FIRE BEHAVIOR AND FIRE EFFECTS ON TALLGRASS PRAIRIE

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CHAPTER I

INTRODUCTION

This dissertation is comprised of three manuscripts formatted for submission to the Journal of Range Management. This chapter introduces the rest of the dissertation. The three manuscripts are complete as written and do not need supporting material. The manuscripts include: Chapter II, Effects of spring headfires and backfires on tallgrass prairie; Chapter III, Behavior of headfires and backfires on tallgrass prairie; and Chapter IV, Prediciton of fire effects on tallgrass prairie herbage production.

Chapter II

EFFECTS OF SPRING HEADFIRES AND BACKFIRES ON TALLGRASS PRAIRIE

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Key Words: Fire behavior, fire effects

Abstract

We compared responses of tallgrass prairie vegetation to late spring headfires and backfires on a moderately stocked (2.4 AUM ha^{-1}) shallow prairie range site 15 km southwest of Stillwater, Oklahoma. We replicated treatments four times in a randomized complete block design on 10 X 20 m plots oriented with the prevailing wind direction. Treatment factors included burning treatments (headfire, backfire, and unburned check) and treatment years (1986 and 1987). Herbage standing crop was clipped to ground level in five, 0.25 m^2 quadrats per plot in June and August and separated into vegetation categories. Standing crop of tallgrasses in August was 21% (400 kg ha^{-1}) greater on headfired than backfired plots. Forb standing crop in August was 26% (98 kg ha^{-1}) greater on backfired plots than headfired plots. On tallgrass prairie managed for livestock, the area headfired should be maximized within the constraints of the burn prescription. Backfiring in late spring can be used to increase wildlife habitat on small areas.

INTRODUCTION

Fire has been an important environmental component of many ecosystems, especially grasslands, and has been responsible for determining vegetation over thousands of years (Humphrey 1962, Pyne 1982). Fire affects soil nutrients, soil moisture, and soil temperature which in turn influence the growth, reproduction, and distribution of many plant species (Ahlgren 1960, Kuchler 1964, Bragg 1982). As Europeans settled the Great Plains, natural prairie fires were suppressed because of fear of economic loss and lack of understanding of the role of fire in the grassland ecosystem. Because of fire suppression, there has been an increase of brush, including fire susceptible species such as eastern redcedar (Juniperus virginiana L.) (Ahlgren 1974) and sprouting species such as oaks (Quercus spp.) (Bragg and Hulbert 1976). Renewed interest in fire as a range management tool has resulted from an increased awareness of the role of fire in maintenance of the grassland ecosystem.

Our understanding is somewhat advanced on the effects of season of burning on tallgrass prairie vegetation, but our understanding is incomplete on the effects of other factors (e.g., fire frequency and fire type) on grassland vegetation response to fire (Wright and Bailey 1982). Towne and Owensby (1984), for example, have reported on the response of tallgrass prairie vegetation to long-term repeated seasonal burning. Responses to fire intensity also have been documented for woody vegetation (Van Wagner 1973), and more recently for herbaceous vegetation (Armour et al. 1984, Griffen and Friedel 1984, Roberts et al. 1988). The behavior of headfires and backfires in grasslands differ (Roberts et al. 1988), but we have found no studies which compare the effects of headfires and backfires on herbaceous vegetation in grasslands. Therefore, the objective of our study was to determine if there are differences in response of tallgrass prairie vegetation to late spring headfires and backfires.

STUDY AREA

The study area is located on the Agronomy Research Range approximately 15 km west southwest of Stillwater, Oklahoma. Mean annual precipitation is 81 cm (Meyers 1982). Precipitation in the 1986 early growing season (last 2 weeks of March, April, and the first 3 weeks of May) was 26 cm. Approximately 8 cm of precipitation was received during the same period in 1987 that normally receives more than 24 cm. The study area is located on a shallow prairie range site within the Central Rolling Red Prairies Land Resource Area (USDA Soil Conservation Service 1981). The soils are Grainola clay loam with a clay B horizon (Grainola series) and are members of the fine, mixed thermic family of Vertic Haplustalfs. Dominant grasses include big bluestem (Andropogon gerardii Vitman), switchgrass (Panicum virgatum L.), indiangrass (Sorghastrum nutans (L.) Nash), and little bluestem (Schizachyrium scoparium (Michx.)

