FUEL LOAD AND HEAT EFFECTS ON NORTHERN MIXED PRAIRIE AND FOUR PROMINENT RANGELAND GRAMINOIDS

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ABSTRACT

Plant mortality following fire has been a concern of many people and agencies. There is little information, relating to the direct effect fire has on grass mortality, biomass production, and tillers at the community and individual levels. The objectives of this research were to determine the survival, tiller numbers, and biomass response to fuel load and direct measures of heat of four prominent graminoid species at the individual and community levels. The community level consisted of 24 plots measuring 20 X 20 meters. The plots were burned in autumn 2008 and 2009. Regression analyses were used to assess relationships of fuel load, degree-seconds, duration of heat, and maximum temperature, with relative biomass and frequency of species and species groups. The results illustrated fuel load, degree seconds, and duration were good predictors of total biomass. Threadleaf sedge increased in biomass to pre-treatment measures. Threadleaf sedge and needle-and-thread biomass was negatively related to fuel load, degree-seconds, and duration of heat. Neither blue grama nor western wheatgrass changed in biomass. A burn cage was used to apply the burn treatments for the individual plant study using range of fuel loads 500-9000 kg·ha^{-1}. Relationships of fuel load with degree-seconds, heat duration, and maximum temperature were tested independently. Probabilities of plant mortality were estimated based on fuel load, duration of heat, maximum temperature, and degree-seconds. Of 120 plants of each species, only one western wheatgrass and one threadleaf sedge plant died following fire. Mortality occurred for 20 blue grama plants and 17 needle-and-thread plants. Degree-seconds, duration, maximum temperature, and fuel load were good predictors of mortality for blue grama and needle-and-thread. Neither duration of heat or maximum temperature explained changes in biomass or tillers for any species. Plant response was less in the field than the burn cage even at heavier fuel loads. This study found that as fuel load increased, degree-seconds, duration, and maximum temperature increased. Fuel load was the primary factor increasing degree-second, duration, and maximum temperature and provided an alternative way to predict plant mortality following fire. Understanding direct fire effects on plants will provide better management decisions following a fire.

CHAPTER 1

INTRODUCTION

Plant mortality following fire has been a concern of many people and agencies that work or show interest in prescribed fires and wildfires. However, there is little information relating to the direct effect fire has on grass mortality, biomass production, and tillers numbers. It is suspected plant mortality will increase with greater heat from fire (Stinson and Wright 1969; Britton and Wright 1970; Wright and Bailey 1982; Ewing and Engle 1988; Engle et al. 1989; Iverson et al. 2004; Ansley and Castellano 2007).

The role of maximum temperature in causing plant mortality is uncertain. Several factors have been suggested as affecting maximum fire temperature which include weather, fuel load, fuel arrangement, fuel moisture and wind speed (Lata and Werich 1998). Of these factors, fuel load is the most predictable and manageable from year to year. A relationship between fuel load and direct plant response needs to be determined.

Degree-seconds, duration of heat, and maximum temperature are measures of heat dosage that may be influenced by fuel load, but the relationship of each with direct fire effects on plant response is not known (Ewing and Engle 1988; Engle et al.1989). Degree-seconds, duration, and maximum temperature have been shown to affect plant mortality, but threshold values for causing mortality are unknown (Stinson and Wright 1969; Britton and Wright 1970; Wright and Bailey 1982; Ewing and Engle 1988; Engle et al. 1989; Bochert and Odim 1995). If a close relationship can be described with an easily estimated factor such as fuel load, understanding and prediction of direct fire effects will improve.

Plant response may differ by growth habit with an increase in fuel load (Robberecht and Defosse 1995; Ansley et al. 2006; Morgan and Lunt 1999; Ansley and Castellano 2007). For example, bunchgrasses tend to be more sensitive to fire than rhizomatous grasses (Ansley et al. 2006; Ansley and Castellano 2007) because of excess accumulation of biomass around the base of the plant. However, indirect effects, such as precipitation and grazing following fire, may have more of an influence than the direct fire effects.

Statement of Problem

The objectives of this research were to determine the survival, tiller numbers, and biomass response to fuel load and direct measures of heat of four prominent graminoid species and determine how these factors influence plant community response. I hypothesized that fuel load, degree seconds, duration of heat, and maximum temperature are negatively related to survival, tiller number, and biomass. Bunchgrasses were expected to be more sensitive to fuel load and heat than rhizomatous grasses. Thresholds for fuel load and heat measures were expected for each species, which when exceeded, would lead to negative effects on plants.

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CHAPTER 2

LITERATURE REVIEW

Plant response to fire is variable, and measuring and predicting plant mortality because of fire can be challenging over large areas due to the variability of fuel, microclimates, and topography (Iverson et al. 2004). However, direct fire effects are often considered the main cause of plant mortality following fire. Research from most fire studies have occurred at the community level with few studies occurring at the individual plant level. While these studies at the community level are important, they do not answer the questions of how individual plants respond or describe the mechanisms responsible for a negative plant response to direct fire.

Maximum temperature is the most common variable used to relate plant response to fire (Stinson and Wright 1969; Ansley and Jacoby 1998; Brooks 2002). Others have found degree-seconds (the area under the time-temperature curve) and duration (the time heat remains above a stated temperature) as possible predictors of direct fire-induced plant mortality (Stinson and Wright 1969; Britton and Wright 1970; Wright and Bailey 1982; Ewing and Engle 1988; Engle et al. 1989; Iverson et al. 2004; Ansley and Castellano 2007; Vermeire and Rinella 2009). Most of these studies have determined that degree-seconds, duration, and maximum temperature are related to plant response, but it is not clear which measurement is the best predictor.

Measurement of maximum temperature, degree-seconds, and duration as predictors is difficult because all require specialized equipment. Thermocouples can be used to measure all three, while temperature-sensitive paints can be used to approximate maximum temperature (Wright and Klemmedson 1965; Engle et al. 1989; Iverson et al.2004). These methods of measurement are ideal for small areas, but are not practical at the landscape level because of equipment and logistical constraints.

An alternative approach to measure plant response to direct fire is fuel load. Fuel load (i.e. all combustible material) has been shown to affect degree-seconds, duration, and maximum temperature (Stinson and Wright 1969). Compared to degree-seconds, duration and maximum temperature, fuel load is easy to estimate and does not require much equipment or expense.

Fuel load can be controlled or influenced by grazing management practices, frequency of burns and the type of fuel (Stinson and Wright 1969; Wright and Bailey 1982; Jacoby et al. 1992). Fire is strongly affected by weather, fuel load, fuel arrangement, and fuel moisture (Lata and Weirich 1998), which in turn influences degree-seconds, duration, and maximum temperature. These conditions can vary spatially and temporally (Iverson et al. 2004). Measuring and predicting plant response to fire can be challenging over large areas due to the variability of fuel, microclimates, and topography (Iverson et al. 2004). Predicting plant response is complicated further because fuel load can vary spatially and cause differences in degree-seconds, heat duration, and maximum temperature. This is why it is important to understand how plants respond at a wide range of fuel loads. For example of variation in fuel load, a study in the Mojave Desert measuring the fire temperature around a creosote bush found temperatures were consistently greater under the canopy where fuel load was heavier than interspaces where the fuel load was lighter (Brooks 2002). Using fuel load to predict plant response to fire will allow better understanding of fire effects.

Litter can be a large component of fuel load and can accumulate when a site has not been burned or grazed for multiple growing seasons. If an area has been burned, there is an estimated 3-year lag period on the tallgrass and mixed prairies before the litter reaches pre-burn yields (Wright and Bailey 1982; Fuhlendorf and Engle 2004). Once litter has accumulated, it takes three additional years before it decomposes completely. The smaller vegetation parts will break down rapidly, leaving the courser vegetation (Hopkins 1954) which tends to burn longer. When litter accumulation occurs, heat duration tends to be greater (Engle et al. 1989; Hatford 1992; Morgan and Lunt 1999).

Maximum fire temperature typically increases linearly with increasing fuel load (Stinson and Wright 1969; Ansley et al. 1998). Maximum temperatures may also be influenced by chemical properties, such as flammable oils, and physical properties, such as surface-to-volume ratios, which should be considered before a prescribed fire or following a wildfire (Hopkins 1954; Brooks 2002).

Fires in areas with heavy fuel loads tend to have longer duration and greater degree-seconds of heat associated with them (Ewing and Engle 1988; Engle et al. 1989).

In the tallgrass prairie where fuel loads range from 4,000 to 10,300 kg·ha^{-1}, four times more degree-seconds of heat resulted from fires with heavy fuel loads compared to those with light fuel loads (Engle et al. 1989). This illustrated degree-seconds and duration increase with greater fuel loads, but the authors did not examine the relationships with plant response at the individual plant level.

The limited information about the threshold for degree-seconds, duration, and maximum temperature that induce plant negative plant response to fire makes it difficult to determine if fire is the direct cause plant mortality, or if post-fire factors such as weather and herbivory may have more of an influence (Stinson and Wright 1969; Britton and Wright 1970; Wright and Bailey 1982; Ewing and Engle 1988; Engle et al. 1989; Iverson et al. 2004; Ansley and Castellano 2007).

Plant response to fires is not fully understood without the ability to measure the direct effects of fire. In general, for heat to be detrimental to a plant, tissues must reach approximately 60°C (Yarwood 1961). However, there are little data showing how long a plant must stay at or above this temperature during a fire. Yarwood (1961) used a water bath study in a laboratory to illustrate how long the temperature needs to exceed 60^{o}C to damage plant proteins. Plants exposed to temperatures ranging from 75 to 90^{o}C for 3 s started to show heat damage 15 min following heat exposure. Similar methods were used to find 60 to 71°C were needed to be lethal to dormant blue grama (*Bouteloua gracilis* (Willd *ex*. Kunth) Lag. *ex* Griffiths) (Jameson 1961). These studies provide a baseline for understanding how plants respond to temperature, but do not provide a direct test of fire effects.

Plant response to fire has been measured as influenced by differences in shrub stem size, grass tiller number, seedling emergence, and plant basal area (Engle et al. 1989; Iverson et al. 2004; Vermeire and Rinella 2009). These measurements are widely used to measure plant response to fire in laboratory and field studies. While such measurements can be time-consuming, the resulting understanding of how individual plants respond to fire can be extrapolated to community level responses.

Plant response to fire varies with fire intensity. In California chaparral (Bochert and Odim 1995), fire was categorized as high or low intensity then related to maximum temperature, heat released, and duration using resprouting of stems as an indicator. As fire intensity increased, resprouting of plants following fire decreased within chamise (*Adenostoma* sp. (Hook. & Arn) shrublands. Larger plants had greater survival and faster resprout rates compared to smaller plants (Borchert and Odim 1995). Mesquite (*Prosopis glandulosa* Torr.) shrublands in New Mexico showed similar results, with canopy cover and stem growth decreasing following a high-intensity fire (Brooks 2002; Drewa 2003).

Perennial grasses are believed to respond similarly to resprouting shrubs because the tiller buds are located near or below ground (Anderson 2006). However, few studies measure grass response based upon tiller growth and individual plant production, which makes it difficult to predict how an individual grass plant responds to fire. Plants are commonly measured examining biomass following fire, which provides an understanding of plant response at the community level, but may not represent individual species or plant response to direct fire effects because effects are confounded by post-fire environment and species interactions (Trlica and Schuster 1969; White and Curry 1983; Schacht and Stubbendieck 1985; Parmenter 2008).

Blue grama, the dominant warm-season grass found on much of the Great Plains, tends to respond variably to fire. In Texas, New Mexico and Montana plants exposed to fire developed later than nonburned plants, but with a positive or neutral change in cover and biomass. Plants burned while dormant may respond positively to fire. In New Mexico, fire increased blue grama if burned during dormancy (Brockway et al. 2002), but this response may be driven more by precipitation following fire than the fire itself (Engle and Bidwell 2001; Arychuk et al. 2002; Scheintaub et al. 2009).

Studies in Texas have shown a delayed recovery in western wheatgrass (*Pascopyrum smithii* (Rydb.) A. Löve) and buffalograss (*Bouteloua dactyloides* (Nutt.) J.T. Columbus) when compared to nonburned plants (Ansley et al. 2006; Ansley and Castellano 2007). In the tallgrass prairie, tiller numbers did not decrease when big bluestem (*Andropogon gerardii* Vitman) was burned at high or low intensity (Ewing and Engle et al. 1988). However, this study did not take into account post-fire conditions, such as weather and its effects on tiller numbers.

Bunchgrasses tend to be less tolerant of fire than rhizomatous species like western wheatgrass (Pelaez et al. 1997 and Ansley et al. 2006). Stems of a rhizomatous grass tend to be more widely spaced and the buds are underground, whereas bunchgrass buds are often elevated above ground, causing them to be more vulnerable and exposed to heat (Morgan and Lunt 1999). In addition to the buds becoming elevated, litter accumulation occurs at the crown, which increases heat duration around the buds (Morgan and Lunt 1999). Bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) A. Löve) and Idaho fescue (*Festuca idahoensis* Elmer) biomass increased under a less intense fire, but when the fire reached moderate or greater intensity, productivity decreased (Robberecht and Defosse 1995). Moderate heat stimulated the dormant buds, but once exposed to a greater intensity fire, with presumably more heat, the buds were damaged. Thus, it is important to understand how much heat grass can endure before mortality occurs.

