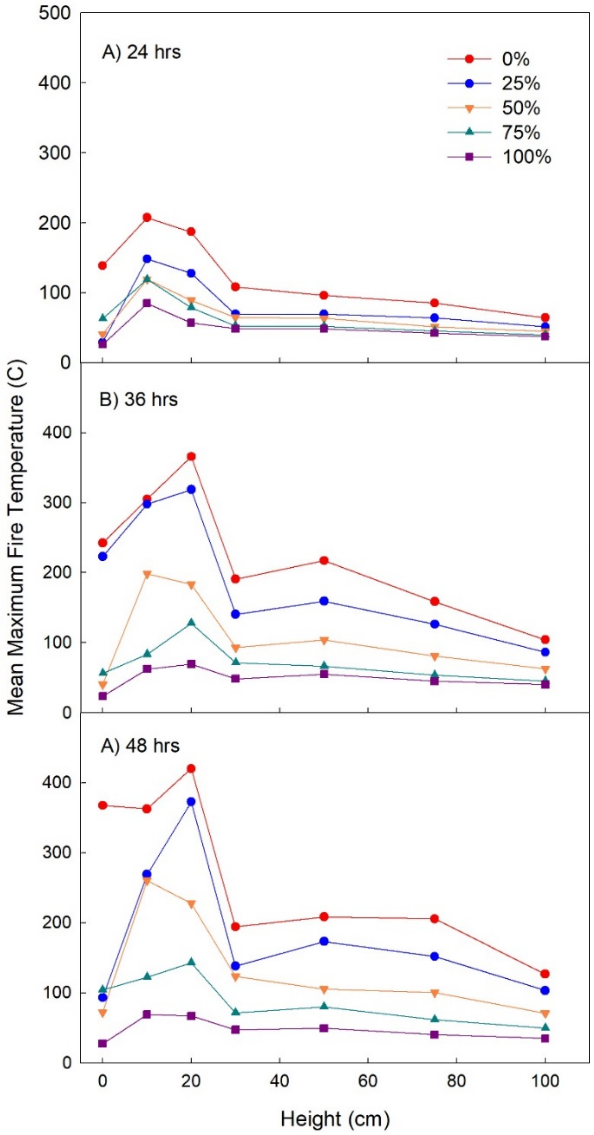

Mean Maximum Fire Temperature (C)
700
600
500
400
300
200
100
0
0
20
40
60
80
100
Height (cm)
Grass
Sericea
20 g
35 g
50 g
65 g
80 g

Fig. 1-6. Average max temperature at drying times (24 h, 36 h, and EMC) and varying proportions of sericea (0%, 25%, 50%, 75%, and 100%) at measured heights above the fuel bed (0 cm, 10 cm, 20 cm, 30 cm, 50 cm, 75 cm, and 100 cm).


A) 24 hrs
0%
25%
50%
75%
100%
B) 36 hrs
A) 48 hrs
Mean Maximum Fire Temperature (C)
Height (cm)
0
100
200
300
400
500
0
20
40
60
80
100

CHAPTER 2

Management Techniques for *Lespedeza cuneata*: The Devil's Lettuce

Introduction

Non-native plant species cause ecological and environmental damage to ecosystems as they become naturalized (Cronk and Fuller 1995; Vitousek et al. 1997). Ecosystems decline in biodiversity as a result of species loss and change caused by non-native plants (Salles and Mallon 2014). The introduction of invasive plant species can negatively impact the environment as well as industries dependent on agriculture, forests, fisheries, and land owners (Pimental 2000; Houlahan and Findlay 2004). Non-native plant species damage the US economy each year from reductions in agricultural yields amounting to $27 billion (Pimental 2009; Barbier et al. 2013). Management is difficult because invasive plant species can reduce disturbances (e.g. grazing, prescribed burns, etc.) through increased plant densities, high propagule pressure, or allelopathic compounds (Chapin et al. 2000; Brooks et al. 2004; Clavero and Garcia-Berthou 2005; Nowacki and Abrams 2008).

The tallgrass prairie was once one-third of the Great Plains. Europeans arrived in the tallgrass prairie by the 1600s, but conversion from tallgrass prairie to agricultural use has recently come to pass in the last 100 years. Less than 4% of the original 70 million ha of the Great Plains is intact and undisturbed today, and approximately 30% is fragmented throughout the Flint Hills of Eastern Kansas (Samson and Knopf 1994). Fragmentation causes a loss of species richness and vulnerability to invasive species infestation as a result of fire suppression, removal of large ungulates, and urban development (Hobbs and

Heunnek 1992). Common invasive species in the tallgrass prairie are: smooth brome (*Bromus inermis*) Leyss, Johnson grass (*Sorghum halepense*) [Linnaeus] Persoon, bull thistle (*Cirsium vulgare*) [Savi] Tenore, and sericea lespedeza (*Lespedeza cuneata*) [Dum. Cours.] G. Don.

In Kansas, sericea lespedeza is considered a noxious weed (Eddy et al. 2003). Sericea lespedeza produces five-times more seeds than native plants, rapidly colonize areas, and remain viable for many years (Ohlenbusch et al. 2001; Woods et al. 2009). The Kansas Department of Agriculture determined that over 250,900 ha in Kansas and 8,090 ha in the Flint Hills were infested with sericea lespedeza in 2009 (Kansas Department of Agriculture 2014). Avoidance to disturbances like grazing increases productivity, seed dispersal, and density of sericea lespedeza and leads to a homogeneic landscape. Management of sericea lespedeza has mixed results and the solution to treat it is unknown, however, there are management techniques to reduce the range of sericea lespedeza.

Management techniques for sericea lespedeza include herbicide applications, grazing/mowing, and prescribed burns. Herbicide applications can be expensive, prohibitive, and ineffective if not targeted correctly. Silliman and Maccarone (2005) estimated costs for treating sericea lespedeza ranged from $0.15-$40.45 per ha for sparse to dense stands of sericea lespedeza. Traditional grazing with cattle (*Bos taurus*), is ineffective due to the unpalatability of sericea lespedeza (Clarke et al. 1939). Sericea lespedeza is highly nutritious and palatable early in its growth; however as the plant matures grazers avoid the plant due to an increase in condensed tannins (Donnelly 1954). Annual prescribed burns are used to target sericea lespedeza and commonly conducted in the spring by land managers (Towne and Owensby 1984; Parmenter 2008; Towne and Kemp 2008).

Annual spring burns have not been successful at reducing the distribution of sericea lespedeza. Annual prescribed burns target the dormant life cycle are ineffective at treating sericea lespedeza (Wong et al. 2012). The timing of spring burns is also inconsequential for sericea lespedeza seeds that have been incorporated into the soil seed bank, well insulated from fire. Sericea lespedeza seed mortality occurs at 250°C for a 2 minute exposure (Bell 2012). However, annual spring burns are unlikely to reach this temperature for a duration long enough to cause mortality because they occur as high frequency, low intensity burns (Young 2000).

Current land owners do not regularly burn in the fall due to misconceptions (Engle and Bidwell 2001) regarding increased erosion and decreased herbaceous production and growth (Anderson 1965; McMurphy and Anderson 1965; Towne and Owensby 1984; Mitchell et al. 1996; Engle et al. 1998; DiTomaso et al. 2006). However, contradicting studies have shown that summer and fall burns do not increase erosion rates and increase vegetative growth the following year (Towne and Owensby 1984; Engle and Bidwell 2001; Towne and Kemp 2003; Towne and Craine 2014). Prescribed burns in the fall have the potential to target different life stages of sericea lespedeza. These fall burns can potentially decrease sericea lespedeza growth, seed production, productivity, and reproduction, in conjunction with secondary treatments (mowing/grazing and herbicide applications; Bell 2009; Lingenfelter 2016).

To better understand how seasonal variation of prescribed burns impact sericea lespedeza in tallgrass prairie, we conducted our experimental burns at Marais des Cygnes

National Wildlife Refuge (MCNW) in eastern Kansas. We had four major goals for this research: (1) determine if burn season fire metrics have a negative influence on sericea lespedeza characteristics; (2) identify the effect of secondary treatments such as grass height, litter depth, grass standing biomass, fuel load, and fuel moisture on fire metrics and their influence on sericea lespedeza characteristics; (3) determine the effect of burn season in conjunction with secondary management treatments fire metrics influence on sericea lespedeza characteristics; and (4) determine how fire metrics affect fire intensities.

Materials and Methods

Study site and Site Setup

The study site is located at Marais des Cygnes National Wildlife Refuge managed by the U.S. Fish and Wildlife Service near, Pleasanton, Kansas, USA. The site is a typical prairie restoration planted with native tallgrass species approximately 25 years ago with a widespread sericea lespedeza infestation. The four most common grasses in tallgrass prairie are: switchgrass (Panicum virgatum L.; Vogel et al. 2011), indiangrass (Sorghastrum nuans [L.] Nash; Moser and Vogel 1995), big bluestem (Andropogon gerardii Vitman; Moser and Vogel 1995), and little bluestem (Schizachyrium scoparium [Michx.] Nash; Pfeiffer and Hartnett 1995), all of which are highly resilient to fire and grazing disturbances. Plots (50 m x 50 m) were randomly assigned treatments of spring annual and fall annual prescribed burns. There were four replicates of each treatment type. Fall annual treatments were burned each October, and spring annual treatments were burned every March-April. Each subplot (25 m x 25 m) was randomly assigned as either a mow, litter addition (as a fuel supplement), herbicide, or burn only treatment. A single prescribed burn was conducted across the entire site during spring 2014 to set the site to a uniform state. Prescribed burns were conducted from fall 2014-spring 2017. However, due to incomplete data collection the first year, data was analyzed from fall 2015-spring 2017.