Nash). The study area was grazed at a moderate to heavy stocking rate (2.4 AUM ha^{-1}) from mid-July to mid-November in 1985 and 1986 before the treatments were applied in the spring of 1986 and 1987.

METHODS AND MATERIALS

We replicated treatments four times in a randomized complete block design on 10 X 20 m plots oriented with the prevailing wind direction. Treatment factors included burning treatments (headfire, backfire, and unburned check) and treatment years (1986 and 1987). Plots were burned in March and April, as growth of C4 grasses was beginning, as recommended for tallgrass prairie by Launchbaugh and Owensby (1978). Burning conditions are given in Table 1. Current year's standing crop was measured to determine fire effects on vegetation. We clipped herbage standing crop to ground level in five 0.25 m^2 quadrats per plot in early July (peak of cool-season standing crop) and again in mid-August (peak of warm-season standing crop). Clipped samples were separated into five categories: (1) tallgrasses including big bluestem, indiangrass, and switchgrass; (2) little bluestem, (3) other perennial grasses and grass-like plants, primarily talldropseed (Sporobolus asper (Michx.) Kunth), silver bluestem (Bothriochola saccharoides (Sw.) Rydb.), scribner panicum (Panicum oligosanthes Schultes), fall witchgrass (Leptoloma cognatum Schult.), rattail grass (Manisuris cylindrica (Michx.) Ktze), sedges (Cyperus spp.), (Carex spp.), rushes (Juncus); (4) forbs, primarily common broomweed (Gutterrezia dracunculoides (DC.) Blake), trailing ratany (Krameria secundiflora DC)., western ragweed (Ambrosia psilostachya DC.), yarrow (Achillea lanulosa Nutt.); legumes, primarily purple prairie clover (Petalostemum purpureum (Vent.) Rydberg), scurfpea (Psoralea simplex (Nutt.) T. & G.), wild indigo (Baptisia australis (L.) R., Br.); and (5) cool-season annual grasses, primarily downy brome (Bromus tectorum L.). We selected these five vegetation categories because of their relative importance as forage sources for both cattle and wildlife, or because of their expected response to fire. Standing crop data were subjected to analysis of variance with repeated measures in time (split plot = clipping date) and 1 d.f. pre-planned orthogonal contrasts to test for burning treatment effects (backfire vs. headfire = type; burn vs. unburned = burn). Contrast differences were considered statistically different at the 10% level of probability.

RESULTS AND DISCUSSION

The only vegetation category of standing crop with a treatment-by-year interaction was total standing crop, so standing crop for other vegetation categories was pooled for 1986 and 1987. Standing crop of several herbage categories differed between fire type and burn treatments. Fire type differences were more evident in August, when growth rate of herbage in tallgrass prairie slows because of high air temperatures and low available soil water (Powell et al. 1986). Tallgrass standing crop was not different at the June clipping date, but by August headfired plots had more tallgrasses than backfired plots and burned plots had more than unburned plots (Figure 1a).

Little bluestem generally responds negatively to late spring burning (Towne and Owensby 1984). Although we expected little bluestem to respond similarly to backfires because of its growth form, it was not affected by either burning or fire type (Figure 1b). Because of its caespitose growth habit and accumulation of dead plant material within the crown, little bluestem appears especially susceptible to fire injury if conditions are dry (Towne and Owensby 1984). Precipitation before burning was average or above average in both years of our study, so fuel moisture was apparently adequate to protect little bluestem from injury.

Burning reduced the standing crop of other perennial grasses in June, but by August, burned and unburned plots were not different (Figure 1c). Standing crop of forbs was less on headfired plots than backfired plots in August (Figure 1d). It is well documented that perennial forbs are responsive to season of burning. Late spring burning in the tallgrass Kansas Flint Hills reduces forbs, whereas winter burning increases forbs (McMurphy and Anderson 1965, Towne and Owensby 1984). Forbs in tallgrass prairie may escape lethal temperatures within backfires because of the mosaic of differential fuel loading or micro-site soil differences. High levels of fuel moisture, particularly in grazed spots with accumulated mulch and litter, may prevent efficient combustion of some fuels, thus providing protection for emerging forbs.