Growth buds negative response in *Stipa* species have been used as an indicator of fire intensity on grasslands in Argentina (Busso et al. 1993). With an average fuel load of 2850 kg·ha^{-1} Busso et al (1993) determined bud viability decreased with the heavier fuel loads. Bunchgrasses grow from the center of the plant and expand outward. This type of growth pattern will cause greater biomass accumulation in the center of the plant than the outer edges. Bud mortality was greater in the middle of bunchgrasses where the biomass accumulation was greatest compared to the outer edge where biomass was less (Morgan and Lunt 1999).

While most studies have looked at plant response to degree-seconds, duration, and maximum temperature, few have shown how fuel load affects maximum temperature, duration, and degree seconds and how fuel load can be used to predict plant response to fire. The purpose of this study was to determine what measures of heat best describe plant response to fire and whether fuel load may be a good predictor of fire effects at individual and plant community levels.

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CHAPTER 3

FUEL LOAD AND HEAT EFFECTS ON NORTHERN MIXED PRAIRIE RESPONSE TO AUTUMN FIRE

Abstract

Autumn prescribed fires are common on grasslands because they tend to burn “cooler” and there is more control over a fire. However, there is limited information about how fuel load and heat affect plant response following an autumn fire. Twenty-four plots were selected in northern mixed prairie with fuel loads ranging from 1745 to 5662 $kg\cdot ha^{-1}$. Frequency of the vegetation was measured using line point intercept, and biomass was measured by clipping 10, 0.25 m^2 circular frames per plot. Differences in fuel load were primarily caused by differences in litter mass. Twelve plots were burned during autumn 2008 and 12 were burned in autumn 2009. The heat of the fire was measured using thermocouples staggered across plots. Degree-seconds, duration of heat, and maximum temperature were positively related to fuel load. Threadleaf sedge increased in biomass by 27% relative to pre-treatment measures. Needle-and-thread biomass decreased 15% relative to pre-treatment measures and was negatively related to fuel load, degree-seconds, and duration of heat. The changes in blue grama and western wheatgrass biomass were not related to fuel load or measures of heat. Combined across all fuel loads, threadleaf sedge and needle-and-thread frequency increased 15% and 10%, respectively, one year after fire relative to pre-treatment measurements. Total species biomass was negatively related to fuel load, degree-seconds, and duration, but not explained by maximum temperature. Cool-season plants responded more positively to autumn fire than warm-season plants. Fuel load and other conditions that may affect heat near the soil surface should be considered in predicting direct fire effects on vegetation.

Introduction

Autumn prescribed fires are common on grasslands because they tend to burn “cooler “and are more easily contained (Ansley and Jacoby 1998; Govender et al. 2006). During autumn, plants are typically dormant, which increases resistance to heat and may reduce fire effects (Wright and Klemmendson 1965; Whisenant and Uresk 1989). However, there is limited detailed information about how fuel load and heat affect plant response following an autumn fire.

There is even less information about relationships of degree-seconds, heat duration, maximum temperature, and fuel load with plant response following an autumn fire. It is speculated that increasing fuel loads, which increase degree-seconds, heat duration, and maximum temperature, will negatively affect plants, but thresholds have not been identified for grass species or native forbs (Stinson and Wright 1969; Britton and Wright 1970; Wright and Bailey 1982; Ewing and Engle 1988; Engle et al. 1989; Iverson et al. 2004; Ansley and Castellano 2007, Vermeire and Rinella 2009).

Fuel loads in autumn may be greater than in the spring or summer because the vegetation has had a full growing season to accumulate. Equally important, the livestock management of the area may influence fuel load (Davies et al. 2008); producing less fuel in grazed areas than those that have not been grazed.

The purpose of this study was to determine the effects of degree-seconds, heat duration, and maximum temperature on plant response in native range following an autumn burn and the relationships of each with fuel load. Degree-seconds, heat duration, and maximum temperature were all expected to increase with increasing fuel load. Bunchgrasses were expected to have a more negative response than rhizomatous grasses; rhizomatous grasses were expected to have a neutral to positive response and forbs were predicted to have a neutral response (Erichsen-Arychuk 2002).

Materials and Methods

Study Area

The study was conducted on the northern mixed prairie of eastern Montana near Miles City at Fort Keogh Livestock and Range Research Laboratory (lat 46°19’48”N, long 105°58’54”W). The annual precipitation for the area is 25 to 36 cm. Elevation at the study site is 800 m. Temperatures range from 38°C in the summer to -40°C in the winter. Growing seasons have 110 to 135 frost-free days.

Topography of the site is relatively flat with minimal slope (0-4%). The major soil component (85%) is Degrand loam (Fine-loamy over sandy or sandy-skeletal, mixed, superactive, frigid Aridic Argiustolls). Minor soil components include Bigsheep (Loamyskeletal, mixed, superactive, frigid Typic Calciustolls), and Chinook (Coarse-loamy, mixed, superactive, frigid Aridic Haplustolls) (Web Soil Survey July 2010).

The dominant vegetation found on the site consisted of needle-and-thread (*Hesperostipa comata* (Trin. & Rupr.) Barkworth), blue grama (*Bouteloua gracilis* (Willd *ex*. Kunth) Lag. *ex* Griffiths), western wheatgrass (*Pascopyrum smithii* (Rydb.) A. Löve), threadleaf sedge (*Carex filifolia* Nutt. var. *filifolia*), and to a lesser extent, sand dropseed (*Sporobolus cryptandrus* (Torr.) A. Gray), purple threeawn (*Aristida purpurea* L.), sedge species (*Carex* spp. L.), and buffalograss (*Bouteloua dactyloides* (Nutt.) J.T. Columbus). Annual grasses included six week fescue (*Vulpia octoflora* (Walter) Rydb.), Japanese brome (*Bromus japonicus* Thunb.), and cheatgrass (*Bromus tectorum L.*). The primary shrub species on the site was silver sagebrush (*Artemisia cana* Pursh.) and half shrub fringe sage (*Artemisia frigida* Wild.). The succulent, prickly pear cactus (*Opuntia polyacantha* Haw.), was a minor component. The site has a history of being grazed annually by cattle at moderate rates (1 animal unit month/ha) until the study area was fenced in 2008.

Methods

Prescribed fire was applied to 24 plots measuring 20 X 20 m, differing in fuel load, and separated by 5-m buffers. Plots were selected to have similar productivity, but a range of fuel loads were present which was caused by grazing effects on standing dead material and litter. Twelve plots were openly accessible to cattle until a few months before fire and grazing was excluded for most of two growing seasons on the other12 plots burned in 2009. Each of the 24 plots had a 25-m transect line that ran diagonally across the plot. Transects were permanently marked with reinforcing bars to measure the same transect line for each plot before treatment and one year after treatment.

Pre- and post-treatment data were collected on all plots. Frequency was estimated for each plot using a 100-point line intercept with measurements at 25-cm increments. Ten 0.25 m^2 circular frames were randomly placed in each plot and clipped to estimate biomass, fuel load, and species composition. The plants were clipped at ground level and sorted as western wheatgrass, needle-and-thread, blue grama, threadleaf sedge, other warm-season grasses, other cool-season grasses, annual forbs, annual grasses, perennial forbs, and half shrub fringed sage. After standing vegetation was clipped, litter was collected and included in the fuel load estimates. Samples were dried to a constant weight at 60°C to measure fuel load and biomass before and after fire. Mass was weighed to the nearest 0.01g.

Pre-treatment data were collected 6-12 July 2008 on 12 plots, and pre-treatment data was collected on 12 additional plots, 19-30 June 2009 to 10 July 2009 and post-treatment data were collected 31 June-10 July 2009, and 6-15 June 2010 for the post-treatment plots. Plot borders were mowed to create a firebreak and separate plots. A wet line was applied around the borders of the plots minutes before the burn to prevent the fire from spreading outside the plots. Temperature and relative humidity were measured using a sling psychrometer approximately every hour**.** Plots were burned individually using a ring fire technique on 31 October 2008 and 4 November 2009.

Eight thermocouples were placed 6 meters apart into the plots for 2008 fires and 12 thermocouples were used per plot in 2009. The thermocouples were pinned at the soil surface and recorded temperature every second. Fire data were recorded using a Campbell Scientific 21X micrologger with a SM4M Storage module (Campbell Scientific Inc. Logan UT, USA) and monitored in real time with a laptop computer. The data logger and computer were located on the upwind edge of plots and shielded from heat with a sheetrock panel. Thermocouples were left in place until fires had passed and readings cooled to less than 50°C. Data were used to determine maximum temperature, duration of heat above 60°C, and degree-seconds above a base temperature of 60°C.

Three needle-and-thread plants were selected within each plot before treatment based upon similar size, and biomass and litter. Surrounding plants were removed from a circular 0.25-m^2 quadrat centered on the individual needle-and-thread bunches. Biomass that had been removed from the circular frame was re-applied at known list them rates to measure plant response to fuel loads. Fuel loads of the collected biomass applied to the plants were 1000, 3 000, and 5 000 kg·ha^{-1}. Both live and dead tillers were counted before the fire and the following spring to describe plant response to fire and fuel load.

Analyses

Community composition was estimated as percent of total standing crop by species or species group and analyzed with the MIXED procedure of SAS (Littell et al. 1996), with model terms for year of fire, time relative to fire (pre-treatment and one yr post-treatment), and their interaction. Post-treatment biomass and frequency were converted to relative measures of pre-treatment biomass and frequency to account for initial component differences among plots. Regression analyses were used to assess relationships of mean plot fuel load, degree-seconds, duration of heat, and maximum temperature, with relative biomass and frequency of species and species groups. Indicator regression was used to test for differences in slopes by year (Neter et al. 1990) with the GLM procedure of SAS. If year differences were not detected, data were analyzed across years. Blue grama, threadleaf sedge, needle-and-thread, and western wheatgrass were analyzed as individual species because of their prominence in northern mixed prairie. Species groups tested for biomass relationships were warm-season grasses, cool-season grasses, perennial forbs, and annual grasses. The species analyzed for frequency were western wheatgrass, blue grama, needle-and-thread, threadleaf sedge, silver sage, Japanese brome, cheatgrass, needleleaf sedge (*Carex duriuscula* C.A. Mey), Sandberg bluegrass (*Poa secunda* J. Presl), scarlet globemallow (*Sphaeralcea coccinea* (Nutt.) Rydb.), dandelion (*taraxicum officinale* F.H. Wigg.), goat's beard (*Tragopogon dubius* Scop.), and six-week fescue. Needle-and-thread tiller counts, relative to pre-treatments counts, were analyzed as an analysis of covariance using the

MIXED procedure of SAS (Littell et al. 1996), with model terms for year, fuel load, their interaction, and pre-treatment tiller counts as the covariate. Significance for all tests was declared with $P \leq 0.05$.

Results

Fire weather conditions were similar between 2008 (18^{o}C, 36% RH, 4.0 m s^{-1}) and 2009 (14^{o}C, 37% RH, 3.7 m s^{-1}). Post-treatment spring precipitation was 88 and 154% of the 74-yr median, with 137 and 241 mm from April through June during 2009 and 2010, respectively (Figure 3.1). Degree-seconds, duration of heat, and maximum temperature were positively related to fuel load for all plots (Figure. 3.2).

Composition was similar between plots burned during 2008 and those burned during 2009 for all components except western wheatgrass (16.7 versus 11.7 ± 2.3%) and fringed sage (1.2 versus 0.1 ± 0.5%), both of which were a greater percentage of total standing crop in plots burned during 2008. Composition shifted between pre-treatment and post-treatment years, with relative biomass of western wheatgrass and other cool-season perennial grasses increasing following fire and annual grasses decreasing following fire (Table 3.1). Composition of blue grama and other warm-season perennial grasses each tended to decrease following fire.

The response of relative biomass to fuel load and heat measures was similar across years. Mean total biomass was 16% less after fire, relative to pre-treatment estimates, which included standing dead material. Fuel load, degree seconds, and duration were negatively related to total biomass (Table 3.2), with fuel load and duration of heat explaining the most variation. Maximum temperature was not a good predictor of total post-fire biomass when compared to degree-seconds and heat duration.

Fuel load as a predictor of individual species and species group biomass response to fire was limited to threadleaf sedge, needle-and-thread, and annual grasses. Threadleaf sedge and needle-and-thread biomass were negatively related to fuel load, degree-seconds, and duration of heat across the two years (Table 3.2). Annual grasses had a tendency ($P < 0.06$) to decrease with increasing duration of heat (Table 3.2). Despite negative relationships for needle-and-thread, reductions in other species allowed needle-and-thread to maintain its relative composition in the community (Table 3.1). In no case was maximum temperature as good a predictor of plant biomass following fire (Table 3.2) as were degree-seconds and heat duration.

Changes in frequency of individual species predicted by fuel load or heat were limited to threadleaf sedge, needle-and-thread, and Japanese brome. Threadleaf sedge frequency decreased as degree-seconds and duration of heat increased (Table 3.3). Needle-and-thread frequency decreased as degree-seconds, duration of heat, and fuel load increased (Table 3.3). However, frequency of threadleaf sedge and needle-and-thread increased between by 15 and 10% respectively relative to pre-treatment measures. In contrast, Japanese brome frequency decreased by an average of 95% following fire, and decreased with increasing degree-seconds of heat (Table 3.3).