Herbicide applications (n=8) were of Dow Remedy® EC (3,5,6-trichloro-2-pyridinyloxyacetic acid) applied by ATV using a broadcast sprayer in June. Herbicides were prepared and applied at the manufacturer's suggested rate. Mowing treatments (n=8) were applied in early July with a tractor and double deck mower. Clipped biomass remained after mowed treatments because sericea lespedeza densities were high enough that biomass could not be hayed, or grazed. Litter addition treatments (n=8) were applied 1-3 weeks prior to prescribed burns to allow hay to settle before prescribed burns. Litter was obtained from a round bale of hay, with half of the bale being spread by hand across the 25 m x 25 m subplot. Litter addition was applied at a rate approximately twice the productivity level for grasslands. The burn only subplots (n=8) did not receive secondary treatments. Treatments were applied annually from summer 2015-summer 2017.

Fuel Load and Fire Characteristics

Pyrometer poles were used to evaluate temperature profiles and seed viability. The poles were 3 m high with pyrometer plates set at 50 cm intervals from 0 cm-300 cm. Four pyrometer poles with pyrometer plates were set in the interior of the subplot approximately 5 m adjacent to the four corners. Pyrometer poles were used to hold pyrometer plates and seed viability pouches. The pyrometer plates had temperature sensitive paint ranging from 232°C-510°C, consisting of 13 different temperature categories. Temperature sensitive paint used was Tempilaq® Temperature Sensitive Paint

(LA-CO Industries Incorporated, Elk Grove Village, Illinois, USA). Paint drops on the plate were approximately 0.5 cm^2 in diameter. When fire temperature hit the threshold for each temperature sensitive paint, it changed to a darker color.

Fuel load, fuel moisture, and vegetation heights, were collected prior to the prescribed burn. Fuel load and fuel moisture was measured 4 times in each subplot. Fuel load was collected once upwind and to the side of each pole, 0.5 m behind the pole so fire temperature was not affected by the missing fuel load. Fuel load was placed into a paper bag then enclosed in a plastic bag to determine fuel load and moisture. Fuel load was measured by collecting all fuel within a 0.1 m^2 quadrat. Fuel load was the weight of the fuel after dying at 70°C for 24-48 h minus the dry weight. Fuel moisture was calculated subtracting the wet weight by the dry weight of the fuel load, dividing it by the dry weight and multiplied by 100 to obtain percent moisture. Vegetation height and litter depth were collected at three points 0.5 m upwind of the pole and averaged for vegetation height at the pole. Vegetation height consisted of either grass or sericea height.

Growing Season Responses to Fire

In August and September, number of stems per crown, sericea lespedeza stem density, and standing biomass of grass and sericea lespedeza at individual markers were collected. We marked five mature sericea lespedeza plants in each subplot and monitored year-to-year. If mortality occurred, we noted this occurrence and we selected the next closest plant available. Sericea lespedeza stem density was measured using 1 m^2 quadrats with 4 quadrats measured in each subplot. Each stem inside the 1 m^2 quadrat was counted. Standing biomass samples were collected near the end of the growing season (late August), and standing biomass was estimated by clipping all biomass at 4 locations in each subplot using a 0.25 m^2 quadrat (Sala and Austin 2000). Samples were sorted into grass, forbs, and sericea lespedeza categories and dried at 70°C for 48 hours. Forb biomass was not used in the analysis because they contributed less than 10% of the total standing biomass.

Sericea Lespedeza Seed Viability

Sericea lespedeza seeds were collected in October 2008 at a site in Chase County, Kansas, USA. Packs of 30 sericea lespedeza seeds were created by aluminum foil pouches. Seed pouches were enclosing seeds attached on the same hook as pyrometer plates and placed at 0, 50, and 100 cm heights. Seed pouches that fell off the pyrometer poles were discarded due to uncertainty if they fell during or after the fire passed. After the fire treatment, the seeds were returned to the lab and had the husks removed and seed coat punctured. The seeds were placed in water for 24 h to imbibe, covered with Tetrazolium (2,3,5 Triphenyltetrazolium Chloride) and placed an incubator at 30°C for 24 h. Seeds were then evaluated under a microscope to determine viability. If the seed turned pink/red, the seed was viable; if there was no color change, the seed was deemed not viable.

Statistical Analyses

Dependent variables of fuel load, fuel moisture, litter depth, sericea height, grass height, sericea lespedeza percent seed viability at 0 and 50 cm, percent moisture, number of sericea lespedeza stems per crown, grass productivity, and sericea lespedeza productivity were analyzed by ANOVA (Analysis of Variance) to determine the effects of the independent variables of burn season and secondary treatments. Differences between groups were considered significant at α=0.05. A Levene's Test and Shaprio-Wilk's Test were used to test homogeneity of variance and normal distribution. Tukey's post-hoc test was conducted to test differences among main effects.

Our fire metrics were analyzed by PCA (Principal Component Analysis) and PERMANOVA (Permutational Multivariate Analysis of Variance). We conducted a PCA to reduce the dimensionality of the observed dependent variables. The variables included in the PCA were grass height, litter depth, fuel load, percent moisture, and standing biomass of grass. The independent variables were burn season and secondary treatments. Principal component analysis were compared with standardized values (mean=0, standard deviation=1) for each of the fire metric variables. We only considered axes that resulted in >35% of the cumulative variation explained. Principal factors extraction with were used in analysis of burn season, burn frequency, and secondary treatments, independently. Factor scores were compared using PERMANOVA to test for main effects and interactions followed by Tukey post-hoc test with significance at α=0.05. All analysis were conducted using R v 3.5.2 (Vienna, Austria).

Results

Litter Depth and Grass Height

Fall prescribed burns had a trend for increased litter depth compared to spring prescribed burns (P=0.0582; Fig. 2-1B). However, mowed treatments in spring prescribed burns were higher than fall prescribed burns by 38%. Grass height (P=0.436; Fig. 2-2B) did not differ between fall and spring prescribed burns. Fall prescribed burns were conducted at the end of the growing season and had significantly higher litter depth and grass height. Herbicide treatments had a direct, positive, impact on grass heights by reducing sericea lespedeza in competition for grasses. Grass height increases as sericea lespedeza height decreases in fall prescribed burns in conjunction with mowed, litter addition, and burn only treatments. In contrast when burning in spring, sericea lespedeza is taller and leads to shorter grass height when either mowed when burning in spring, or burned only treatments.

Fuel Load and Fuel Moisture Content

Fire season and secondary treatments impacted fuel load and also had a significant interaction on fuel load (P<0.001; Fig. 2-1C). Fuel load was 69% higher in fall prescribed burns compared to spring burns. Fuel load was significantly lower in mow treatments and significantly higher in litter addition treatments. Fuel load is higher during fall prescribed burns because decomposition of litter has not occurred.

Fuel moisture content was higher during fall prescribed burns than spring prescribed burns (P<0.001), and higher in mowed treatments compared to the other secondary treatments (P<0.001; Fig. 2-1A). During the growing season, plant matter has more moisture compared senesced plant matter in spring (Jolly et al. 2014). Spring prescribed burns were conducted at the end of the dormant period, resulting in lower fuel moisture content. Plants that have higher moisture content do not burn as well as plants with lower moisture when comparing senesced and living plant matter (Montgomery and Cheo 1969). Fuel load increased 4-8x, and fuel moisture content increased 4-7x in fall prescribed burns with secondary treatments compared to spring prescribed burns with secondary treatments. The higher fuel load and fuel moisture content relationship shows fall prescribed burns have higher fuel loads and increased fuel moisture.

Grass Standing Biomass

Grass standing biomass was significantly different between secondary treatments (P<0.001; Fig. 2-3B), but not between fire seasons (P=9.990), nor was there an interaction between secondary treatments and fire season (P=0.603). As expected, herbicide treatments had significantly more grass standing biomass compared to all other secondary treatments and fire season (P=*0*.001). However, mowed, litter additions, and burn only treatments did not differ between one another and fire season.

Fire Loading Effects on Seasonality and Secondary Management Treatments

Flammability metrics varied across fire loadings for each fire season and secondary treatment. Correlations between flammability metrics were apparent and supported combining metrics. The strongest correlation was between fuel load and percent moisture (r=0.680). Combining correlated flammability metrics using principal component analysis (PCA) resulted in two factors: Flam1, which explained 36.26% of the variance, and Flam2, which explained 28.65% of the variance. Eigenvalues for Flam1 and Flam2 were 1.3466 and 1.1969, respectively. However, we only considered axes that resulted in >35% of the cumulative variation explained. Fire loadings in Flam1 scores with negative values show an increase in litter depth, grass height, and grass standing biomass. Fire loadings in Flam1 scores with positive values show an increase in fuel load and percent moisture.

Results from our Permutational Multivariate Analysis of Variance (PERMANOVA) showed significant differences for fire season (P<0.001; Fig. 4), secondary treatments (P<0.001; Fig. 5), and their interaction between fire season and secondary treatments (*P*=0.026). Fall and spring prescribed burns had significantly different fire metrics. The PERMANOVA also showed fall prescribed burns have significantly higher percent moisture and fuel loads compared to spring prescribed burns, whereas, spring prescribed burns have significantly higher grass height, litter depth, and grass standing biomass (Fig. 4). Fall burns have higher fuel loads, however, fuel moisture was also higher resulting in reduced fire intensity. Herbicide applications had significantly different fire metrics from mowed, litter additions, and burn only treatments. Herbicide applications have significantly higher grass height, litter depth, and grass standing biomass. Alternatively, mowed, litter additions, and burn only treatments have significantly higher fuel loads and percent moisture.

Sericea Lespedeza Height

Sericea lespedeza height was not influenced by fire season (*P*=0.502) but was influenced by secondary treatments (*P*<0.001). No interaction between fire season and the secondary treatments on sericea lespedeza height existed (*P*=0.838; Fig. 2-2A). Prescribed burns conducted at the end of the growing season in fall resulted in fire season effects in height. Sericea lespedeza height decreases when mowing and herbicide treatments are applied. Sericea lespedeza heights were the lowest in herbicide treatments and highest in litter additions, regardless of fire season.