Total standing crop in June and August 1986 was not affected by either spring burning or fire type (Figure 2a). In June 1987, however, total standing crop on burned plots was less than on unburned plots (Figure 2b). The response may be explained by an abnormally dry March and April, the effects of which did not carry over to August. Towne and Owensby (1984) reported that neither long-term annual burning nor burning at the proper time in late spring will reduce productivity (end of season yield) in the tallgrass prairie of the Flint Hills of Kansas, but we measured a reduction of early season standing crop in a dry spring. Tallgrass prairie species composition is responsive to burning, but peak or post-peak standing crop is unaffected by burning, even late summer wildfire (Ewing and Engle 1988). The reduced early growing season standing crop we measured in burned plots in 1987 may have resulted from reduced water available to plants following burning (Hulbert 1969, Owensby 1973, Peterson 1983), coupled with abnormally dry weather during the maximum tallgrass herbage growth period (Gillen and McNew 1987).

MANAGEMENT IMPLICATIONS

Fire type may be used with late spring burning to manipulate the standing crop of tallgrasses and forbs in the tallgrass prairie to meet different management objectives. Headfires produced 21% (400 kg ha^{-1})

more tallgrass standing crop in August than backfires and 40% (775 kg ha^{-1}) more tallgrass standing crop in August than unburned plots. Therefore, burning with headfires is more appropriate management in tallgrass prairies when the primary land use is cattle grazing. Under this landuse senerio, the backfired area should be minimized within the constraints of the fire prescription.

Most fire prescriptions to increase forbs for wildlife habitat improvement call for winter burning (Guthrey 1986, Landers and Mueller 1986). However, our data suggest that late spring backfires will increase forbs, provided the management unit was grazed in the previous year and fine fuel is discontinuous. Backfires increased forbs by 26% (98 kg ha^{-1}) over headfires and 14% (53 kg ha^{-1}) over unburned plots. Backfires also tended to leave areas of herbaceous plants unburned. Such patches of standing plants are beneficial to nesting birds, such as bobwhite quail (Colinus virginianus) (Lehmann 1984). The advantages of late spring burning over fall or winter burning also include reduced loss of standing dry forage for livestock, reduced loss of food and cover for wildlife in winter and early spring, and reduced labor and equipment costs when compared to burning in winter for wildlife habitat and spring for livestock forage quality improvement. Late spring backfires may not produce as much standing crop of forbs and legumes as winter burning (Towne and Owensby 1984), and may also destroy nests of game birds (e.g. wild turkey Meleagris gallopavo).

The logistics of using either headfiring or backfiring techniques must be considered when planning a burn. Rates of spread in our study indicate that headfires would advance approximately 2.7 km during a normal 6 hour burning period unless the fire front is disrupted by large areas of discontinuous fine fuel or dissected topography. Backfires would advance only approximately 0.2 km during a 6 hour period, but the advance of the fire front is even more dependent than headfires on continuous fine fuel and undissected topography. Backfires require more labor and have practical application only to small areas for wildlife habitat manipulation.

Literature Cited

Ahlgren, C. E. 1960. Some effects of fire on reproduction and growth of vegetation in northeastern Minnesota. Ecology 41:431-445.

Ahlgren, I. F. 1974. The effect of fire on soil organisms. p. 47-92 In: T.T. Kozlowski and C. E. Ahlgren (eds.). Fire and Ecosystems. Academic Press, New York.

Armour, C. D., S. C. Bunting, and L. F. Neuenschwander. 1984. Fire intensity effects on the understory in ponderosa pine forests. J. Range Manage. 37:44-49.

Bragg, T. B. 1982. Seasonal variations in fuel and fuel consumption by fires in bluestem prairie. Ecology 63:7-11.

Bragg, T. B., and L. C. Hulbert. 1976. Woody plant invasion of unburned Kansas bluestem prairie. J. Range Manage. 29:19-24.

Ewing, A. L., and D. M. Engle. 1988. Effects of late summer fire on tallgrass prairie microclimate and community composition. Am. Midl. Nat. 120:212-223.

Gillen, R. L., and R. W. McNew. 1987. Seasonal growth rates of tallgrass prairie after clipping. J. Range Manage. 40:342-345.

Griffin, G. F., and M. H. Friedel. 1984. Effects of fire on central Australian rangelands. I. Fire and fuel characteristics and changes in herbage and nutrients. Aust. J. Ecol. 9:381-393.

Guthrey, F. S. 1986. Beef, brush, and bobwhites: quail management in cattle country. Caesar Kleberg Wildlife Research Institute, Texas A&I Univ., Kingsville, TX.

Hollies, H. L. 1973. Management of wild turkey habitat in southern forest types. p. 245-252 In: G. C. Sanders on and H. C. Schult (eds.). Wild turkey management: current problems and programs. Missouri Chap. The Wildl. Soc. and Univ. Missouri Press, Columbia.