Species for which changes in frequency occurred but were not explained by fuel load or heat were blue grama (-16%), cheatgrass (-52%), dandelion (-17%), goatsbeard (-68%), and sixweek fescue (-90%). Relative frequency increased for western wheatgrass (2%), needleleaf sedge (52%), Sandberg blue grass (32%), and scarlet globemallow (13%).

Although biomass and frequency of needle-and-thread decreased with increasing fuel load and heat (Tables 3.2 and 3.3), there was no fuel load effect on needle-and-thread tiller numbers (62 ± 5 tillers; $P>0.21$) when fuel loads were set to 1 000, 3 000, or 5 000 kg ha^{-1}.

Discussion

Degree-seconds, duration, and maximum temperature increased with fuel load, which in turn had an effect on plant response to fire (Fig. 3.2). Threadleaf sedge, needle-and-thread, and total biomass illustrated a negative response to an increase in fuel load. Other species measured had a neutral response to fuel load.

Maximum temperature increased with fuel load, but the time spent at a detrimental temperature may be more important than the actual temperature itself (Yarwood 1961; Wright 1971). This explains why heat duration was more closely related to plant response than maximum temperature.

The pre-treatment data included previous years' vegetation whereas post-treatment data was limited to current year's growth. Therefore, positive relative changes in biomass clearly indicated increased biomass, but an undefined portion of negative relative changes reflected removal of standing dead material and not necessarily a loss of production. Others have observed standing dead from previous years to comprise 18 to 57% of standing crop for nongrazed grasslands in the region (Sims and Singh 1978).

Grazing is not a uniform process and fuel distribution varied across plots which led to an increase in fuel load, degree seconds, and duration in some areas of the plots. The old growth remaining around nongrazed plants may have resulted in a more negative plant response than experienced by the plants that were grazed because of the greater fuel loads and heat. Therefore, highly preferred species or individual plants may be less susceptible to fire than species that are avoided by cattle. Needle-and-thread would have moderate amount of biomass removed from around the plant while threadleaf sedge and western wheatgrass will have most of the biomass removed from around the plant because of their order preference by cattle (Samuel and Howard 1982; Uresk 1986).

Species composition will be expected to change in favor of species that have a higher tolerance to heat. Plants that have a more negative response to fire will decrease within the plant community and plants that have a more positive response to fire and an increasing fuel load will increase. The increased fuel load around the plants may have damaged growth buds (Wright 1971) causing a decline in biomass at heavier fuel loads in these areas. Drewa et al. (2006) showed medium sized bunchgrasses had more post-fire biomass and less mortality than large or small plants.

Threadleaf sedge has a growth habit of a bunchgrass, which would suggest that threadleaf sedge would have a similar response to fuel load as other bunchgrasses. In this study, threadleaf sedge frequency and biomass decreased with some measures of heat, but maintained its relative biomass in the community. Heavier fuel load tended to cause a decrease in biomass. Others have generally shown a neutral to positive response of threadleaf sedge to fire (White and Currie 1983; Whisenant and Uresk 1989). Few studies use frequency to measure plant number response following fire, but if mortality of threadleaf sedge had occurred, there would be a decrease in frequency of the plant unless losses were compensated by recruitment or additional production of surviving tillers.

Blue grama decreased after fire treatment, which was not expected because it tends to show no change in frequency following fire at normal fuel loads (Parmenter 2008). Furthermore, blue grama may respond to weather patterns and post-fire competition more than fuel load itself. Ford (1999) found blue grama response can vary across years, with weather as the driving factor. Average and above average rainfall occurred in 2009 and 2010. Blue grama's negative response may have been compensated for with average or above average precipitation following fire (White and Currie 1983; Drewa et al. 2006).

Blue grama is a low growing bunch grass and/or sod forming grass minimally affected by fire because it produces little biomass, leading to fewer degree-seconds, shorter heat duration, and lower maximum temperatures duration a fire. For fire to be detrimental, neighboring plants would have to elevate fuel loads enough to produce heat necessary to penetrate below the soil surface to cause damage to growth buds. Blue grama produces approximately 40 to 250 $kg \cdot ha^{-1}$ on the northern Great Plains (Sims and Singh 1978), and our sites averaged 45 $kg \cdot ha^{-1}$ which is not enough to carry a fire across a blue grama community, let alone provide a detrimental fuel load without substantial contributions from other species . Plants may adapt to the level of fuel that they or their community can produce and once this level has been exceeded, mortality is expected.

Blue grama may actually benefit from fire because of reduced shade and competition from other plants. When competition was reduced, bunchgrasses grew larger in size (Wilson and Shay 1990). However, blue grama is a smaller bunchgrass and the decrease in biomass may have occurred on the plots because of the increase in biomass composition of the cool-season grasses.

Western wheatgrass is commonly studied across the Great Plains due to its abundance and wide distribution. Because of its wide range, results following fire vary from place to place. Western wheatgrass biomass had a positive relationship with fire. The positive response may be attributed to the average to above average rainfall that occurred. The same positive response was also seen in a study in Montana conducted by White and Currie (1983), western wheatgrass had the same production on plots burned in the fall and the controlled plots. In another study, post-fire drought reduced western wheatgrass (Launchbaugh 1964).

Plots were burned in the autumn, which may have contributed to the lack of change in western wheatgrass production following fire. In another study, western wheatgrass production increased the year following fall fire and spring burning may result in a decrease in production (Whisenant and Uresk 1989). The time of year and post-fire precipitation may be the driver behind western wheatgrass and its response to fire (Erichsen-Arychuk et al. 2002).

Western wheatgrass may have growth patterns of an opportunistic species that takes advantage of ideal growing conditions when coupled with increased growing space following fire. Western wheatgrass response to fire did not appear to be related to fuel load. The fuel load was low enough across the plots not to produce substantial heat to penetrate to growing points below the soil surface, or the precipitation received allowed western wheatgrass to come back following fire.

Other cool-season grasses increased following fire, which may be attributed to the fire occurring in the autumn followed by higher than normal precipitation in the spring. Warm-season grasses showed a tendency to decline following the autumn burn in this study.

Japanese brome was the most sensitive to fire when compared to the other annual grasses. This could occur because of the spikelet morphology. The glumes of Japanese brome tend to be papery compared to the other annual grasses found in this study, which resulted in a more combustible material and therefore a potentially larger detriment to the seed itself.

Japanese brome tends to respond negatively to fire (Whisenant and Uresk 1990; Vermeire and Rinella 2009). This was confirmed by our results with Japanese brome showing a negative response to heat duration as fuel load increased. It is possible the more heat the seeds are exposed to, the greater the negative response. Vermeire and Rinella (2009) observed there were fewer Japanese brome seedlings as fuel load increased. This was a result of the heat duration applied to the seeds. The seed bank of annual grasses like Japanese brome can be reduced with fire as the fuel loads are high enough (Vermeire and Rinella 2009).

Japanese brome responded negatively to fires and is dependent on previous years' seed source. However, the level of annual grass control by fire appears short lived (Schacht and Stubbendieck 1985). Annual grasses are opportunistic, and one annual grass plant can regenerate a stand within a few years without fire.

Management Implications

Autumn fire shifted vegetation composition, with cool-season perennial plants increasing and annual grasses decreasing. However, some of the dominant cool-season perennial grasses also decreased with increasing fuel load and heat dosage. Variation among species in their relationships between measures of heat and plant response indicates estimation of heat at the soil surface can facilitate explanations of direct fire effects and changes in plant community composition. Direct measures of heat can be difficult to measure during fire and are poorly estimated after fire. The positive relationships of fuel load with degree-seconds, duration of heat, and maximum temperature suggest fuel load may be a good surrogate measure to estimate fire effects due to heat dosage.

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CHAPTER 4

PREDICTING DIRECT FIRE-INDUCED PLANT RESPONSE OF FOUR PROMINENT RANGELAND GRAMINOIDS

Abstract

Few studies have measured direct plant response to degree-seconds, duration, and maximum temperature during fire. Even fewer studies have attempted to find a relationship between individual plant response and fuel load. The study was conducted at the Fort Keogh Agriculture Research Center in Miles City, Montana. 120 plants were collected from each of four prominent rangeland graminoids, potted them in 15-cm diameter pots, watered them weekly, and kept them under favorable growing conditions in a greenhouse. Summer and fall burns were conducted in a burn cage using a range in fuel loads from 0 to 9 000 kg·ha^{-1}. Probabilities of plant mortality were estimated with fuel load, duration of heat, maximum temperature, and degree-seconds using logistic regression. Fuel load explained 58 and 36% of variation in degree-seconds and duration, respectively, with positive quadratic models and 43% of variation in maximum temperature with a negative quadratic model. Only one western wheatgrass and one threadleaf sedge plant died following fire out of 120 plants of each species. Mortality occurred for 20 blue grama plants and 17 needle-and-thread plants of 120 plants for each species. Mortality increased with increasing fuel load and heat, but extreme levels (fuel loads > 8 000 kg ha^{-1}) of each were required to reach 0.5

probabilities. Surviving blue grama was not affected by fuel load or any measure of heat when fuel loads were 0 to 4 500 kg ha^{-1}. Neither duration of heat or maximum temperature explained changes in biomass or tillers for any species. Western wheatgrass relative biomass was greater following summer than fall fire, but decreased at the same rate for both fire seasons as fuel load increased from 500 to 4 500 kg ha^{-1}. Mortality from direct fire effects is not likely with fire conditions common to the tested species, but negative relationships of western wheatgrass and threadleaf sedge biomass with fuel load indicate conditions that increase heat dosage may reduce productivity.

Introduction

Fire effects on plants include direct effects from combustion and heating as well as indirect effects, such altering competitive interactions or making plants more vulnerable to grazing or drought damage. Fire temperatures, duration of heat, and degree-seconds have all been shown to directly affect plant mortality in water bath experiments (Yarwood 1961). The same variables also appear related to plant response in field studies when fires have been conducted, but without control of environmental factors, direct fire effects are confounded with post-fire environment effects, such as weather or herbivory. Few studies have measured degree-seconds, duration, and maximum temperature to explain how these factors affect plant response to fire.

The objectives of this research were to determine which measures of heat best explain grass response to fire, and whether fuel load can serve as an effective surrogate measure to predict direct fire. Four prominent graminoid species from the Great Plains were used to study to a variety of fire and fuel load conditions. I hypothesized that fuel load is positively related to degree-seconds, duration of heat, and maximum temperature. I also hypothesized that degree-seconds, heat duration, and maximum temperature are negatively related to survival, tiller number, and biomass of blue grama, threadleaf sedge, needle-and-thread, and western wheatgrass (*Pascopyrum smithii* (Rydb.) A. Löve). Threadleaf sedge (*Carex filifolia* Nutt.) and needle-and-thread (Trin. & Rupr. Barkworth) were expected to respond more negatively to fuel load and heat than western wheatgrass. Blue grama (*Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths) was expected to have a neutral response to heat. Thresholds for fuel load and heat measures were expected for each species, which when exceeded, induce negative effects on plants.

Materials and Methods

Blue grama, threadleaf sedge, needle-and-thread, and western wheatgrass were potted in 15 cm diameter pots watered weekly and kept in a greenhouse. The study plants were collected at Fort Keogh Livestock and Range Research Laboratory (lat 46°19’48”N, long 105°58’54”W) near Miles City, MT. The site was northern mixed prairie with 334 mm mean annual precipitation and an elevation of 800 m. Temperatures range from 38°C in the summer to -40°C in the winter. Growing seasons have 110 to 135 frost-free days. Topography of the site is nearly level, with 0-4% slopes.

The major soil component (85%) is Degrand loam (Fine-loamy over sandy or sandy-skeletal, mixed, superactive, frigid Aridic Argiustolls) (Web Soil Survey July 2010).

I collected 37 plants of each species (blue grama, western wheatgrass, needle-and-thread, and threadleaf sedge) over 7-8 July 2008. This produced 120 experimental plants per species. The plants were watered once a week until established. Individuals within species were randomly assigned to fire treatments; two seasons of fire, two fuel types, and 10 fuel loads. Each treatment combination was then replicated 3 times. Tillers of the grasses were counted before they were burned and categorized whether they were dead or alive.

The amounts of fuel used in the burn cage were 25, 50, 75, 100, 125,150, 175, 200, and 225 g per a burn to represent fuels loads of 0 (control) 500, 1 000, 1 500, 2 000, 2 500, 3 000, 4 000, and 4 500 kg·ha^{-1}. The 500-1 500 kg·ha^{-1} fuel load treatments were burned 29 July 2008, fuel loads 2 000-3 500 kg·ha^{-1} on 30 July 2008, and fuel loads 4 000-4 500 kg·ha^{-1} on 31 July 2008.

The same process was conducted again in late 23-30 September 2008. However, only 30 plants of each species were collected. With the fall study, water was reduced to half. This forced the plants into drought induced dormancy before fires were applied. The fuel load range was the same as in the 2008 summer burn.