Sericea Lespedeza Standing Biomass

Sericea lespedeza standing biomass was significantly different in secondary treatments (*P*<0.001). Conversely, there were no difference between fire seasons (*P*=0.982) and the interaction of fire season and secondary treatments (*P*=0.528; Fig. 2-

3A). Sericea lespedeza standing biomass was higher in fire season and burn only and litter additions compared to fire season and herbicide and mowed treatments (*P*<0.001). Sericea lespedeza standing biomass did not differ between litter addition and burn only treatments (*P*=0.170) or mowed and herbicide treatments (*P*=0.942). All other treatments were significantly different from each other (*P*<0.001). As expected, mowed and herbicide applications had significantly lower sericea lespedeza standing biomass compared to burn only and litter additions regardless of burn season, but mowed and herbicide applications did not differ between each other for either burn season. Sericea lespedeza standing biomass also did not differ between burn only and litter addition treatments regardless of burn season.

Sericea Lespedeza Seed Mortality

Sericea lespedeza seed mortality at 0 cm was significantly impacted by burn season (*P*=0.016), secondary treatments (*P*<0.001), and their interaction (*P*=0.046; Fig. 2-6A). Seed mortality, at ground level, significantly increased by fall fire compared to spring prescribed burns. Mowed and burn only treatments burned in fall had approximately 2.5-3x lower sericea lespedeza seed mortality compared to spring prescribed burns. Spring burn only and mowed treatments increased for seed mortality as a result of vegetation height lower than all over treatments. Litter additions significantly increased sericea lespedeza seed mortality compared to other secondary treatments. Sericea lespedeza seed mortality was significantly higher for fall litter additions compared to other treatments, at ground level. Litter additions increased sericea lespedeza seed mortality compared to other secondary treatments, but fall litter additions increased sericea lespedeza mortality more than all other fire season and secondary treatments.

Although sericea lespedeza seed mortality at 50 cm was not impacted by fire season, it was affected by significantly higher mortality in secondary treatments ($P<0.001$) and the interaction between fire season and secondary treatments ($P<0.001$; Fig. 2-6B). Sericea lespedeza seed mortality decreased approximately 2.5x in fall mowed treatments compared to spring mowed treatments. Sericea lespedeza seed mortality at 0 cm and 50 cm decreased approximately 2.5x for fall mowed treatments as a result of lower vegetation height.

Fire Loading Effects on Sericea Lespedeza

Differences in fire season were apparent when fire metrics (Flam1) were compared to sericea lespedeza characteristics consisting of sericea lespedeza height (Fig. 2-7), stems per crown (Fig. 2-8), and standing biomass (Fig. 2-9). Spring prescribed burns consistently loaded on the negative y-axis and fall prescribed burns consistently loaded positively on the y-axis. This shows that regardless of sericea lespedeza characteristic evaluated, sericea lespedeza has a significant relationship with fall prescribed burns. Sericea lespedeza characteristics have a positive relationship with spring prescribed burns, however, it is not as strong as fall prescribed burns.

Differences in secondary treatments were also apparent when fire metrics (Flam1) were compared to sericea lespedeza characteristics consisting of sericea lespedeza height, stems per crown, and standing biomass. Unsurprisingly, herbicide applications were the most successful at decreasing sericea lespedeza height, stems per crown, and biomass in relation to fire metrics. Burn only and litter additions loaded similar when compared to fire metrics and sericea lespedeza characteristics. Burn only and litter additions were subjectively the least successful at reducing sericea lespedeza height, stems per crown, and standing biomass; however, litter additions in conjunction with fall fire were able to effectively reduce the number of sericea lespedeza stems per crown nearly as effective as herbicide treatments.

Maximum Fire Temperature

Maximum fire temperatures were higher in spring prescribed burns compared to fall prescribed burns at heights of 50 cm and 100 cm. Maximum fire temperatures did not have significant differences for season at 0 cm (P=0.136; Fig. 2-10A); however, burning in spring resulted in significantly higher maximum fire temperatures at 50 cm (P=0.008; Fig. 2-10B) and 100 cm (P=0.008; Fig. 2-10C) heights compared to fall burning. Maximum fire temperatures during spring burns independently and in combination with litter addition and herbicide applications were higher at all measured heights (P<0.001) compared to fall burns. Significantly higher maximum fire temperatures during spring prescribed burns at 50 cm and 100 cm is related to lower fuel moisture compared to fall fuels (P<0.001). However, mowed treatment maximum fire temperatures were 18% higher at ground level in fall prescribed burns compared to spring mowed treatments. Clippings from summer mowing treatments increased dry fuel loads leading to higher maximum fall temperatures. Conversely, mowed fuel loads during spring prescribed burns were not as abundant as fall prescribed burns as a result of over winter decomposition that resulted in lower maximum fire temperatures in mowing treatments.

Mowed treatments resulted in higher fuel moisture content during fall burns compared to the spring burns ($P<0.001$).

Fire Loading Effects and Fire Intensity

Fire metrics loaded negatively on the x-axis had higher temperatures compared to positively loaded fire metrics for temperature intensity measured at 50 cm (Fig. 2-11). Data for fire metrics and maximum fire temperature are not shown for 0 cm and 100 cm heights because the same patterns are seen at all heights. Spring prescribed burns with secondary treatments consistently loaded on the negative x-axis towards fire metrics of increased grass height, litter depth, and grass standing biomass. Fall prescribed burns with secondary treatments had a negative relationship with temperature and fire metrics and loaded towards fire metrics of increased fuel load and fuel moisture. Intense prescribed burns loaded on the negative x-axis and had a negative relationship as fire metrics loaded towards a positive trend on the x-axis. The exceptions with this trend were fall prescribed burns with burn only and mowed treatments. Temperature intensity had a positive relationship with temperature as fire metrics increased on the x-axis.

Discussion

Combining fire season with a secondary management treatment of mow, herbicide applications, or litter additions may be useful management tool for landowners with an infestation of sericea lespedeza. In conjunction with the use of secondary management treatments, altering the fire season from spring to fall may reduce sericea lespedeza, while maintaining native grasses. Current management practices utilize spring prescribed burns to control sericea lespedeza with no success, alternatively, prescribed burns with no secondary treatment help promote sericea lespedeza densities (Ohlenbusch et al. 2001; Stevens 2002; Cummings et al. 2007).

Spring burns result in increased fire metrics due to increased grass height, litter depth, and grass standing biomass. Conversely, fall burns result in increased fire metrics due to increased fuel load and fuel moisture content (Fig. 4). The significant difference between the two seasons is a result of plant living matter. Spring burns are conducted when plants are in dormancy, while fall burns occur prior to dormancy of all vegetation. The increase of fuel moisture content for fall burns reduces fire intensities, but target seeds before they drop from the plant. Fall fires can also impact first year plants because they may not have the resources to survive intense fall fires (Wong et al. 2012).

Herbicide applications increased fire metrics due to increased grass height, litter depth, and grass standing biomass (Fig. 5). However, burn only, litter additions, and mowed treatments resulted in an increase in fire metrics due to increased fuel load and fuel moisture content. Herbicide applications increased grass characteristics as a result of its ability to selectively target sericea lespedeza and not harm grasses and forbs. As a result of herbicide applications, grass standing biomass and densities increase and ultimately increases the probability of a complete burn. However, litter additions, burn only, and mowed treatments do not selectively target sericea lespedeza, and as a result may negatively impact native tallgrass plants. We speculate that sericea lespedeza increases fuel moisture content and fuel load. Sericea lespedeza litter has a high surface area and consequently increases water retention and decreases oxygen availability and inhibits flammability (Barnes 2019).

Prescribed burns in the fall, target sericea lespedeza prior to its dormancy and is lethal to sericea lespedeza seeds produced that year (Wong et al. 2012; Lingenfelter 2016). Spring burns do not successfully control because sericea lespedeza is dormant. Fall burns target living plant matter at intensities that are lethal to plant tissue and exposed sericea lespedeza seeds. Fall litter additions successfully increase rates of sericea lespedeza seed mortality as a result of intense fall prescribed burns. Fall litter addition burns target vulnerable sericea lespedeza seeds before they enter the soil seed bank. Spring burns do not impact sericea lespedeza seeds because the seeds have been incorporated in the soil seed bank and are protected from fast moving grassland fires, regardless of intensity.

Fall fires can reach intensities that are lethal to sericea lespedeza seeds up to 100 cm, but these intense burns did not decrease sericea lespedeza standing biomass (Fig. 2-10; Fig. 2-3A). Sericea lespedeza standing biomass and stem height were significantly higher in fall burns with litter additions; however, stems per crown decreased significantly and fire intensity significantly increased compared to fall herbicide applications, mowed, and burn only treatments. Fall fire with increased fuel loads increased fire intensity causing sericea lespedeza plants to grow taller, but reduced the number of stems per crown. This change in growth may be a stress response to increased fire intensity or its associated effects on winter soil temperature. Fall fires remove the litter layer exposing soil throughout the winter. The exposed soil receives sunlight exposure and other environmental factors that influence soil temperature. Soil temperatures will be lower in the winter compared to spring burns that have a litter layer insulating the soil. Lingenfelter (2016) reported a similar stress response to fall fire with increased fuel loads where sericea lespedeza standing biomass and the ratio of seed mass changed. Litter additions, in the fall, increased sericea lespedeza standing biomass; however, seed mass decreased significantly. Alternatively, litter additions in the spring did not have a significant decrease in sericea lespedeza seed mass to standing biomass ratio. Stress on sericea lespedeza is a result of intense fall burns during the growing season. Sericea lespedeza alters resource allocation from reproduction to survival due to intense fires in the fall with litter additions.