Hulbert, L. C. 1969. Fire and litter effects in undisturbed bluestem prairie in Kansas. Ecology 50:874-877.

Humphrey, R. R. 1962. Range ecology. Ronald Press, New York.

Kuchler, A. W. 1964. Potential natural vegetation of the conterminous United States. Manual to accompany the map. Amer. Geog. Soc. Spec. Pub. 36.

Landers, J. L., and B. S. Mueller. 1986. Bobwhite quail management: a habitat approach. Misc. Pub. 6, Tall Timbers Research Station, Tallahassee, FL.

Launchbaugh, J. L., and C. E. Owensby. 1978. Kansas rangelands: their management based on a half century of research. Kansas Agr. Exp. Sta. Bull. 622., Kansas State Univ., Manhattan.

Lehmann, V. W. 1984. Bobwhites in the Rio Grande Plain of Texas. Texas A&M Univ. Press, College Station.

Meyers, H. R. 1982. Climatological data of Stillwater, Oklahoma 1893-1980. Okla. Agr. Exp. Sta. Res. Rep. P-821.

McMurphy, W. E., and K. L. Anderson. 1965. Burning flint hills range. J. Range Manage. 18:265-269.

Owensby, C. E. 1973. Burning true prairie. p. 1-4 In: L. C. Hulbert (ed.). Proc. Third Midwest Prairie Conf., Kansas State Univ., Manhattan.

Peterson, N. J. 1983. The effects of fire, litter, and ash on flowering in *Andropogon gerardii*. p. 21-24 In: R. Brewer (ed.). Proc. Eighth North American Prairie Conf. Western Michigan Univ., Kalamazoo.

Powell, J., S. J. Stadler, and P. L. Claypool. 1986. Weather factors affecting 22 years of tallgrass prairie production and quality. J. Range Manage. 39:354-361.

Pyne, S. J. 1982. Fire in America: a cultural history of wildland and rural fire. Princeton Univ. Press, Princeton, N. J.

Roberts, F. H., C. M. Britton, D. B. Wester, and R. G. Clark. 1988. Fire effects on tobosograss and weeping lovegrass. J. Range Manage. 41:407-409.

Towne, G., and C. E. Owensby. 1984. Long-term effects of annual burning at different dates in ungrazed Kansas tallgrass prairie. J. Range Manage. 37:392-397.

USDA Soil Conservation Service. 1981. Land resource regions and major land resource areas of the United States. Agric. Handb. 296, USDA Soil Cons. Serv., U.S. Government Printing Office, Washington, DC.

Wolfe, C. W. 1972. Effects of fire on a sandhills grassland environment. Proc. Tall Timbers Fire Ecol. Conf. 12:241-255.

Wright, H. A., and A. W. Bailey. 1982. Fire ecology: United States and southern Canada. John Wiley, New York.

Van Wagner, C. E. 1973. Height of crown scorch in forest fires. Can. J. For. Res. 3:373-378.

Table 1. Fuel loading and weather conditions for spring headfires and backfires on tallgrass prairie in northcentral Oklahoma, 1986 and 1987.

	1986					
	Headfire			Backfire		
	$\overline{X}$	SE	Range	$\overline{X}$	SE	Range
Fuel load (kg/ha)	2981	378	2544-4052	2967	493	2372-4440
Air temp. °C	19	2	15-23	18	1	15-20
Wind speed (km/h)	12	4	5-24	11	4	5-23
Rel. humidity (%)	40	4	33-51	42	3	34-46

	1987					
Fuel load (kg/ha)	4156	559	3208-5584	4176	420	3064-5104
Air temp. °C	23	1	21-24	24	1	21-26
Wind speed (km/h)	9	1	8-10	9	1	8-10
Rel. humidity (%)	28	3	21-36	25	4	18-36

Figure 1. Standing crop of tallgrasses (a), little bluestem (b), other perennial grasses (c), and forbs (d).