In summer 2009, the same four species were collected 16-17 June 2009 to test more extreme fuel loads because the plants in 2008 trial did not show any negative effects. The fuel load was increased in an attempt to establish thresholds for fuel loads and heat measures, and two types of fuel loads were used with the intention of increasing maximum temperature, duration, and degree-seconds. Sixty plants of each species were randomly collected and assigned to two different fuel types grass and shrub material. The fuel loads for this experiment were increased to 0 (control), 5 000, 5 500, 6 000, 6 500, 7 000, 7 500, 8 000, 8 500, 9 000 kg·ha^{-1}. Fuel type was a native grass fuel found where the plants were collected, while the other type of fuel was comprised of 3 000 kg·ha^{-1} of native grass, and the remaining amount was silver sage (*Artemisia cana*) was mixed together. The plants were burned the first two weeks of August 2009. Air temperature and humidity was recorded every hour or when the fuel load treatment changed. Two identical burn cages were used to improve the efficiency of the burning process.

The burn cages were 1.5mX0.5mX0.5 m and 0.3m off the ground. The cage frame was constructed from 2.54 cm square tubing and covered with hardware cloth (Vermeire and Rinella 2009). The cage bottom was made of a 3 mm steel plate with two 15.25 cm in diameter holes cut into the center of the plate. Potted plants were placed under the metal plate into holes until the pot was level with the cage floor. The fuel was mowed with a sickle mower and collected where the test plants were collected. Once collected, the fuel was oven dried at 60°C for 48 hours; weighed and placed in bags until used in the burn cage. The fuel was distributed evenly across the cage floor, and a piece of chicken wire measuring the same dimensions as the cage floor was placed on top of the fuel to reduce movement of the fuel. A drip torch containing a fuel mixture of 60:40 diesel and gas and a lighter was used to ignite the fire. A box fan was used to distribute fire evenly across the cage.

Maximum temperature, degree-seconds (^{o}C·s > 60^{o}C), and the duration of heat (s > 60^{o}C) were recorded using thermocouples at the soil surface within each pot. Data were logged using a Campbell Scientific 21X micrologger with a SM4M Storage module (Campbell Scientific Inc. Logan UT, USA). Two thermocouples were placed on each plant, one centrally at the base of the plant and one at soil level on the edge of the plant. Once the burn was complete, thermocouples were allowed to cool below 50°C to adequately account for temperatures the plant experienced. Before the burn was conducted, the outside temperature was allowed to reach 27°C. Outside air temperature was measured using a sling psychrometer. After the plants were burned, they were moved into the greenhouse and grown under favorable conditions. Temperature was maintained at 16 to 21°C for June to September and 10 to 21°C from October to February. Needle-and-thread, western wheatgrass, and threadleaf sedge received 100 mm of water every week, and blue grama received 50 mm of water weekly. Four to five days following the burn, tillers were counted to measure the number of green tillers post fire. Tillers were counted every two weeks until day 77 when no more changes were observed. If the plant did not produce tillers, it was considered dead. After day 120, the plants were clipped and the biomass was collected. Biomass was dried for two days in a drying oven at 60C° then sorted for live and dead based upon the presence or absence of green plant tissue. The biomass was used to estimate an average weight of each tiller based upon the number of tillers found.

Analyses

The relationship between fuel load and degree-seconds, heat duration, and maximum temperature was tested independently by species for differences between years, season of fire, and fuel type using indicator regression (Neter et al. 1990) with the GLM procedure of SAS (SAS 1990). Influence of relative humidity and ambient temperature on heat measures were also examined along with fuel load using multiple regression and a forward selection process with the REG procedure of SAS (SAS 1990). Probabilities of plant mortality were estimated with fuel load, duration of heat, maximum temperature, and degree-seconds using logistic regression with the LOGISTIC procedure of SAS. C-statistics represent the proportion of pairs with different observed outcomes for which the model correctly assigns a greater probability (Peng et al. 2002) and were used to select the best models. Post-treatment tiller counts were converted to relative measures of pre-treatment tiller counts and post-treatment biomass was converted to a relative measure of mean non-burned plant biomass. Difference in relative tiller counts and biomass of surviving plants due to fuel load, duration, maximum temperature, and degree-seconds were tested independently by species and year, season of fire in 2008 and fuel type in 2009 using indicator regression. An $\alpha \leq 0.05$ was used to establish significance.

Results

Conditions during summer burns in 2008 and 2009 were generally hotter and drier than during autumn 2008 (Table 4.1). Wind speeds were similar across all experiments. Fuel moisture was approximately 4% during burns.

Models described degree-seconds, duration, and maximum temperature for summer burned grass fuel across years, so years were combined (Table 4.2). Slopes did not differ for fuel load effects on duration or maximum temperature between summer and fall fires with fuel loads up to 4 500 kg·ha^{-1} (Table 4.2). However, slopes indicate degree-seconds increased more with fuel load for summer than fall fire. Degree-seconds and duration increased more with fuel load when shrub fuel was added than with grass alone, but maximum temperature did not change with fuel type (Table 4.2).

Fuel load was the primary driver of heat across seasons and fuel types (Table 4.2). Relative humidity affected degree-seconds, duration and maximum temperature, explaining an additional 1, 7, and 3% of variation, respectively, when fuel load was in the model. Ambient temperature was not a significant factor in degree-seconds or duration models, but explained an additional 2% of variation in maximum temperature when fuel load and relative humidity were in the model. Regardless of weather, season, and fuel type effects, degree-seconds, duration, and maximum temperature were fairly well modeled with fuel load alone across all variables. Fuel load explained 58 and 36% of variation in degree-seconds (Fig. 4.1) and duration (Fig. 4.2) with positive quadratic terms (p=<0.01) and 43% of variation in maximum temperature (Fig. 4.3) with a negative quadratic term (*p*=<0.05).

Of the 120 plants for each species, only one western wheatgrass and one threadleaf sedge plant died following fire. Mortality occurred for 20 blue grama plants and 17 needle-and-thread plants. *C*-statistics from logistic regression models indicated degree-seconds, duration, maximum temperature, and fuel load were good predictors of mortality for blue grama and needle-and-thread. Blue grama had similar *C*-statistics among degree-seconds, duration, and fuel load, (Table 4.3) indicating the model correctly assigned a greater probability for at least 90% of all live: dead pairs of plants. Maximum temperature (Fig. 4.3) had lower *C*-Statistics, which illustrated maximum temperature was the weakest predictor of post-fire plant mortality for blue grama. Needle-and-thread showed similar C-Statistics for degree-seconds, duration, maximum temperature, and fuel load when related to plant mortality (Table 4.3). Conditions required to produce greater than 0.5 probabilities of mortality were 39 926^{o}C s; 7.5 min above 60^{o}C; 612^{o}C maximum temperature; 8 000 kg ha^{-1} fuel loads) for blue grama (Fig. 4.4-4.11) and 56 985^{o}C s; 10.4 min above 60 °C; 628^{o}C maximum temperature; 8 500 kg ha^{-1} fuel load for needle-and-thread.

Neither duration of heat (P>0.07) nor maximum temperature (P>0.12) explained relative changes in biomass or tillers for surviving plants of any species. The surviving blue grama was not affected by fuel load or any measure of heat when fuel loads were 500 to 4 500 kg ha^{-1} based on changes in biomass relative to non-burned plants or tillers relative to pre-treatment counts. Western wheatgrass relative biomass was greater following summer than fall fire (Table 4.4), but decreased at the same rate for both fire seasons as fuel load increased from 500 to 4 500 kg ha^{-1} (Fig. 4.13). For threadleaf sedge, 30% of the biomass decrease was attributed to the increase in fuel load (Table 4.4 and Fig. 4.16). Fuel load was not related to change in biomass for blue grama or needle-and-thread or change in tiller numbers for any species when burned in 2008. Degree-seconds explained the decrease in western wheatgrass biomass better than fuel load (Fig. 4.13; Table 4.4). More than 96% of the variation in needle-and-thread tiller numbers was explained by degree-seconds (Fig. 4.14; Table 4.4). Neither duration of heat or maximum temperature described changes in tiller number or biomass for any species.

With fuel loads between 5 000 and 9 000 kg ha^{-1}, reductions in western wheatgrass biomass (Fig. 4.13; Table 4.4) were well explained by fuel load across fuel types. Fuel load was also negatively related to changes in blue grama tiller number and biomass across fuel types (Figs4.17 and 4.18; Table 4.4). None of the direct measures of heat was related to changes in biomass or tiller number for any species.

Discussion

As predicted degree-seconds, duration, and maximum temperature increased as fuel load increased. However, plant response was variable. Thresholds for mortality were identified for needle-and-thread and blue grama. However, fuel loads required to reach these thresholds are highly unlikely to occur on a large scale in semiarid grasslands because the grasslands are unable to produce that level of biomass (Singh and Sims 1978; Engle et al. 1989; Archibold 1998). Western wheatgrass biomass did decrease, as fuel load increased which was not expected, however, mortality did not occur.

Even though fires differ, as fuel load increases, degree-seconds, maximum temperature, and duration tend to increase, (Engle et al. 1989; Archibold et al. 1998; Drewa 2003; Ansley and Castellano 2007). In agreement with our results, Archibold et al. (1998) observed temperatures were greater for grassland fires as fuel loads increased and fire was hotter with temperatures that were more consistent when a shrub component was added. In this study fuel load influenced degree-seconds, heat duration and maximum temperature as observed in other studies. Fuel moisture was an important factor for fire behavior (Archibold et al.1998). We did not test fuel moisture, however, relative humidity accounted for 3% of variation in maximum temperature when fuel load was in the model and explained 43% of the variation.

Average maximum temperatures were considerably lower when compared to fire studies in Texas. Grassland fire studies showed average maximum temperatures ranging from 461 to 726°C when burned in the winter and summer (Ansley et al. 2006;

Ansley and Costellano 2007). However, maximum temperatures observed were similar to those reported by Engle et al. (1989), ranging from 36-762°C the soil surface.

Engle et al. (1989) observed elevated degree-seconds and duration as fuel load increased. Light (4 430 kg·ha^{-1}) and heavy (10 320 kg·ha^{-1}) fuel loads burned under the same weather conditions indicated degree-seconds and duration increased with fuel load and were three and four times greater with the heavy fuel load(Engle et al. 1989). However, Engle et al. (1989) measured degree-seconds and duration using ambient temperature as a base. Archibold (1998) used the same technique as this study which was measured at a base of 60°C and illustrated as fuel load increased, degree-seconds, and heat duration increased linearly. Using a base temperature of 60°C reduces calculated degree-seconds but is directly related to temperatures at which tissue damage is expected.

Reduced tiller numbers may be a result of bud mortality. Growth buds are often damaged following fire and if enough buds are harmed, a negative plant response or mortality will occur (Robberecht and Defosse 1995; Pelaez et al. 2009). The longer the buds were exposed to heat, the more likely a negative plant response will occur. Bunchgrasses tend to accumulate fuel around the crown of the plant, causing heat duration to increase as well as degree-seconds and maximum temperatures, which in turn cause greater tiller mortality (Pelaez et al. 1997; Morgan and Lunt 1999). Blue grama and needle-and-thread illustrated the most negative response with fewer tillers which might be correlated with buds being harmed or damaged by the direct fire effects. While threadleaf sedge and western wheatgrass showed a negative biomass response to direct fire effects, only one plant of each was killed.

Some plants like threadleaf sedge may protect the growth buds within the sheath of the plant, and top removal of the fine fuels will have minimal affect on the buds. Western wheatgrass and threadleaf sedge were not killed by fire however, biomass decreased as fuel load increased in 2008 and 2009. Following more intense fires, biomass decreased but plant growth probably resulted from activated dormant buds. Activated dormant buds may have been smaller than actively growing buds resulting in smaller tillers (Drewa et al. 2006), or tiller numbers may have been reduced. The fire may not be enough to cause death to the plants but may influence how they respond to fire.

Limited information is available regarding blue grama response to degree-seconds, heat duration, and maximum temperatures. Community level studies make it difficult to understand how blue grama will respond at the plant level. It has been shown at the community level that blue grama responds positively to fire (White and Currie 1983), but production varies depending on the time of year burned. Other studies reported variable responses to fire. Across 34 studies summarized by Ford (1999), blue grama responded positively (16), negatively (12) or neutrally (28) to fire.

In 2008, biomass and tiller numbers of blue grama did not decrease under heavier fuel loads. Needle-and-thread showed tendencies of decreasing with the heavier fuel loads because there was a negative effect on tiller numbers and biomass.

Based on these measured responses fuel loads were elevated in 2009 to test whether a threshold for plant mortality could be identified. Blue grama and needle-and-thread reached 50% of plant mortality at 8 000 kg·ha $^{-1}$ for blue grama and 8 500 kg·ha $^{-1}$ needle-and-thread. This showed that mortality of plants will occur from direct fire effects. Thresholds for direct fire effects, which cause plant mortality or a decrease in biomass, have not been determined before this study. This useful information can be used to predict direct fire effects at the community level.

The plants will respond negatively to the increasing fuel load due to degree-seconds and duration increasing. Needle-and-thread had more of a negative response as heat rose and the base of the plant had longer duration time (Wright 1971). Maximum temperature was not a factor for any of the species.

The surrounding fuel may influence plant response to direct fire effects. Wright and Klemmedson (1965) found squirreltail to be less responsive to fire because the stems were coarser and fuel accumulation was less than needle-and-thread plants. Threadleaf sedge has a very dense base of stems with a fine fuel type leaves. When a fire occurs, it generally sweeps across the top of the plant and does not transfer heat to the base, which may reduce threadleaf sedge plant mortality. Threadleaf sedge did not show mortality which illustrated that heat transfer did not occur to the base of the plant. The base of the plant being compacted may have prevented this transfer from occurring which may also be attributed to the fine fuel found above the base of the plant.