Reproductive allocation is commonly measured as a ratio of seed mass to biomass, with seed production being dependent on plant size, and refers to the proportion of total biomass allocated to reproductive tissues (Bazzaz and Ackerly 1992; Zhou et al. 2015). Reproductive success is inconsequential in regards to sericea lespedeza height and standing biomass. Zhou et al. (2015) state a more accurate estimate of the relative contribution of each individual to the next generation is reproductive rather than vegetative. Ploschuk et al. (2005) confirms that reproductive allocation increases linearly with plant size. The seed mass to plant mass ratio removes the effect of plant size on seed production and shows the relative investment of resources in seed production. In our experiment, fall prescribed burns increased plant height and standing biomass as a result of diverting resources to production of stems. Litter additions increased sericea height in both fire seasons compared to all burn seasons and secondary treatments. However, number of stems per crown decreased significantly in fall litter additions compared to litter additions in spring, burn only and mowed in both fire seasons, and fall herbicide applications.

Long-term effects of fall burns in conjunction with litter additions will negatively affect sericea lespedeza as a result of exhausting resources used for reproduction. Fall prescribed burns in conjunction with late June secondary mow treatments also show great promise to negatively affect sericea lespedeza. Mowed treatments and litter additions with fall burns may not be effective in removing mature sericea lespedeza plants, but they appear to induce stress responses in the plants. I speculate that if we continued the experiment sericea lespedeza height and standing biomass would continue to increase, but number of stems per crown decrease and the ratio of standing biomass and seed mass would be negatively affected. Herbicide applications selectively target sericea lespedeza, but the economic and environmental costs can be very consequential. However, litter additions and mowed treatments are only a partial victory, in regards to sericea lespedeza management.

I suggest using herbicide treatments for sericea lespedeza in the spring, mow/graze in late spring and summer, and fall fire as management tools for land owners. Grass height and grass standing biomass were not negatively impacted by fall prescribed burns, contrary to previous misconceptions. Fall prescribed burns targeted sericea lespedeza plants prior to dormancy and increased stress. Whatever treatments land owners use, prescribed burns must continue in tallgrass prairie ecosystems. Prescribed burns maintain the structural ecosystem of tallgrass prairies. Sericea lespedeza is a prolific seed producer and these seeds can remain viable over twenty years in the soil seed bank. The true test for land owners treating for sericea lespedeza comes to head with two questions. How much time do they have; how much money are you willing to invest?

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Fig. 2-1. Differences in percent moisture (A), litter depth (B), and fuel load (C) for fall and spring prescribed burns in conjunction with secondary treatments. A) There were significant differences between seasonal prescribed burns, secondary treatments and their interaction ($P<0.001$). Fall burn only treatments had significantly more percent moisture than any other treatment, except for fall herbicide applications ($P=0.596$). B) There were significant differences between and secondary treatments ($P<0.001$) and their interaction ($P=0.040$). There was a trend in seasonal differences ($P=0.058$). C) There were significant differences between season, secondary treatments, and their interaction ($P<0.001$).

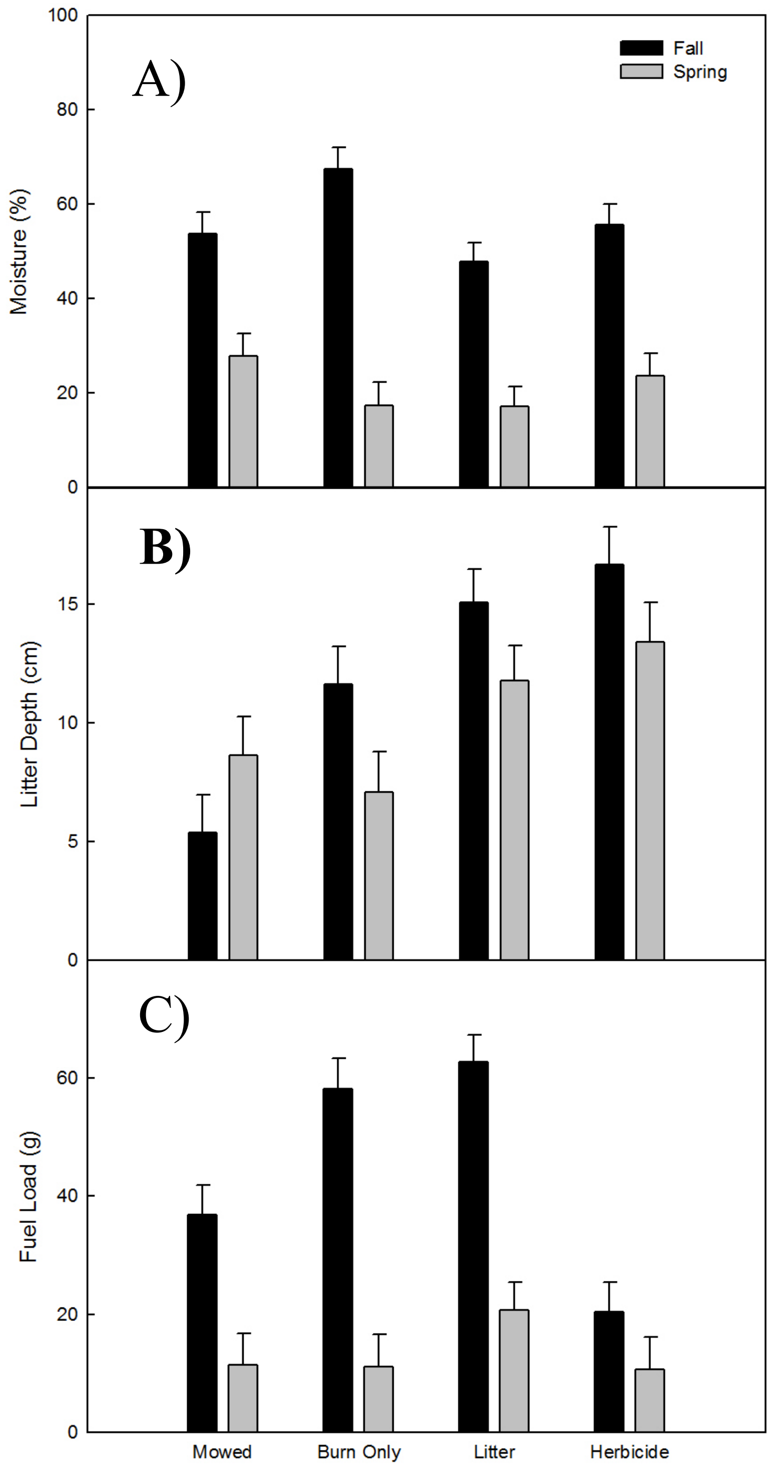

A)
B)
C)
Fall
Spring
Moisture (%)
Litter Depth (cm)
Fuel Load (g)
100
80
60
40
20
0
15
10
5
0
60
40
20
0
Mowed
Burn Only
Litter
Herbicide

Fig. 2-2. Differences in sericea lespedeza height (A) and grass height (B) for fall and spring prescribed burns in conjunction with secondary treatments. A) There were significant differences between and secondary treatments (P<0.001) and their interaction (P=0.036). There was no significant difference in seasonal differences (P=0.436). B) There were significant differences for secondary treatments (P<0.001). There were no significances between season (P=0.502) and the interaction (P=0.838).

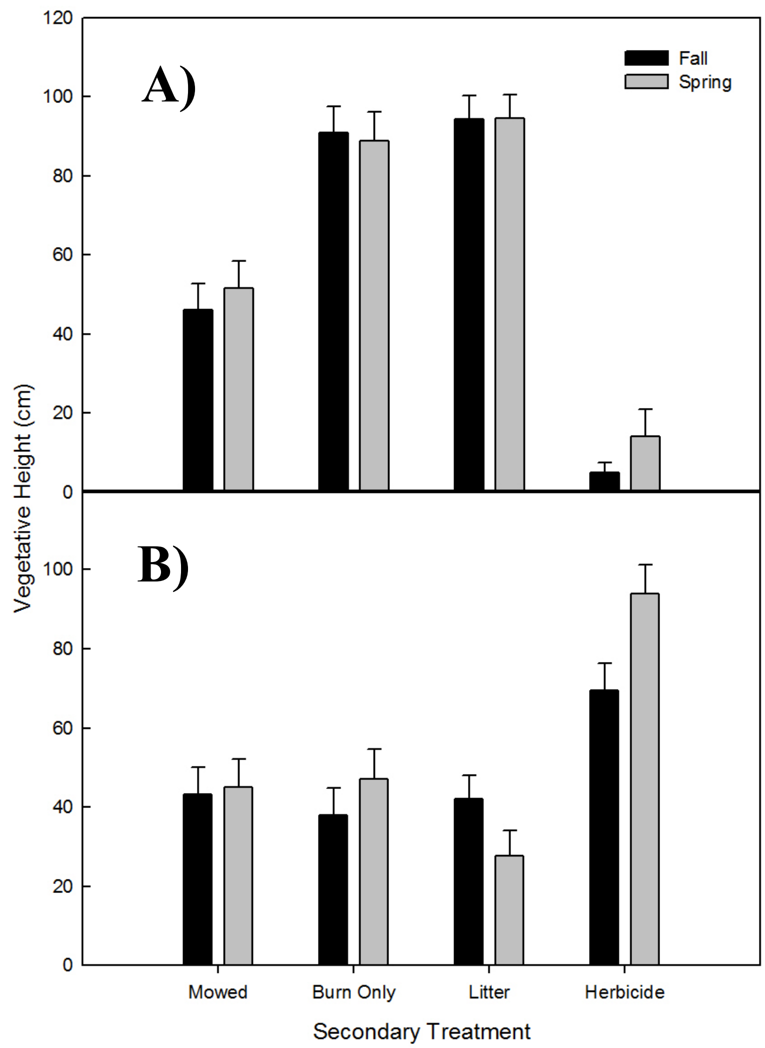

A)
B)
Fall
Spring
Vegetative Height (cm)
120
100
80
60
40
20
0
100
80
60
40
20
0
Mowed
Burn Only
Litter
Herbicide
Secondary Treatment

Fig. 2-3. Differences in grass standing biomass (A) and sericea lespedeza standing biomass (B) for fall and spring prescribed burns in conjunction with secondary treatments. A) There were significant differences between secondary treatments ($P<0.001$). There were no significances between season ($P=0.990$) and the interaction ($P=0.603$). B) There were significant differences between secondary treatments ($P<0.001$). There were no significances between season ($P=0.982$) and the interaction ($P=0.528$).