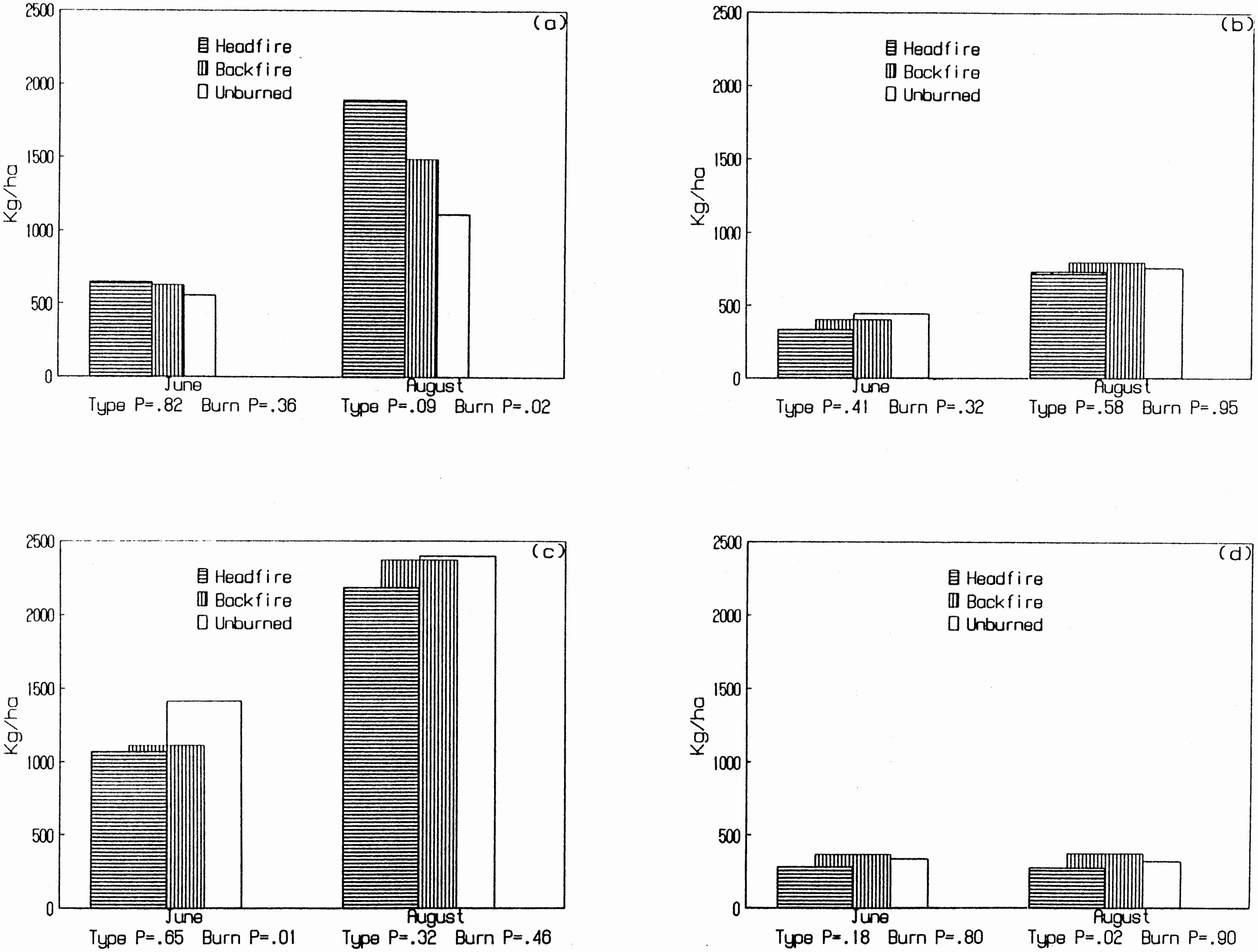
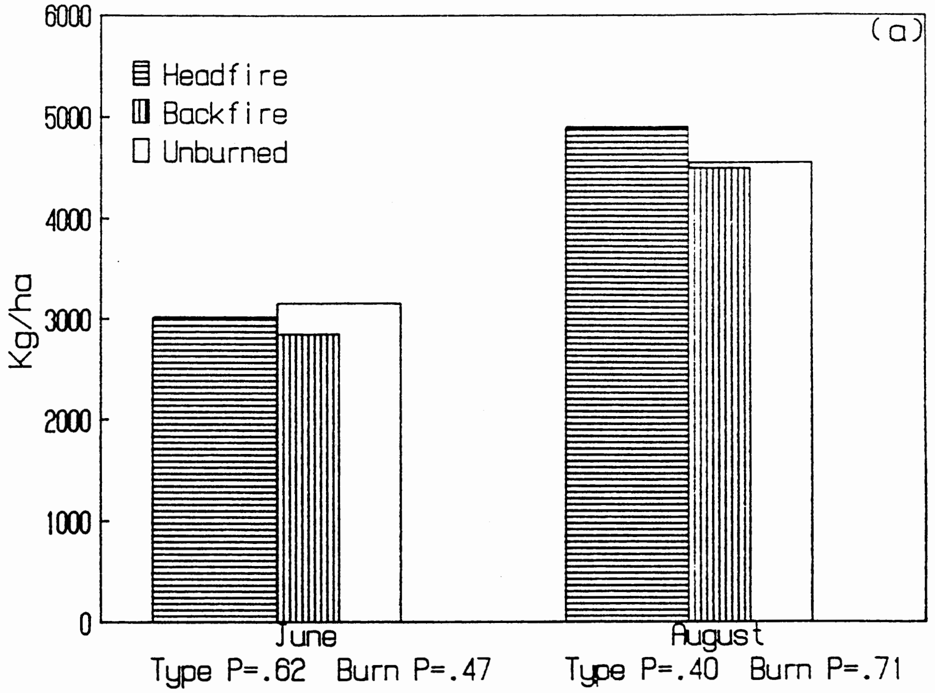