Reductions in western wheatgrass and threadleaf sedge biomass without reductions in tiller number indicate a reduction in tiller mass with increasing fuel load. Desert wheatgrass (*Agropyron desertorum* (Fisch. ex Link) Schult.) and bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) A. Löve) both showed a decline in stem and sheath surface area as defoliation occurred (Busso et al. 1993).

Management Implications

The primary driver for changes in degree-seconds, heat duration, and maximum temperature was fuel load. Degree-seconds, heat duration, and fuel load were all good predictors of mortality whereas maximum temperature was the weakest predictor of direct plant response following fire. Minimal plant mortality occurred for western wheatgrass and threadleaf sedge. However, blue grama and needle-and-thread mortality increased with fuel load. Conditions (fuel load, degree-seconds, heat duration) required to cause a 0.5 probability of plant mortality for blue grama and needle-and-thread exceeded those that would typically be encountered in either blue grama or needle-and-thread’s natural environment. Decreasing biomass and tiller numbers with increasing degree-seconds and fuel load indicate heat dosage is an important factor in describing direct fire effects on plant communities. Heavy fuel loads or conditions that increase heat dosage near the soil surface (e.g. for brush control) may be detrimental to some perennial graminoids while other graminoids will be unaffected by heat dosage.

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CHAPTER 5

SUMMARY

Several species within the burn cage and the plots showed similar results. However, plants in the burn cage were more sensitive than the plants in the field when exposed to the same fuel loads, which may be attributed to the plants being burned under more extreme conditions in the individual plant study than the community study. The individual plant study gave a good prediction of how a plant would respond when exposed to elevated fuel loads and ideal growing conditions, while the field study provided a better understanding to how the plant would respond to autumn fire in the field.

Western wheatgrass did not show a difference in production as fuel load increased in the field, but in the individual plant study, it was reduced by an increase in degree-seconds, heat duration, and fuel load. Part of the difference may be explained by the greater range of fuel loads for the individual plant study. In addition, burning western wheatgrass in the summer may have influenced the biomass production in the individual plant study.

Blue grama biomass was unaffected by degree seconds, duration, and fuel load in the field and individual plant study with the 2008 burns. However, when fuel loads were elevated in the individual plant study, mortality did occur. Using the individual study results, blue grama biomass would be predicted to decrease by 8% at 5 500 kg·ha^{-1} the highest fuel load found in the field portion of the study. In areas with fuel loads less than 5 500 kg·ha^{-1}, blue grama biomass would not be affected by direct fire effects. Once the fuel load goes above 5 500 kg·ha^{-1} biomass, mortality of blue grama is likely to increase.

Needle-and-thread biomass would be expected to decline by 10% at the highest field study fuel load of 5500 kg·ha^{-1}, based on the individual plant study. Needle-and-thread plants marked in the field plots did not decrease in tiller numbers with a fuel load of 5000 kg·ha^{-1} which illustrated needle-and-thread has a higher fuel load threshold than was observed in the individual plant study. The field study illustrated that typical fuel loads found across the Great Plains would not cause plant mortality by direct fire effects. However, post-fire precipitation may play a large part in how a plant will respond following fire beyond direct effects.

Plant response and/or mortality was less in the field than the burn cage even at the heavier fuel loads, which showed plants in general are able to tolerate a high range of heat. The plants in the individual study were tested under more extreme fire conditions with ambient temperature being greater and humidity being lower than the field study. Each of these factors allowed for greater degree-seconds, duration, and maximum temperature to be tested. The field study and individual plant study found as fuel load increased degree-seconds, duration, and maximum temperature increased.

Degree-seconds, heat duration, and fuel load were good predictors of plant response whereas maximum temperature was the weakest predictor of plant response. Autumn fires seemed to shift vegetation composition in the field, with cool-season perennial plants increasing contributions to total biomass. The individual plant study tested the limits of direct fire effects for common Northern Great Plains graminoids. Fuel load proved to be a good estimator for predicting direct fire effects on plants and can be easily measured pre-fire and estimated following a wildfire.

Table 3.1 Pre-and-Post treatment vegetation percent relative biomass. **Bold** indicates significant.

Species	Pre-fire %	Post-Fire %	Standard Error	P>value
Hesperostipa comata	60.6	58.2	2.8	0.3913
Pascopyrum smithii	**10.7**	**17.7**	**2.3**	**0.0043**
Annual grass	**7.1**	**0.7**	**0.7**	**<.0001**
Carex filifolia	5.8	8.1	1.5	0.1248
Perennial forb	4.6	4.9	0.8	0.7265
Bouteloua gracilis	3.6	1.5	1.2	0.0805
Cool-season grass	**2.2**	**8.0**	**1.5**	**0.0003**
Warm-season grass	1.3	0.6	0.4	0.0582
Artemsia frigida	1.0	0.3	0.5	0.1449
Annual forb	0.8	0.1	0.6	0.2295
Aagropyron cristatum	0.4	0.0	0.4	0.3228

Table 3.2-Fuel load (100s kg ha^{-1}), degree-seconds (1000s^{o}C s above 60^{o}C), duration (min. above 60^{o}C), and maximum temperature (^{o}C) effects on change in field biomass relative to pre-fire estimates. Slope, Intercept, and r^{2}. **Bold** indicates significant at $p<0.05$

Species	Variable	Slope	Intercept	r^{2}	P-value
Bouteloua gracilis	Fuel load	-0.003	-0.40	0.03	0.44
Bouteloua gracilis	Degree-seconds	-0.006	-.45	0.008	0.67
Bouteloua gracilis	Duration	0.116	-0.29	0.05	0.30
Bouteloua gracilis	Maximum	0.000	-0.52	0.0001	0.97
Carex filifolia	**Fuel Load**	**-0.047**	**2.05**	**0.28**	**0.0074**
Carex filifolia	**Degree-Seconds**	**-0.166**	**1.82**	**0.24**	**0.0163**
Carex filifolia	**Duration**	**-1.534**	**3.16**	**0.37**	**0.0016**
Carex filifolia	Maximum Temperature	-0.0043	1.54.049	0.0594	0.2509
Hesperostipa comata	**Fuel load**	**-0.023**	**0.74**	**0.50**	**0.0001**
Hesperostipa comata	**Degree-seconds**	**-0.053**	**0.35**	**0.17**	**0.0421**
Hesperostipa comata	**Duration**	**-0.492**	**0.78**	**0.27**	**0.0087**
Hesperostipa comata	Maximum Temperature	-0.0014	0.26	0.04	0.3260
Annual grass	Fuel Load	0.8574	-0.00162	0.0193	0.5179
Annual grass	Degree-seconds	-0.01379	-0.01379	0.0930	0.1473
Annual grass	**Duration**	**-0.131**	**-0.67**	**0.15**	**0.0575**
Annual grass	Maximum Temperature	-0.8362	-0.0003	0.0145	0.5756
Total biomass	**Fuel load**	**-0.021**	**0.64**	**0.68**	**<0.0001**
Total biomass	**Degree-seconds**	**-0.056**	**0.36**	**0.32**	**0.0039**
Total biomass	**Duration**	**-0.529**	**0.84**	**0.53**	**<0.0001**
Total biomass	Maximum Temperature	0.17	-0.001	0.476	0.3057

Table-3.3 Fuel load (100s kg ha^{-1}), degree-seconds (1000s^{o}C s above 60^{o}C), duration (min. above 60^{o}C), and maximum temperature (^{o}C) effects on change in field frequency relative to pre-fire estimates. Slope, Intrcept, and r^{2}. **Bold** indicates significant at p<0.05

Species	Variable	Slope	Intercept	r^2	P-value
Bouteloua gracilis	Fuel load	0.68	-0.02	0.08	0.20
Bouteloua gracilis	Degree-seconds	0.34	-0.05	0.03	0.46
Bouteloua gracilis	Duration	0.72	-0.46	0.04	0.48
Bouteloua gracilis	Maximum	-0.001	0.27	0.0075	0.69
Carex filifolia	Fuel load	-0.02	0.72	0.05	0.29
Carex filifolia	**Degree-seconds**	**-0.11**	**1.16**	**0.18**	**0.04**
Carex filifolia	**Duration**	**-0.80**	**1.68**	**0.18**	**0.04**
Carex filifolia	Maximum	-0.004	1.23	0.08	0.19
Hesperostipa comata	**Fuel Load**	**-0.03**	**1.30**	**0.68**	**<0.0001**
Hesperostipa comata	**Degree-seconds**	**-0.10**	**0.99**	**0.41**	**0.0007**
Hesperostipa comata	**Duration**	**-0.88**	**1.76**	**0.65**	**<0.0001**
Hesperostipa comata	Maximum	-0.002	0.76	0.09	0.16
Pascopyrum smithii	Fuel load	-0.01	0.49	0.09	0.17
Pascopyrum smithii	Degree-seconds	-0.04	0.43	0.07	0.23
Pascopyrum smithii	**Duration**	**-0.45**	**0.88**	**0.16**	**0.07**
Pascopyrum smithii	Maximum	-0.00004	0.03	0.00	0.98
Bromus japonica	**Fuel Load**	**-0.003**	**-0.82**	**0.13**	**0.08**
Bromus japonica	**Degree-seconds**	**-0.01**	**-0.81**	**0.17**	**0.04**
Bromus japonica	**Duration**	**-0.10**	**-0.77**	**0.14**	**0.07**
Bromus japonica	Maximum	-0.0005	-0.80	0.08	0.17

Table 4.1 Minimum, maximum and average weather conditions during cage burns during autumn 2008 and summers of 2008 and 2009.

Weather variable	Autumn 2008			Summer 2008			Summer 2009		
	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.
Temperature (^oC)	9.4	28.9	22.1	26.1	37.2	32.7	20.6	35.0	28.4
RH (%)	15.0	56.0	27.5	10.0	22.0	14.7	17.0	55.0	30.1
Wind speed (m s^{-1})	2.1	7.7	4.0	1.6	7.2	3.8	1.6	11.3	4.3

Table 4.2. Slope, intercept, coefficient of determination, and p-value model describing fuel load (100s kg·ha^{-1}) effects on degree-seconds (1000s^{o}C s above 60^{o}C), duration (min. above 60^{o}C), and maximum temperature (^{o}C).

Heat variable	Season/Fuel	Slope	Intercept	r^2	P-value
Degree-seconds	Summer, grass fuel	4.30	550	0.56	<0.0001
	Autumn, grass fuel	0.99	7917	0.08	0.0030
	Summer, grass-shrub	12.57	-47820	0.46	<0.0001
Duration	Grass fuel	0.03	59	0.43	<0.0001
	Grass-shrub	0.18	-831	0.34	<0.0001
Maximum Temperature	All seasons and fuels	0.03	262	0.43	<0.0001

Table 4.3 Logistic regression explaining mortality of blue grama and needle-and-thread. Fuel load (100s kg ha^{-1}), Degree-seconds (1000s^{o}C s above 60^{o}C), Duration (min. above 60^{o}C), and Maximum temperature (^{o}C) effects on change in biomass relative to pre-fire estimates. Slope, Intercept, and r^2 C-Statistic.

Species	Predictor Variable	Likelihood ratio ($P>Chi^2$)	Hosmer Lemeshow ($P>Chi^2$)	% concordant	C-statistic	Max r^2
Bouteloua gracilis	Degree-seconds	<.0001	0.0066	89.9	0.900	0.48
	Duration	<.0001	0.0486	90.6	0.909	0.44
	Max	0.0003	0.2773	74.4	0.746	0.18
	Fuel load	<.0001	0.3437	90.7	0.919	0.56
Hesperostipa comata	Degree-seconds	<.0001	0.1663	85.1	0.854	0.47
	Duration	<.0001	0.2419	81.6	0.819	0.37
	Max	<.0001	0.7690	84.7	0.851	0.38
	Fuel load	<.0001	0.9177	84.5	0.863	0.38

Table 4.4- Fuel load (100s kg ha^{-1}), degree-seconds (1000s^{o}C s above 60^{o}C), duration (min. above 60^{o}C), and maximum temperature (^{o}C) effects on change in biomass relative to pre-fire estimates. Slope, Intercept, and r^2.