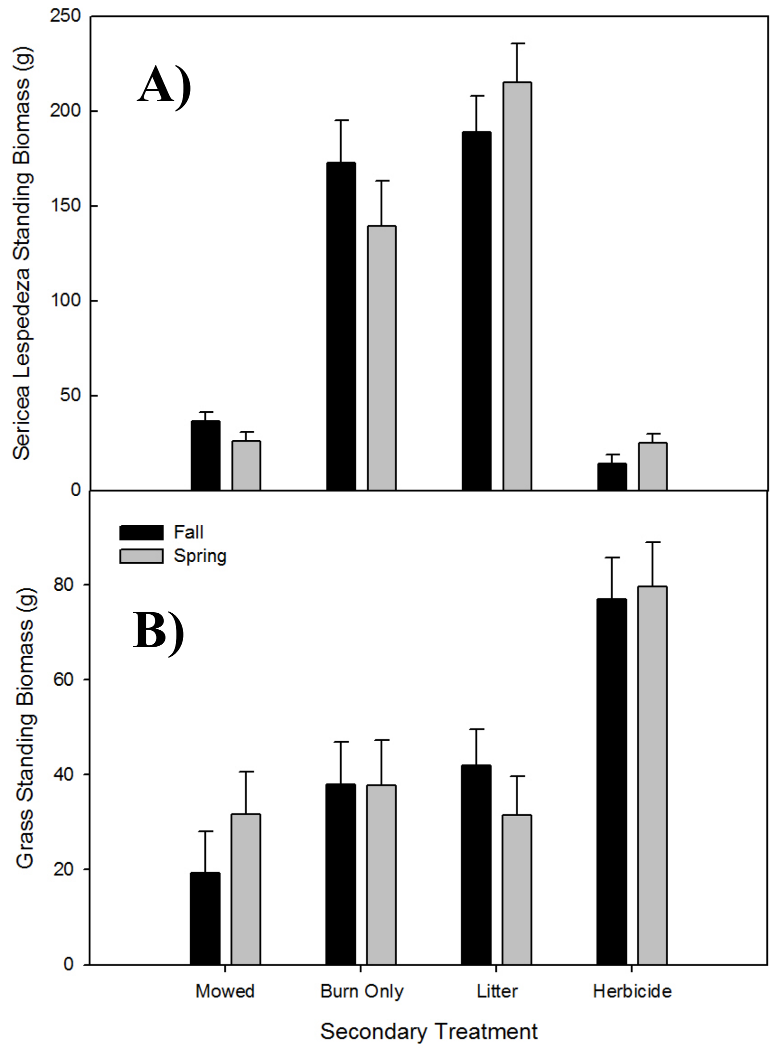
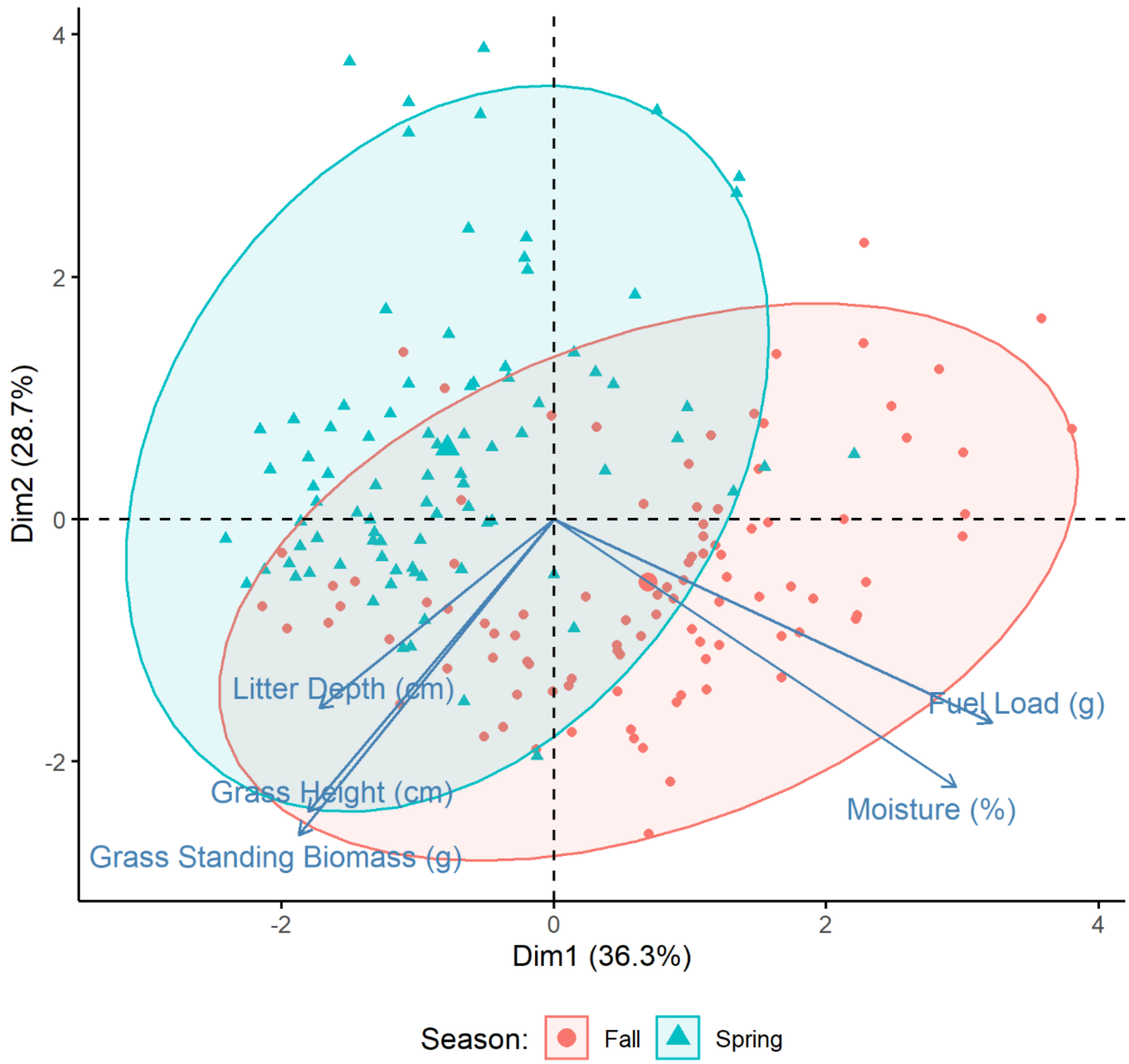

A)
Sericea Lespedeza Standing Biomass (g)
250
200
150
100
50
0
Fall
Spring
B)
Grass Standing Biomass (g)
80
60
40
20
0
Mowed
Burn Only
Litter
Herbicide
Secondary Treatment

Fig. 2-4. Principal component analysis (PCA) of fire metrics. The first two axis (PCA axis 1 and 2) of the PCA explain 65% of the variance. Confidence intervals of 95% show the differences between spring and fall prescribed burns. Dim1 (36.3% of variation) positive values show an increase in fuel load and percent moisture and negative values show an increase in litter depth, grass height, and grass standing biomass. Dim2 (28.7% of variation) negative values show an increase in litter depth, grass height, fuel load, percent moisture, and grass standing biomass. PERMANOVA results show there is a significant difference in fire metrics and fire season ($P<0.001$).



4
2
0
-2
-2
0
2
4
Dim1 (36.3%)
Dim2 (28.7%)
Litter Depth (cm)
Grass Height (cm)
Grass Standing Biomass (g)
Fuel Load (g)
Moisture (%)
Season:
Fall
Spring

Fig. 2-5. Principal component analysis (PCA) of fire metrics. The first two axis (PCA axis 1 and 2) of the PCA explain 65% of the variance. Confidence intervals of 95% show the differences between secondary management treatments. Dim1 (36.3% of variation) positive values show an increase in fuel load and percent moisture and negative values show an increase in litter depth, grass height, and grass standing biomass. Dim2 (28.7% of variation) negative values show an increase in litter depth, grass height, fuel load, percent moisture, and grass standing biomass. PERMANOVA results show there is a significant difference in fire metrics and secondary management treatments ($P<0.001$).