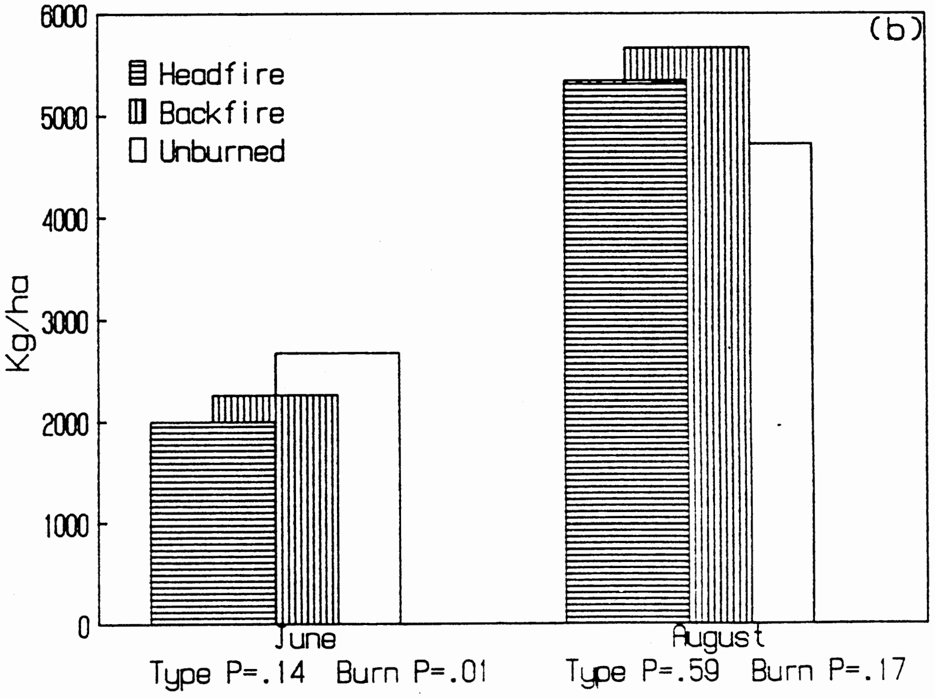