Response variable	Predictor variable	Year	r^2	Slope	P-value
Carex filifolia mass	Fuel load	2008	0.30	-0.006	0.0177
Pascopyrum smithii mass	Fuel load	2008	0.46	-0.004	0.0488
Pascopyrum smithii mass	Degree-seconds	2008	0.62	-0.011	0.0038
Hesperostipa comata tillers	Degree-seconds	2008	0.97	-0.018	0.0292
Bouteloua gracilis tillers	Fuel load	2009	0.47	-0.036	0.0032
Bouteloua gracilis mass	Fuel load	2009	0.42	-0.013	0.0066
Pascopyrum smithii mass	Fuel load	2009	0.70	-0.010	<.0001

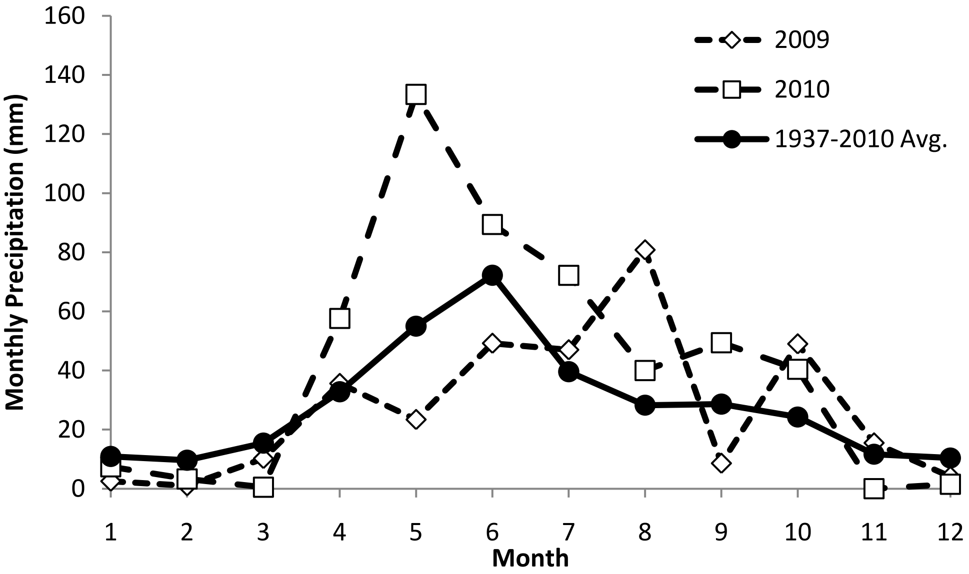

Figure 3.1-Precipitation data for 2009 and 2010 for the study area.

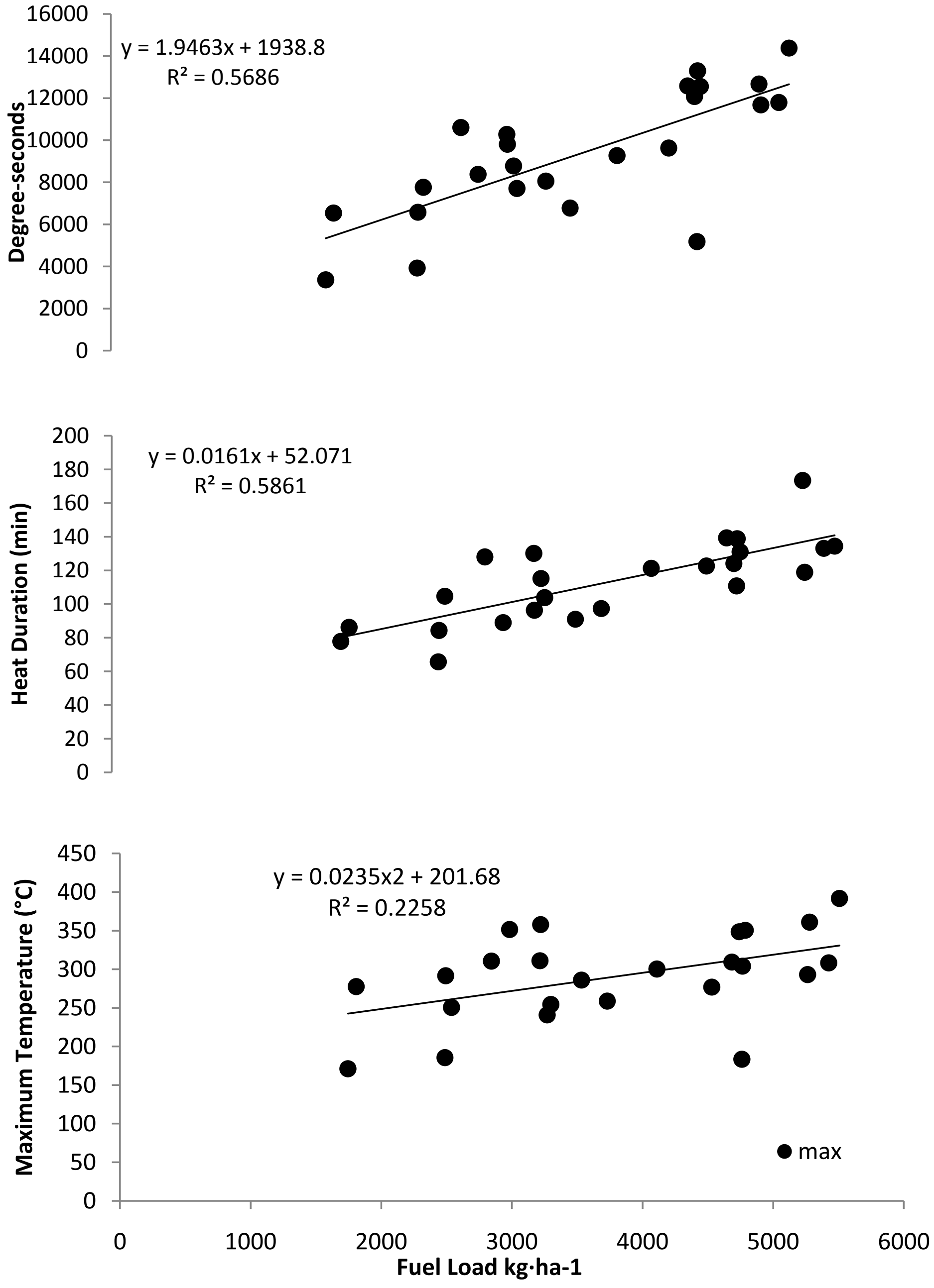

Figure 3.2 Fuel load affect on degree-seconds, heat duration, and maximum temperature.

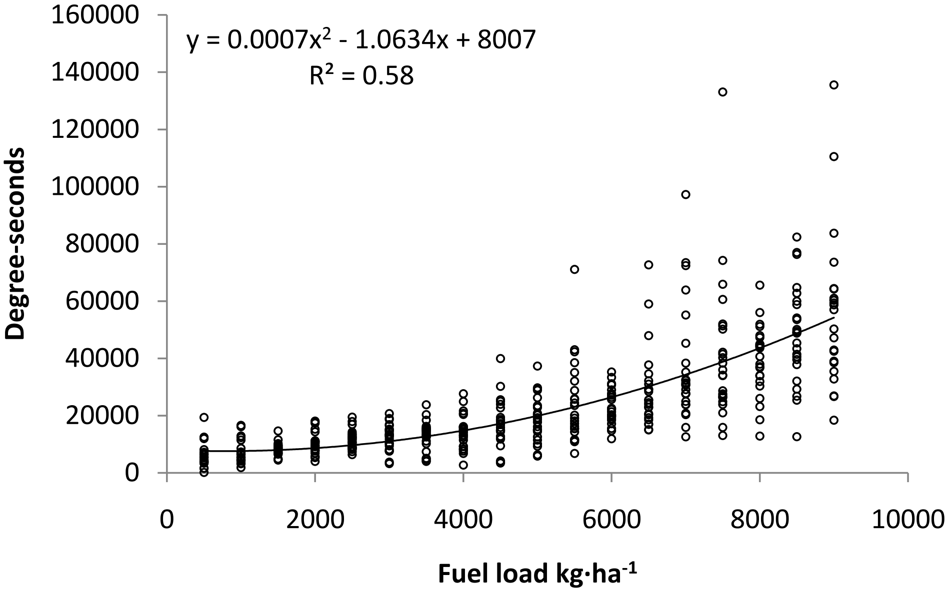

Figure 4.1-degree seconds combined across all treatments with relationship to fuel load.

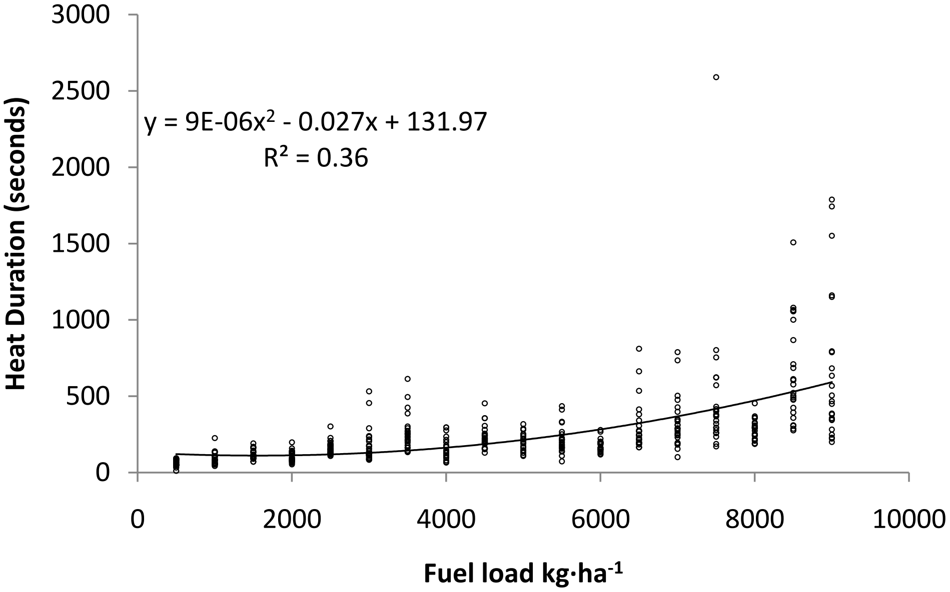

Figure 4.2 heat duration combined across all treatments with relationship to fuel load.

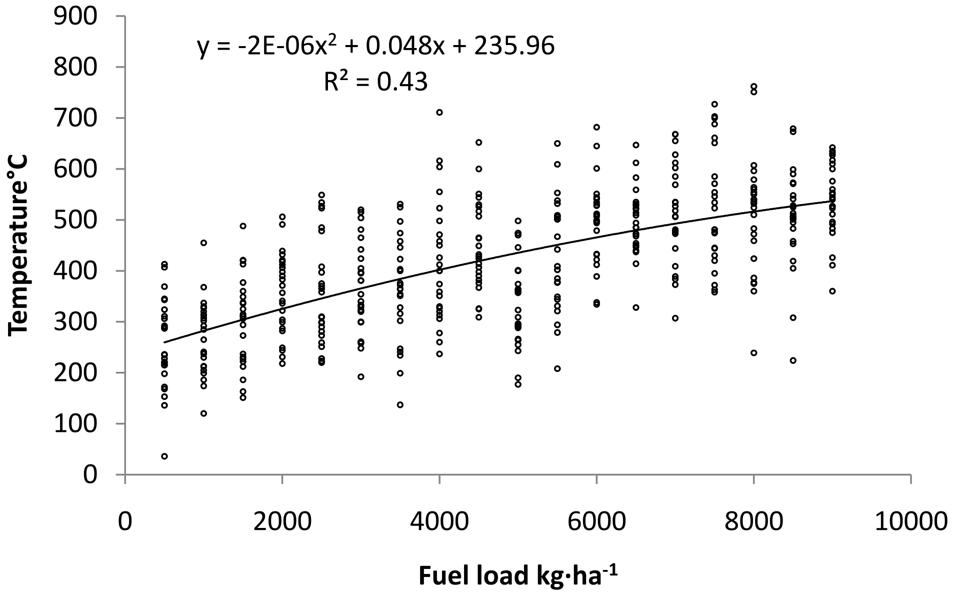

Figure 4.3 Maximum temperature combined across all treatments with relationship to fuel load.

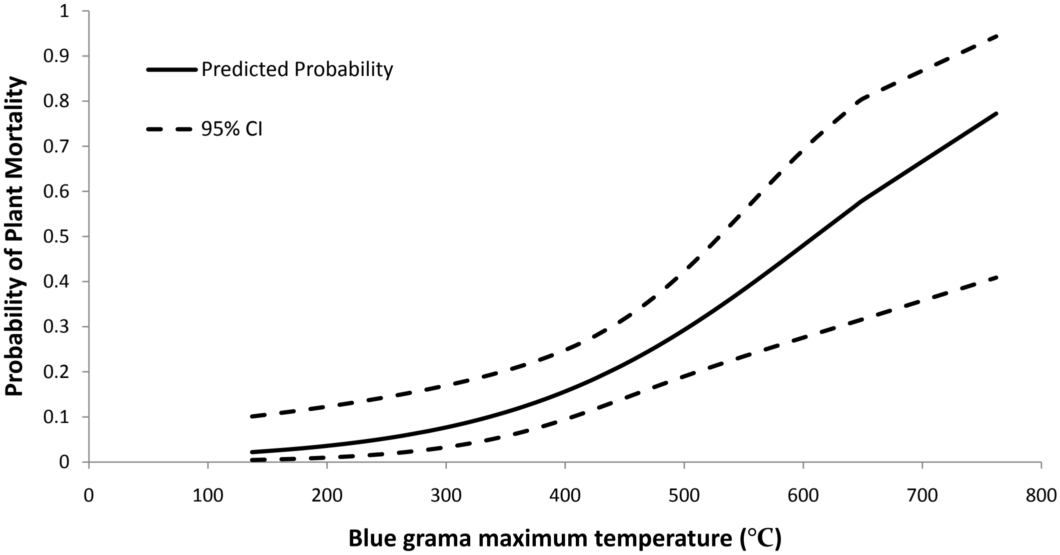

Figure 4.4-Probility of blue grama mortality as maximum temperature increased.