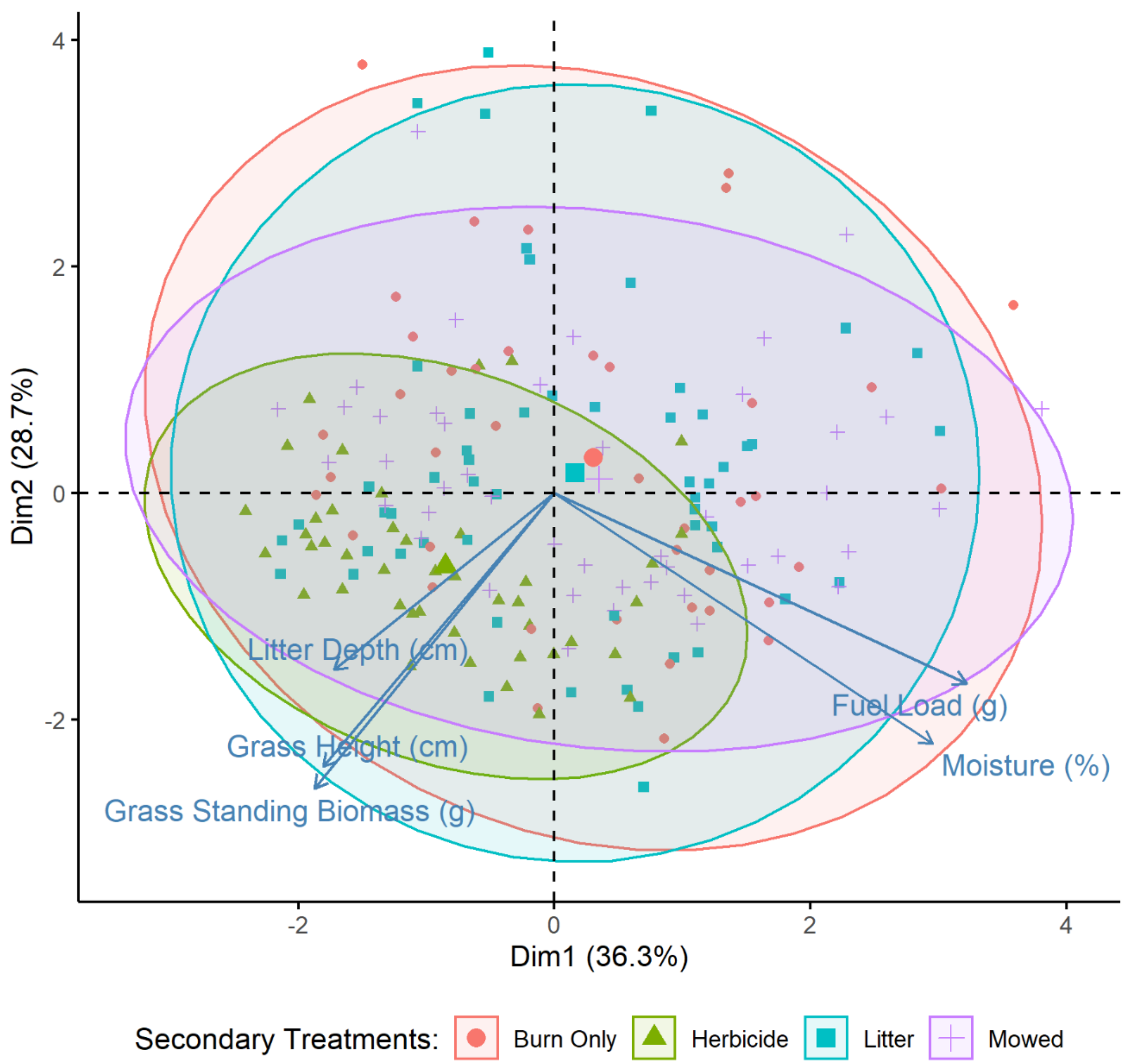
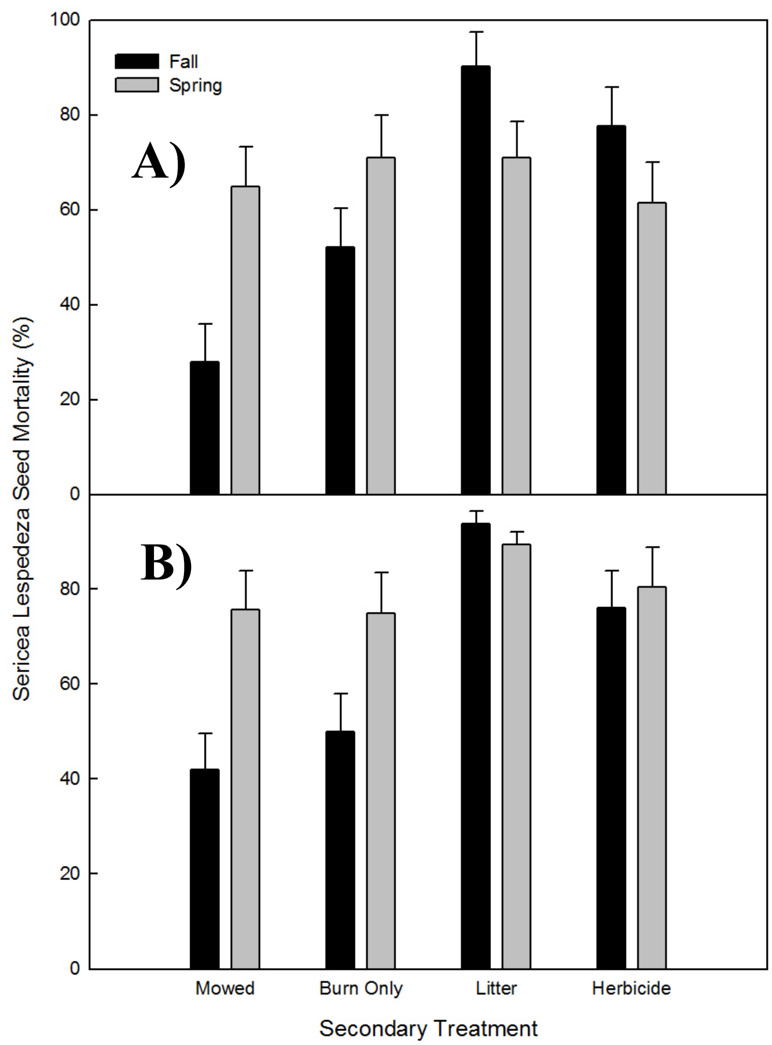

Dim2 (28.7%)
Dim1 (36.3%)
4
2
0
-2
-2
0
2
4
Litter Depth (cm)
Grass Height (cm)
Grass Standing Biomass (g)
Fuel Load (g)
Moisture (%)
Secondary Treatments:
Burn Only
Herbicide
Litter
Mowed

Fig. 2-6. Differences in sericea lespedeza seed mortality at heights of 0 cm (A) and 50 cm (B) for fall and spring prescribed burns in conjunction with secondary treatments. A) There were significant differences between fire season (P=0.016), secondary treatments (P<0.001), and the interaction between fire season and secondary treatments (P=0.046). B) There were significant differences between fire season and the interaction between fire season and secondary treatments (P<0.001). There were no significant differences in secondary treatments (P=0.556).



100
80
60
40
20
0
Fall
Spring
A)
B)
Sericea Lespedeza Seed Mortality (%)
Mowed
Burn Only
Litter
Herbicide
Secondary Treatment

Fig. 2-7. The relationship between fire metrics and sericea lespedeza height. Spring line type and symbols are hashed and triangles. Fall prescribed burns line types are solid lines and symbols are circles. Secondary treatments are denoted by color. Burn only treatments are red, herbicide treatments are blue, litter additions are green, and mowed treatments are purple. Negative loadings on the x-axis have increased grass height, litter depth, and grass standing biomass. Positive loadings on the x-axis have increased fuel moisture and fuel load.