(a)
Headfire
Backfire
Unburned
Kg/ha
0
500
1000
1500
2000
2500
June
Type P=.82 Burn P=.36
August
Type P=.09 Burn P=.02
(b)
Headfire
Backfire
Unburned
Kg/ha
0
500
1000
1500
2000
2500
June
Type P=.41 Burn P=.32
August
Type P=.58 Burn P=.95
(c)
Headfire
Backfire
Unburned
Kg/ha
0
500
1000
1500
2000
2500
June
Type P=.65 Burn P=.01
August
Type P=.32 Burn P=.46
(d)
Headfire
Backfire
Unburned
Kg/ha
0
500
1000
1500
2000
2500
June
Type P=.18 Burn P=.80
August
Type P=.02 Burn P=.90

Figure 2. Total standing crop 1986 (a) and 1987 (b) on a shallow prairie range site in northcentral Oklahoma.


(a)
Headfire
Backfire
Unburned
6000
5000
4000
3000
2000
1000
0
Kg/ha
June
Type P=.62 Burn P=.47
August
Type P=.40 Burn P=.71


(b)
Headfire
Backfire
Unburned
6000
5000
4000
3000
2000
1000
0
Kg/ha
June
Type P=.14 Burn P=.01
August
Type P=.59 Burn P=.17

Chapter III

BEHAVIOR OF HEADFIRES AND BACKFIRES ON TALLGRASS PRAIRIE

Terrence G. Bidwell

Key Words: Fire, fire behavior, fire environment, Oklahoma

Abstract

We measured the behavior of 16 (8 headfires and 8 backfires) spring fires on tallgrass prairie using Byram's fireline intensity model and time-temperature relationships. We measured weather and fuel parameters for use as independent variables in regression models of fire behavior. Fireline intensity was greater for headfires than backfires, but there was less difference between headfires and backfires for time-temperature relationships. Fire type (headfire or backfire) and measurements of fuel continuity, fuel loading, and fuel moisture were good predictors of fire behavior.

INTRODUCTION

Data about the behavior of fire in the tallgrass prairie are needed in order to increase our understanding of the interactions of fire behavior, fire environment, and fire effects. Previous studies of fire behavior have been confined primarily to wildfire in forest and shrublands and described mainly in terms of fireline intensity (Byram 1959, Wright and Bailey 1982). Because of its relationship to crown scorch of conifers (Van Wagner 1973) and its use in describing wildfire behavior (Albini 1976), fireline intensity is thought to be equally useful for describing fire behavior in grasslands (Rothermel 1972, Albini 1976) and for predicting scorch height on rangeland shrubs (Roberts et al. 1988).

Although fireline intensity accounts for the heat or energy released in the initial fire front, it does not account for energy released over the entire depth of the combustion zone (Tangren 1976, Alexander 1982). To describe quantitatively the residual combustion zone that occurs in grassland fires, fire temperatures and time-temperature relationships have been suggested as an alternative to fireline intensity (Engle et al. 1988). Time-temperature relationships have been used to quantify fire behavior and to explain fire effects on herbaceous vegetation (Stinson and Wright 1969, Wright 1971, Hobbs and Gimingham 1984, Ewing and Engle 1988).

Studies of backfires and headfires in grasslands do not agree on which fire type produces the higher maximum temperature at the soil surface (McKell et al. 1962, Daubenmire 1968, Bailey and Anderson 1980). Because both fire types are used in prescribed spring burns in the tallgrass prairie, elucidation of the behavior of headfires and backfires is needed. Time-temperature relationships may be useful in describing differences between headfires and backfires in energy release in the combustion zone.

The environment in which a fire occurs dictates its behavior and may explain the contradictions regarding headfire and backfire behavior. Parameters of the fire environment that are commonly measured by rangeland fire managers may also be useful for predicting fire behavior in tallgrass prairie. The objectives of our study were to compare fire behavior of headfires and backfires and to determine if fire type and the fire environment can be used to predict and explain the variability in behavior of spring fires in the tallgrass prairie.

STUDY AREA

Our study area is located on the Agronomy Research Range approximately 15 km west southwest of Stillwater, Oklahoma. Mean annual precipitation is 81 cm. The study area is a shallow prairie range site in the Central Rolling Red Prairies Land Resource Area (USDA Soil Conservation Service 1981). The soil is Grainola clay loam with a clay B horizon and is a member of the fine, mixed thermic family of Vertic

Haplustalfs. Dominant grasses on the site include big bluestem (Andropogon gerardii Vitman), switchgrass (Panicum virgatum L.), indiangrass (Sorghastrum nutans (L.) Nash), and little bluestem (Schizachyrium scoparium (Michx.) Nash). The study area was grazed at a moderate to heavy stocking rate (2.4 AUM ha^{-1}) from mid-July to mid-November in 1985 and 1986 before the treatments were applied in the spring of 1986 and 1987.

METHODS AND MATERIALS

We replicated treatments four times in a randomized complete block design on 10 X 20 m plots located on nearly level terrain (<2% slope), and oriented southeast to northwest to correspond to the southeast winds that prevail during the spring. Each replication consisted of a headfired plot, a backfired plot, and an unburned plot. We set the fires at plot borders with a drip torch. Burning treatments began in March and ended in April. Each replication was burned within a 4 hour burning period and weather variables and fuel load were sampled immediately before each burn. Weather variables were measured using a belt weather kit and included ambient air temperature, relative humidity, and wind speed at 2 m above the ground. Fuel load was measured by clipping herbaceous material in five quadrats (0.5 X 0.5 m) per plot. Clipped herbage was separated into standing and fallen fine fuels (litter and mulch) and was weighed. Fuel moisture, expressed on a dry weight basis, was determined after samples were oven dried at 70°C for 72 hrs (Table 1).