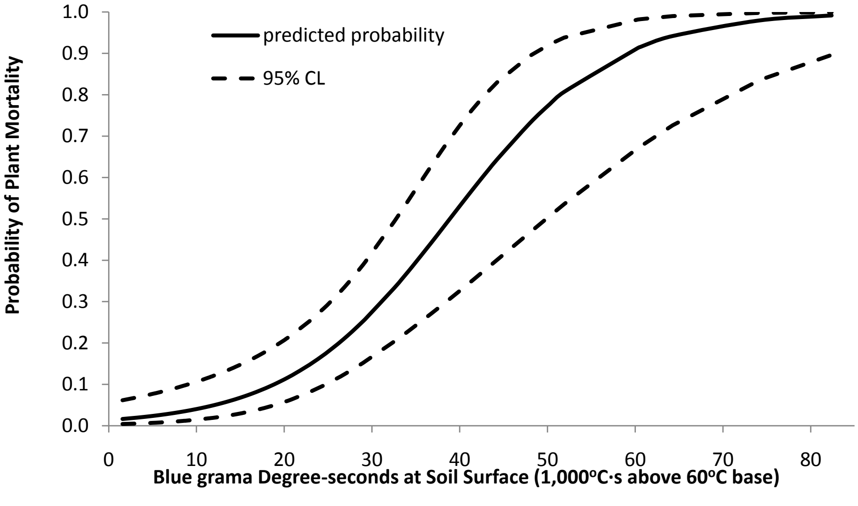

Figure 4.5- Probability of blue grama mortality as degree-seconds increased.

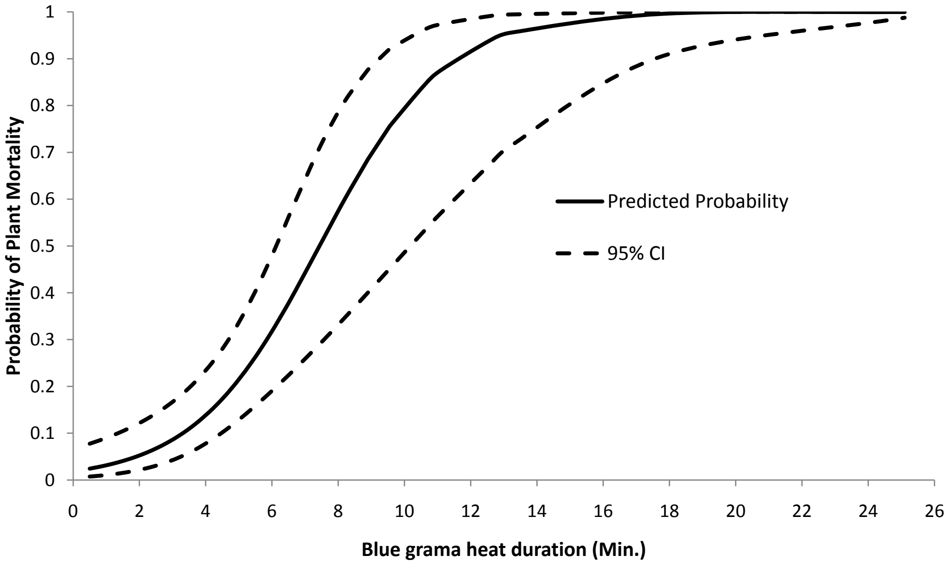

Figure 4.6 Probability of blue grama mortality as heat duration increased.

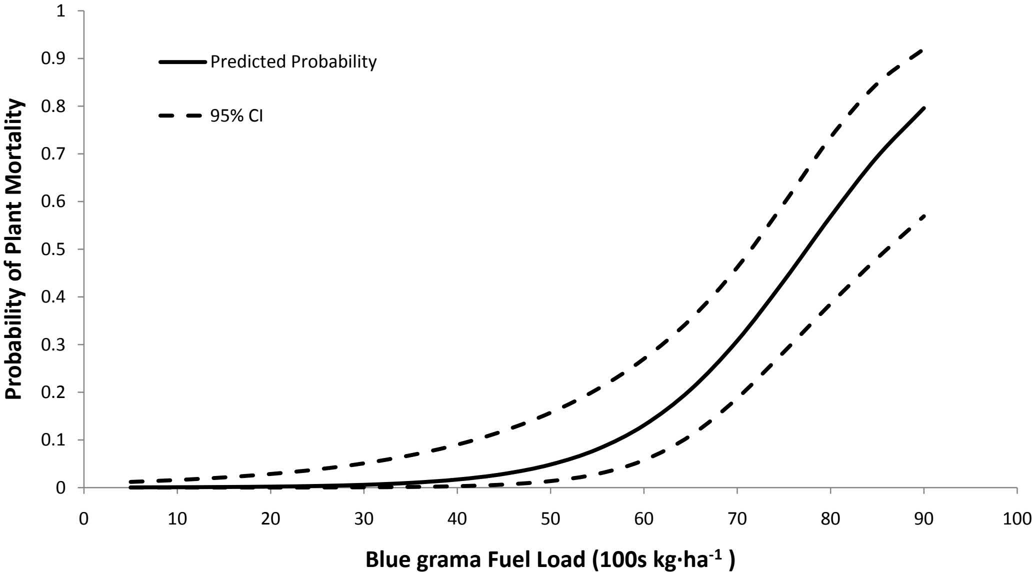

Figure 4.7 Probability of blue grama mortality as fuel load increased.

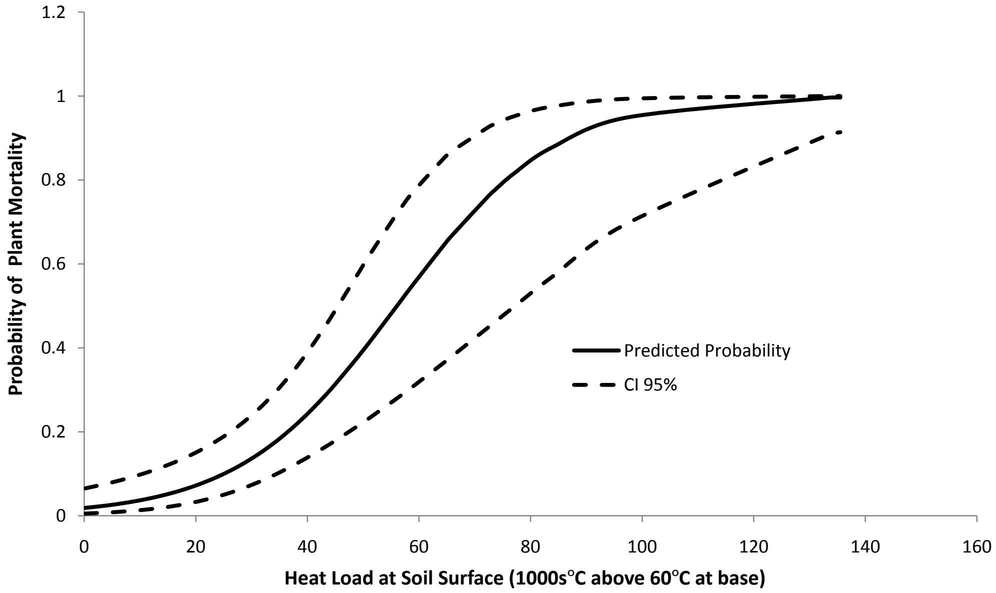

Figure 4.8-Probability of needle-and-thread mortality as degree-seconds increased.

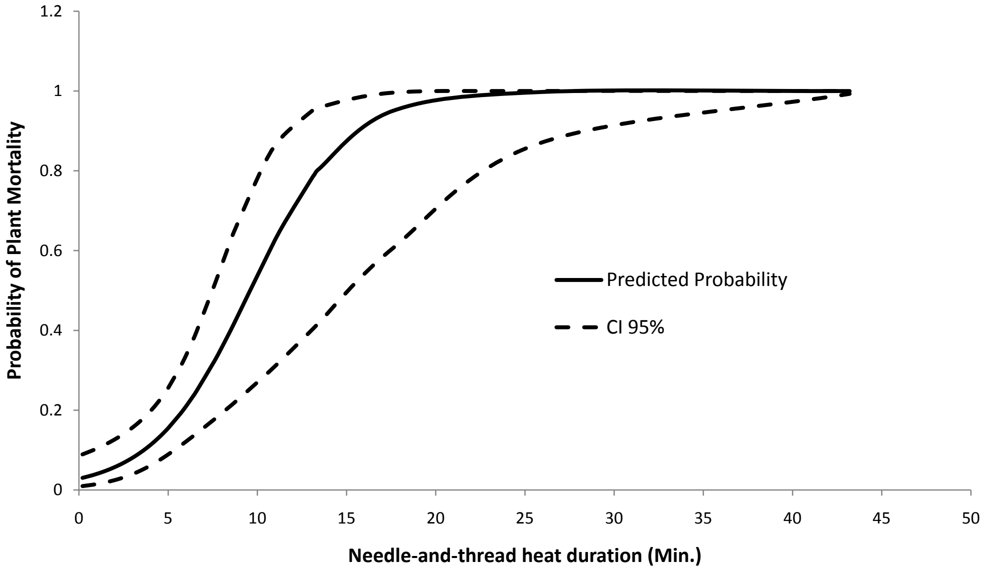

Figure 4.9- Probability of needle-and-thread mortality as heat duration increased.

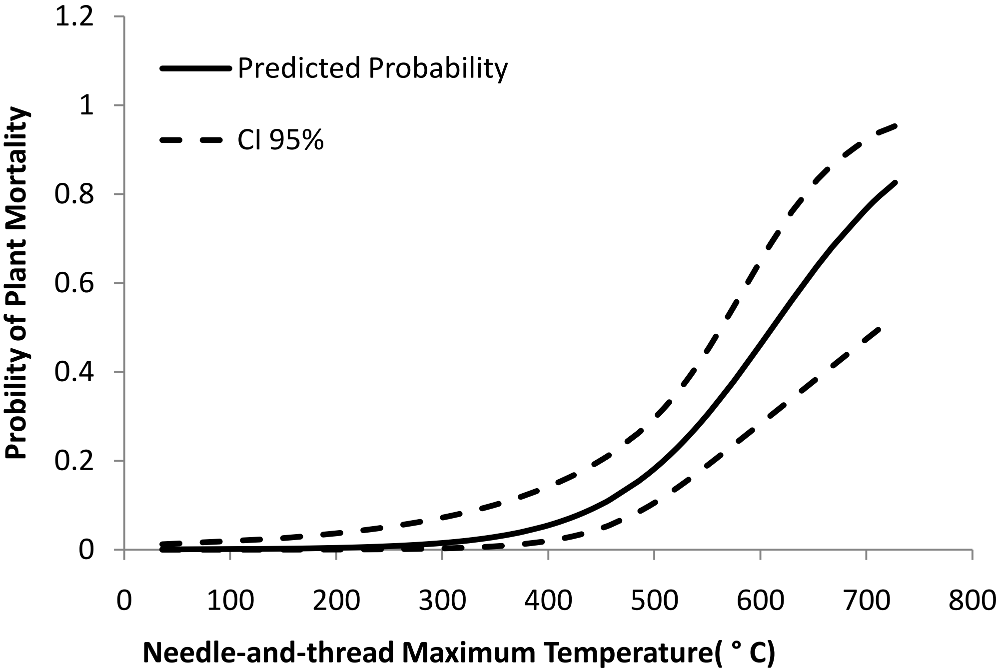

Figure 4.10-Probability of needle-and-thread mortality as maximum temperature increased.

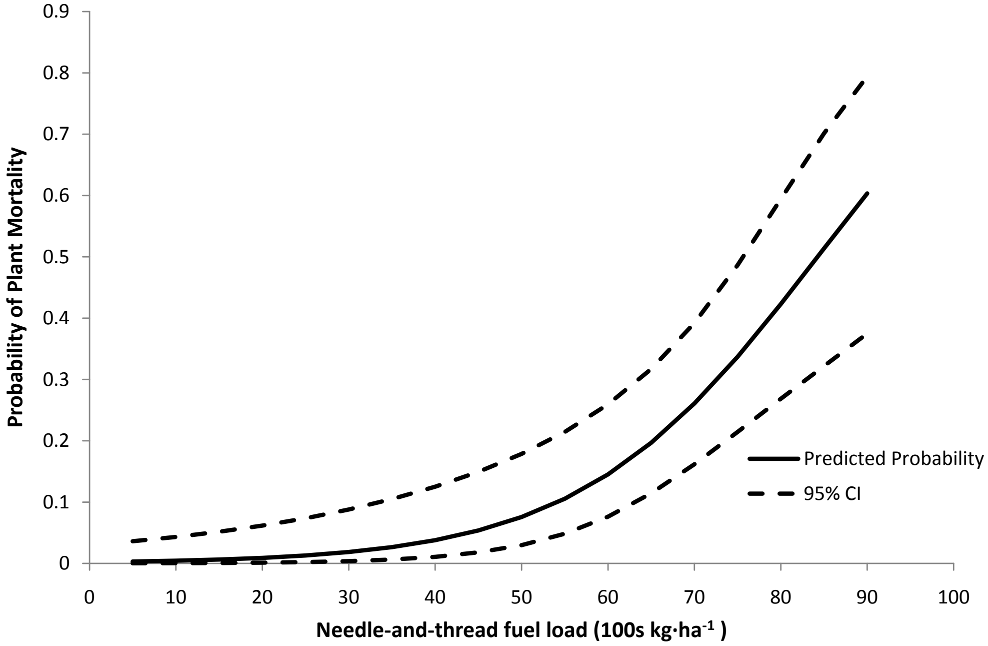

Figure 4.11- Probability of needle-and-thread mortality as fuel load increased.