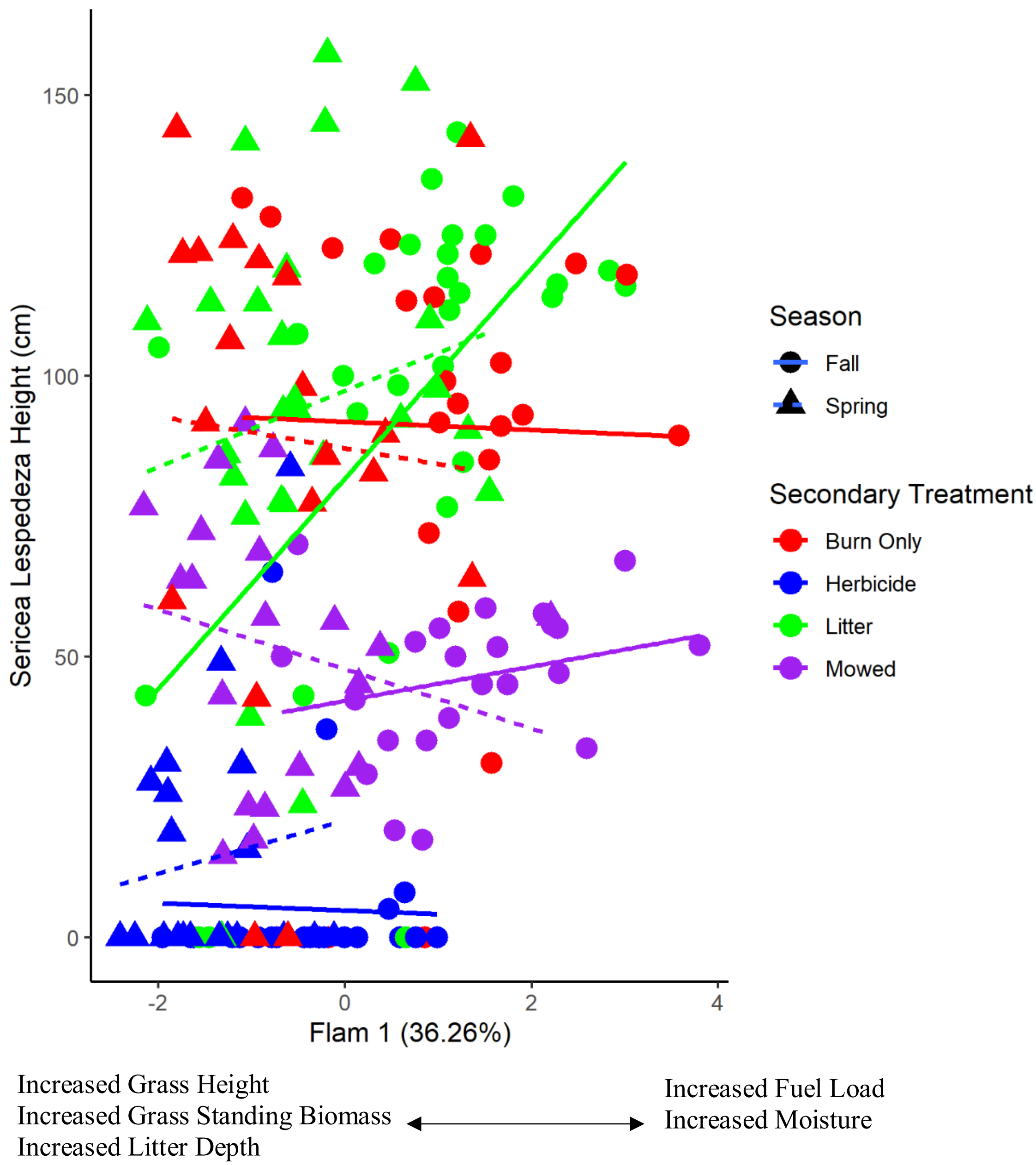
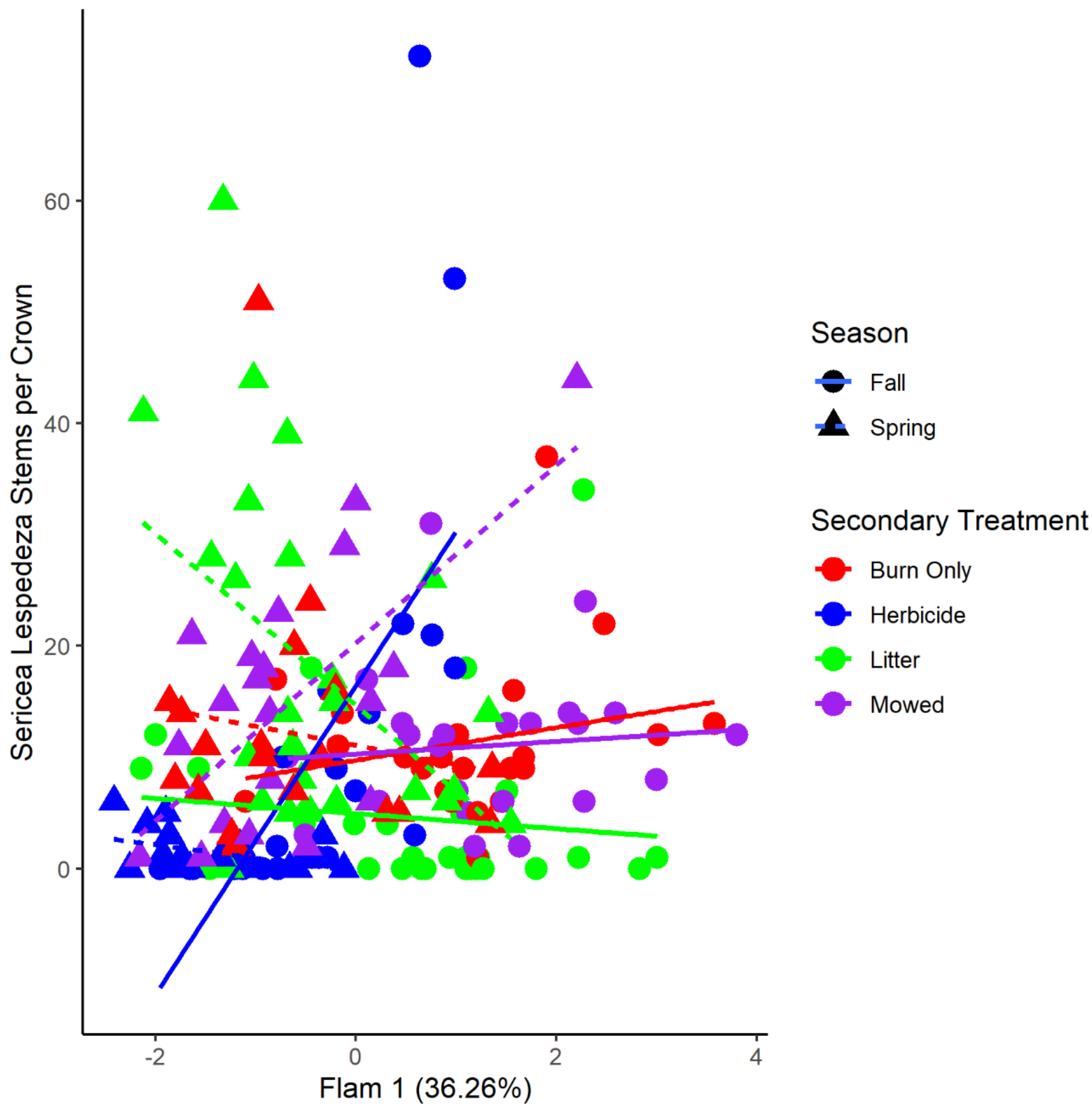

Sericea Lespedeza Height (cm)
150
100
50
0
-2
0
2
4
Flam 1 (36.26%)
Season
Fall
Spring
Secondary Treatment
Burn Only
Herbicide
Litter
Mowed
Increased Grass Height
Increased Grass Standing Biomass
Increased Litter Depth
Increased Fuel Load
Increased Moisture

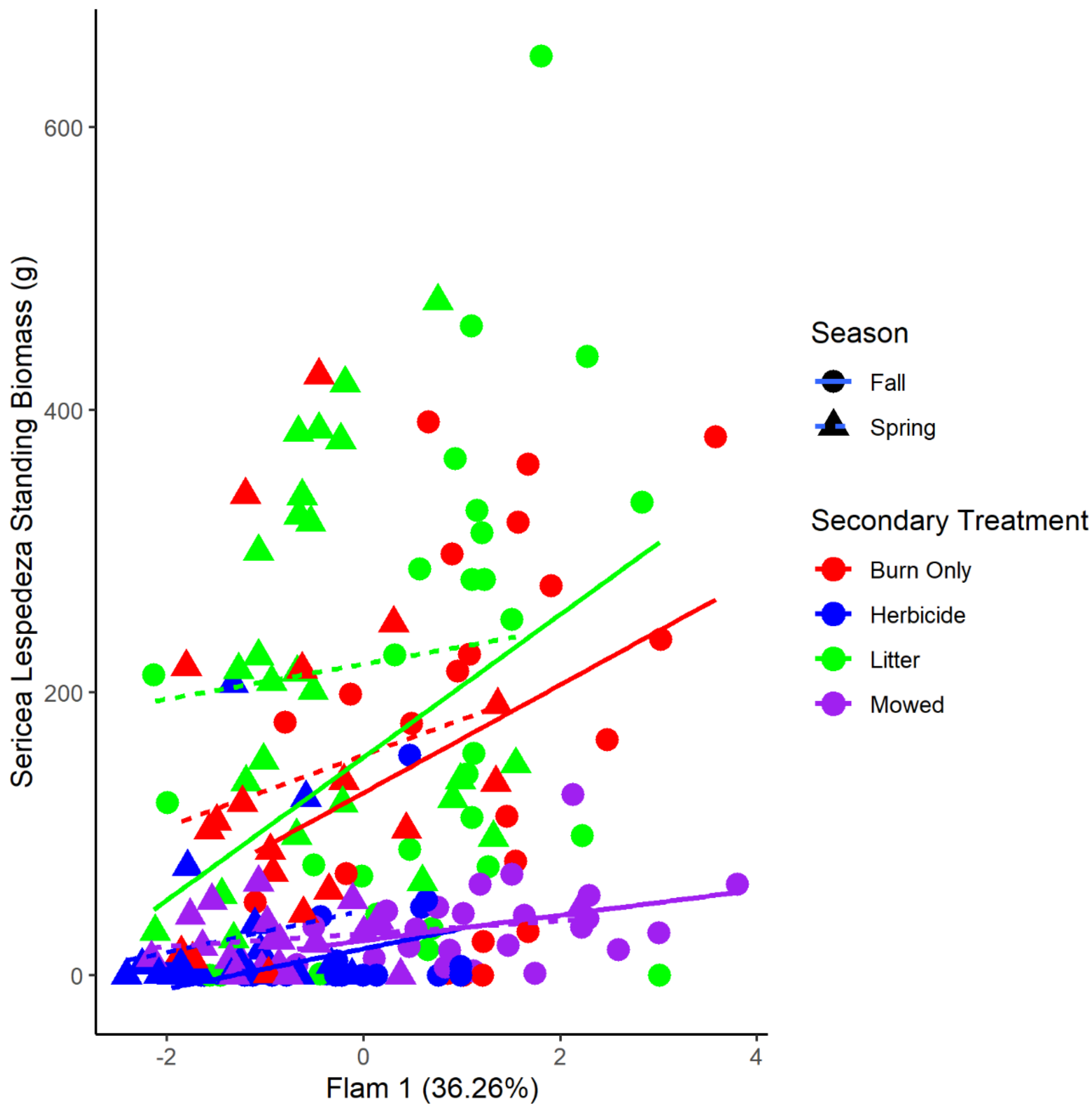
Fig. 2-8. The relationship between fire metrics and sericea lespedeza stems per crown. Spring line type and symbols are hashed and triangles. Fall prescribed burns line types are solid lines and symbols are circles. Secondary treatments are denoted by color. Burn only treatments are red, herbicide treatments are blue, litter additions are green, and mowed treatments are purple. Negative loadings on the x-axis have increased grass height, litter depth, and grass standing biomass. Positive loadings on the x-axis have increased fuel moisture and fuel load.



Increased Grass Height
Increased Grass Standing Biomass
Increased Litter Depth

Increased Fuel Load
Increased Moisture

Fig. 2-9. The relationship between fire metrics and sericea lespedeza standing biomass. Spring line type and symbols are hashed and triangles. Fall prescribed burns line types are solid lines and symbols are circles. Secondary treatments are denoted by color. Burn only treatments are red, herbicide treatments are blue, litter additions are green, and mowed treatments are purple. Negative loadings on the x-axis have increased grass height, litter depth, and grass standing biomass. Positive loadings on the x-axis have increased fuel moisture and fuel load.



Increased Grass Height
Increased Grass Standing Biomass
Increased Litter Depth

Increased Fuel Load
Increased Moisture

Fig. 2-10. Differences in temperature intensities at 100 cm (A), 50 cm (B), and 0 cm (C) for fall and spring prescribed burns in conjunction with secondary treatments. A) There were significant differences between seasonal prescribed burns (*P*=0.008) and secondary treatments (*P*<0.001). There was no significant differences in their interaction (*P*=0.110). B) There were significant differences between seasonal prescribed burns (*P*=0.008) and secondary treatments (*P*=0.002). There were significant differences with their interaction (*P*=0.178). C) There were no significant differences between seasonal prescribed burns (*P*=0.136). There were significant differences between secondary treatments (*P*<0.001) and their interaction (*P*<0.001).

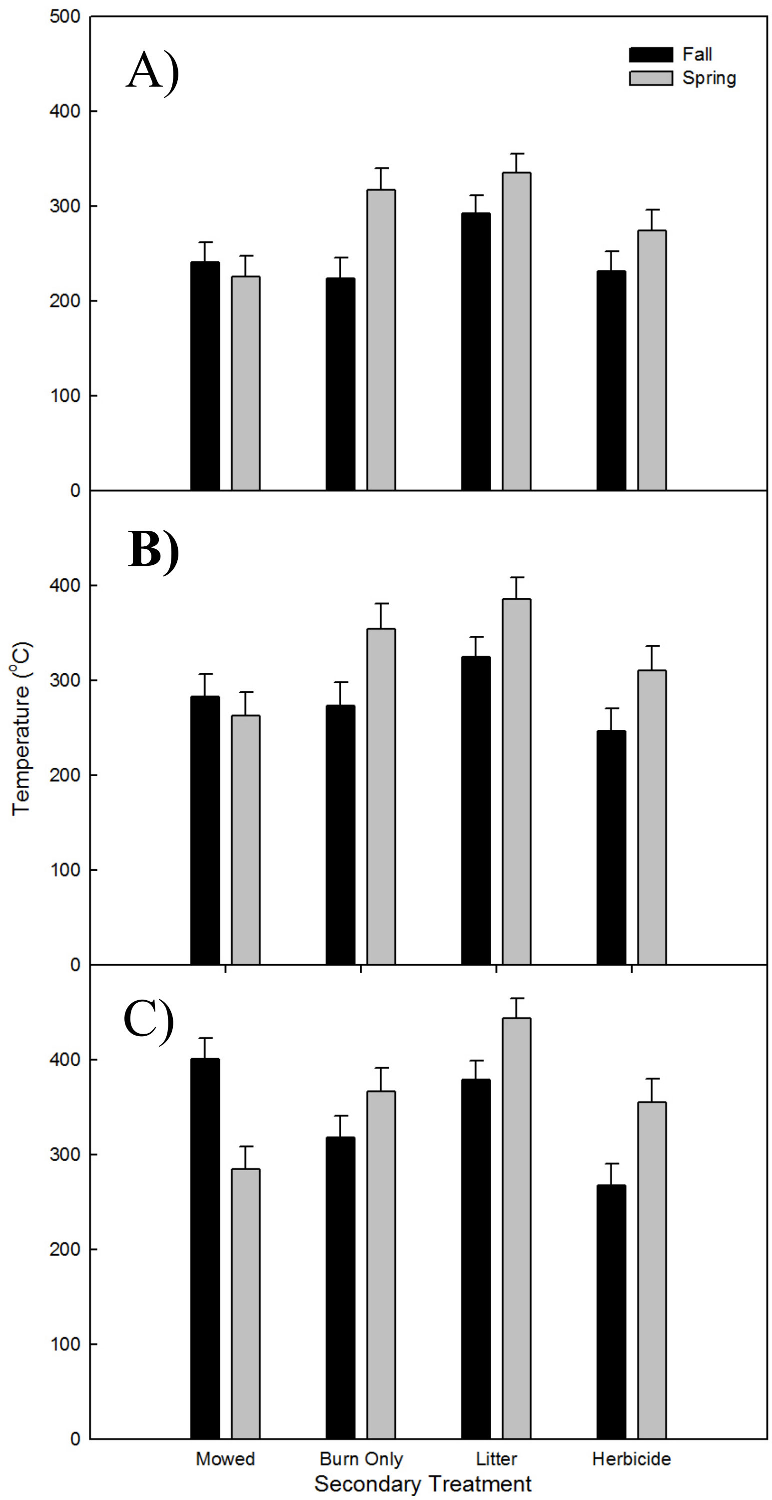
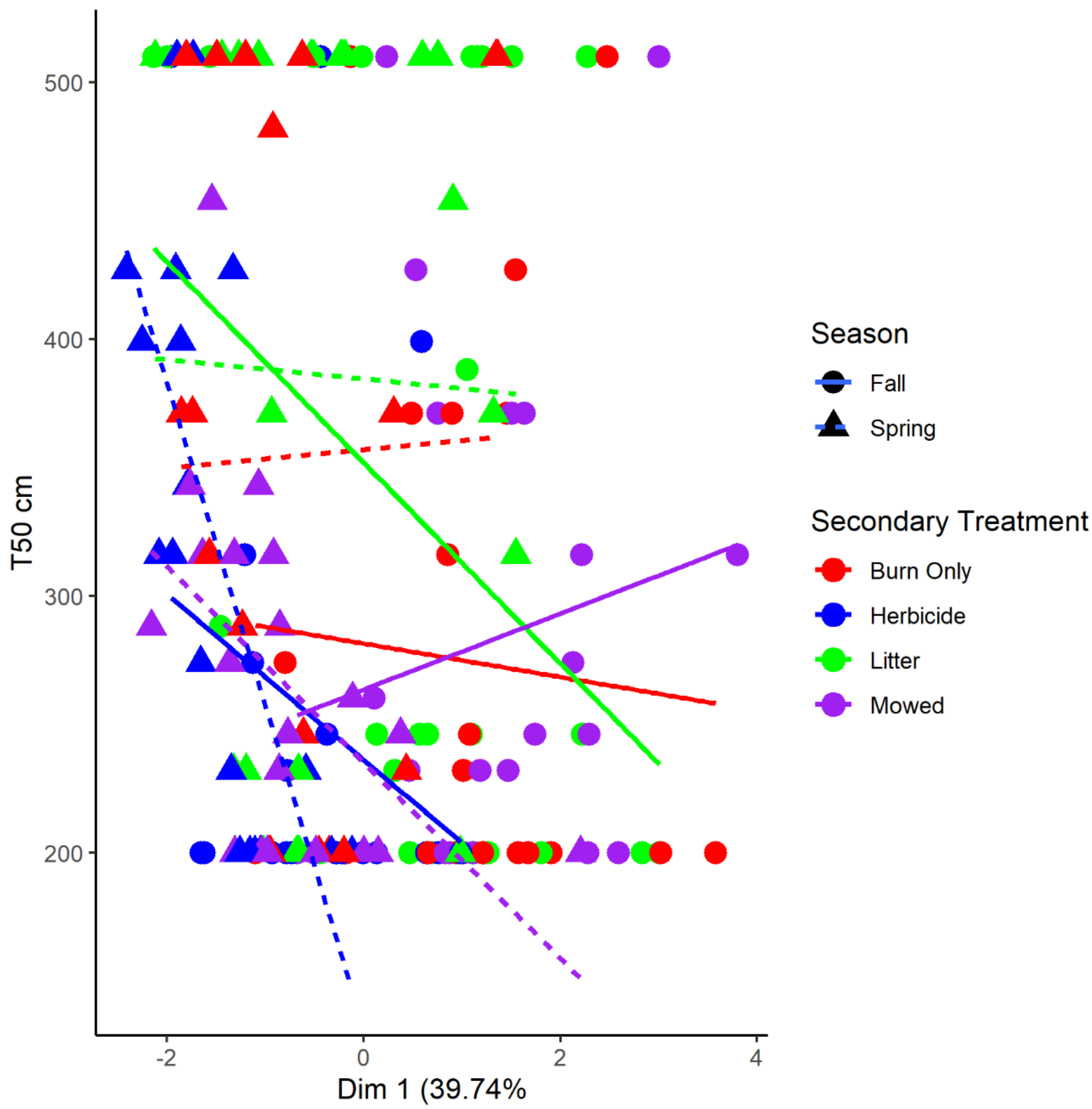

A)
B)
C)
Fall
Spring
Temperature (°C)
Mowed
Burn Only
Litter
Herbicide
Secondary Treatment
0
100
200
300
400
500

Fig. 2-11. The relationship between fire metrics and temperatures at 50 cm. Spring line type and symbols are hashed and triangles. Fall prescribed burns line types are solid lines and symbols are circles. Secondary treatments are denoted by color. Burn only treatments are red, herbicide treatments are blue, litter additions are green, and mowed treatments are purple. Negative loadings on the x-axis have increased grass height, litter depth, and grass standing biomass. Positive loadings on the x-axis have increased fuel moisture and fuel load.



Increased Grass Height
Increased Grass Standing Biomass
Increased Litter Depth

↔

Increased Fuel Load
Increased Moisture

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Signature of the Author

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Date

Lespedeza cuneata: How an invasive legume is altering fire ecology in Tallgrass Prairie

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Title of Thesis

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Signature of Graduate Office Staff

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Date Received