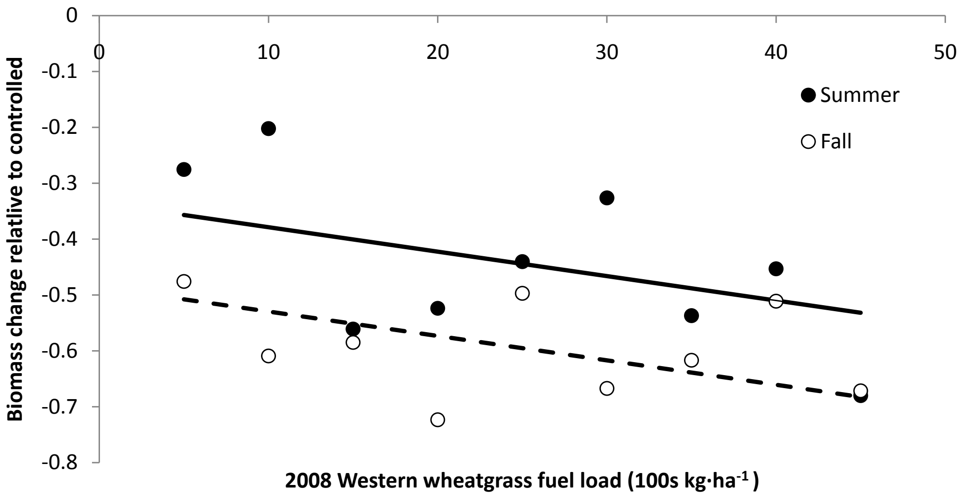

Figure 4.12-2008 Western wheatgrass change in biomass relative to controlled plants as fuel load increased.

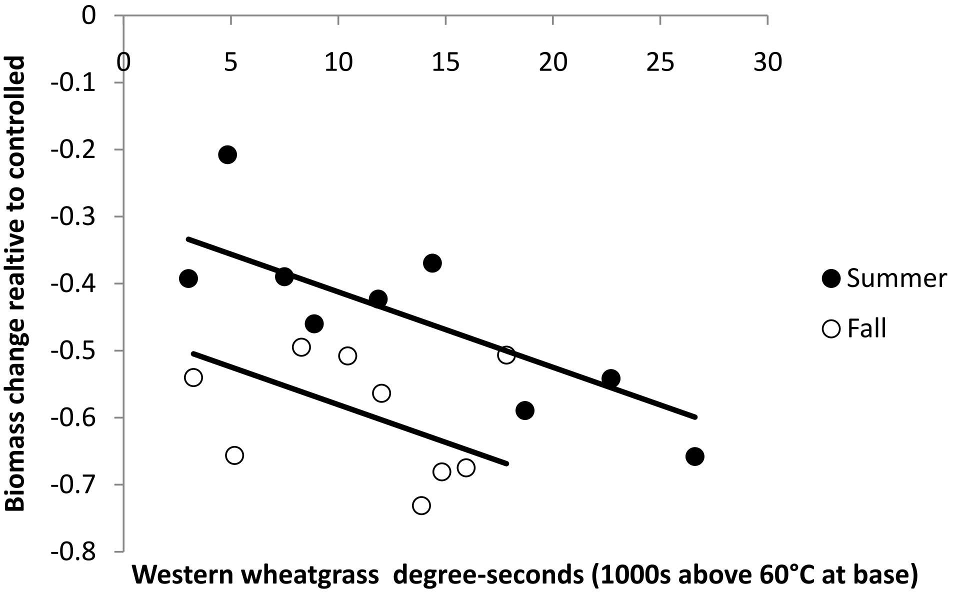

Figure 4.13-2008 western wheatgrass biomass change relative to controlled plants as fuel load increased.

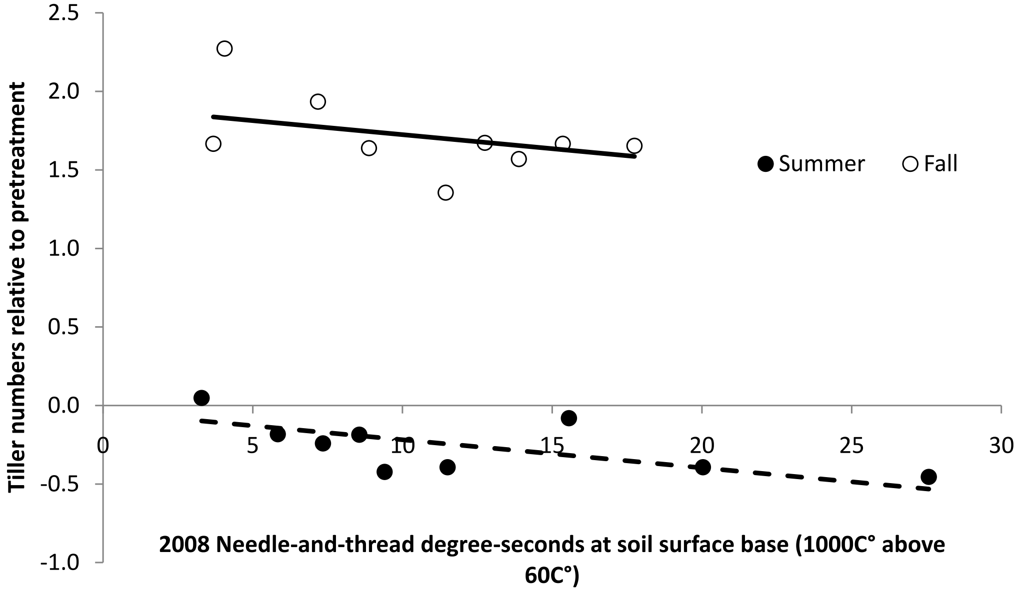

Figure 4.14-2008 Needle-and-thread tiller numbers change relative to pre treatment tiller numbers as degree seconds increased.

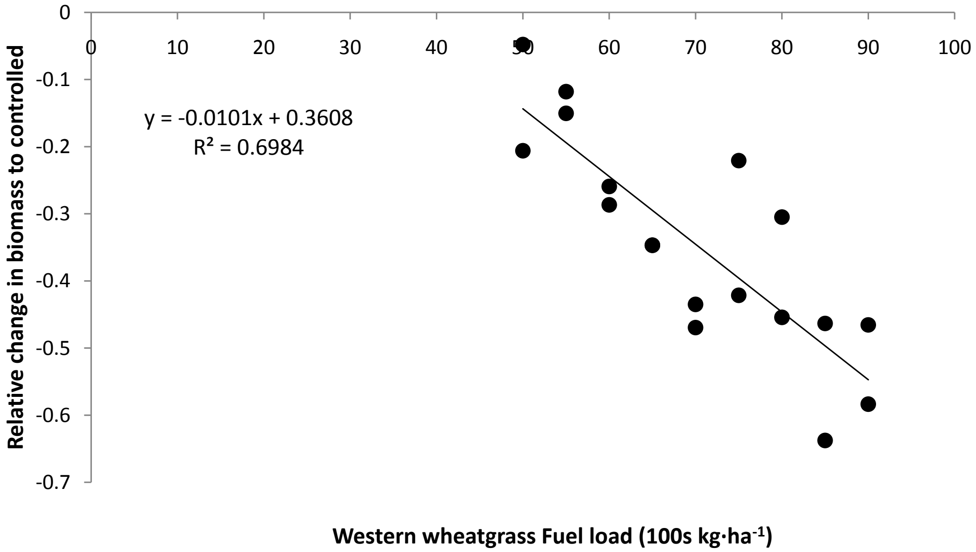

Figure 4.15-2009 Western wheatgrass biomass change relative to controlled plants as fuel load increased.

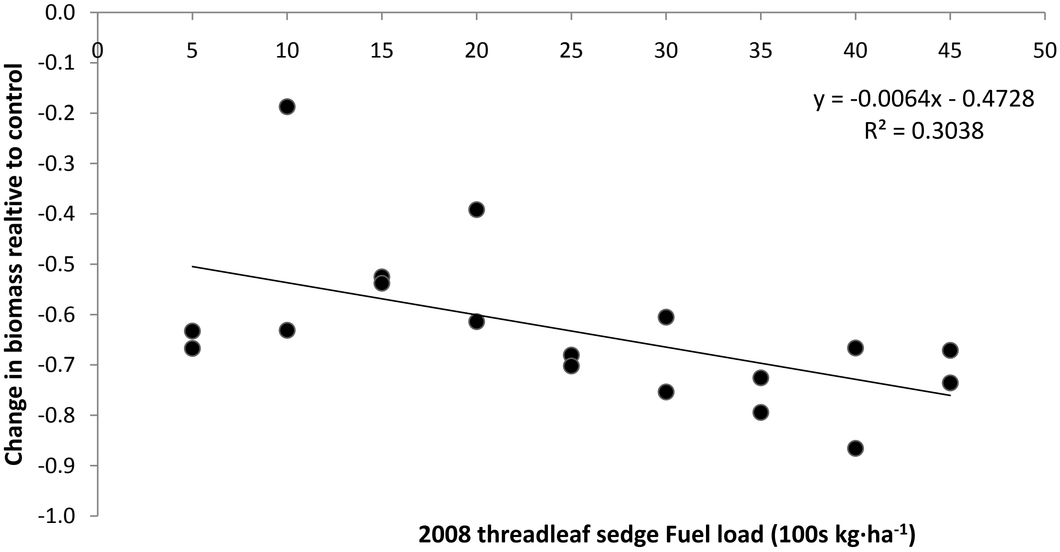

Figure 4.16 –2008 Threadleaf sedge change in biomass relative to controlled as fuel load increased.

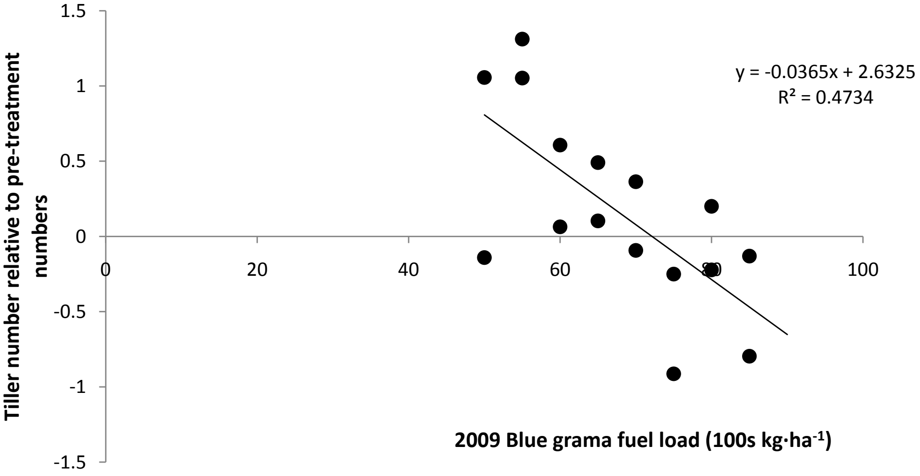

Figure 4.17-Blue grama tiller number change relative to pre-treatment tiller numbers as fuel load increased.

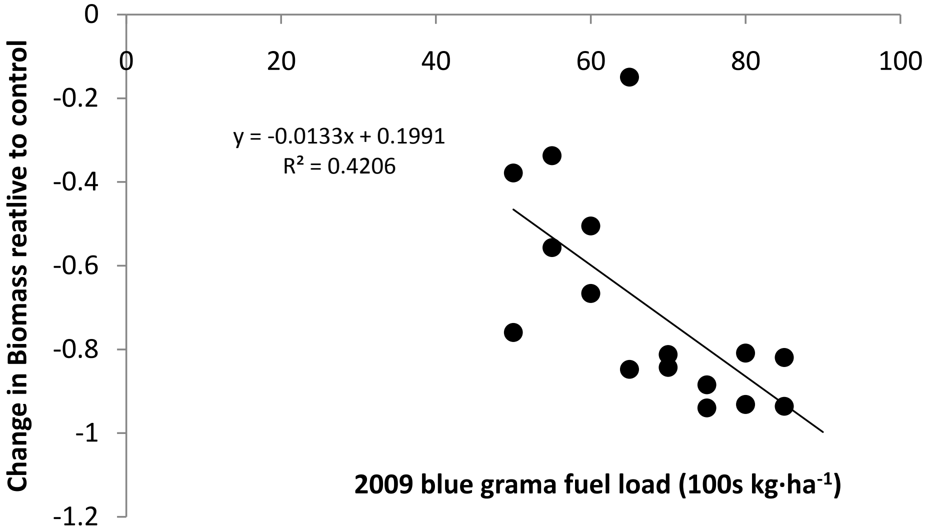

Figure 4.18-2009 change in biomass relative to controlled plants as fuel load increased.