We measured fire temperatures at 2 sec intervals using high-temperature, chromel-alumel thermocouples at three stations per plot and at three heights relative to the soil surface (0 cm = soil surface; 30 cm = top of herbaceous canopy; 60 cm = above the herbaceous canopy). An electronic data logger (Campbell Scientific model 21X with multiplexer) with tape data storage was used to record time-temperature data. Traces of time-temperature that were recorded for each thermocouple allowed an estimate of degree seconds above ambient temperature (Potter et al. 1983), maximum temperature, and residence time (the time from initial temperature rise to time of definite temperature drop) (Rothermel and Deeming 1980).

A program in Turbo Pascal for IBM compatible microcomputers was used to generate each of these variables from the thermocouple data. The program includes a discrete summation algorithm to arrive at an estimate of degree seconds, the area above ambient temperature and under the time-temperature curve (Table 2). The points of definite temperature rise and drop for computing residence time were numerically determined by sequential reverse progression through a 10 second interval of the time-temperature curve to points of 2 °C or greater departure from the postburn ambient temperature (Engle et al. 1988).

Byram's (1959) fireline intensity model is expressed as I = Hwr, where I is fireline intensity, H is the fuel's low heat of combustion (LHOC)(kJ kg^{-1}), w is the weight of fuel consumed per unit area (Kg m^{-2}), and r is the rate of spread (m s^{-1}). Low heat of combustion was determined by bomb calorimetry for the total fuel sample (standing and fallen). Rate of spread was reported in m min^{-1} for all other calculations.

We measured rate of spread with a stopwatch and photographically with a 35 mm camera time-mode device similar to that of Britton et al. (1977). Statistical analyses were performed on fire behavior data using analysis of variance procedures. Stepwise multiple regression techniques were used to construct predictive models of fire behavior from environmental variables listed in Table 1. Variation measures associated with fuel load (i.e., standard deviation, coefficient of variation, and minimum quadrat sample values) were included as regression variables to account for variation in fuel continuity. Variation and minimum values of fuel loading were derived from five quadrats per plot. Differences in means were considered significant at the 10% probability level.

RESULTS

Fireline intensity of headfires averaged 1170 ± 445 kW m^{-1} which was 12 times greater than fireline intensity of backfires (100 ± 18 kW m^{-1}) (P=0.03). Rate of spread, the main influence on Byram's fireline intensity, was greater for headfires (12.6 ± 6.0 m min^{-1}) than backfires (1.2 ± 0.2 m min^{-1}) (P=0.09).

Degree seconds were greater for backfires than headfires only at 30 cm (P=0.02) (Figure 1a). Headfires produced greater maximum temperatures than backfires at 30 cm (P=0.02) and 60 cm (P=0.01) above the soil surface but there was no difference at the soil surface (P=0.97) (Figure 1b). Residence time was not different (P=0.80) between headfires and backfires at any of the three thermocouple heights (Figure 1c). Except for residence time, parameters derived from temperature traces are more precise measurements of fire behavior above the soil surface than at the soil surface (Figure 1a, 1b, 1c).

Fire type was the single most important regression variable and the first entered variable in 7 of 11 models of fire behavior (Table 3). Variables related to fuel were the first to enter in four models and a combination of fuel moisture and fuel discontinuity accounted for 7 of 12 variables that entered the regression models for maximum temperature. Fuel loading, fuel moisture, and fuel continuity made up 73% of the second, third, and fourth variables in all regression models of fire behavior. All variables entering the regression model of residence time at the soil surface were measures of fuel continuity (Table 3).

DISCUSSION

Behavior of Headfires vs. Backfires

Our data do not completely support the generalization that headfires are more intense than backfires (Lindenmuth and Byram 1948). Headfires are considered to be more intense because of more rapid fuel consumption and rate of spread (Lindenmuth and Byram 1948, Trollope 1984). Fireline intensity and rate of spread were greater in headfires in our study, but several time-temperature parameters were not different between fire types. Fireline intensity of both headfires and backfires in our study was similar to those reported in other grassland fire studies (Engle et al. 1988, Roberts et al. 1988). The maximum fireline intensity of 2778 kW m^{-1} we measured in a headfire was one-third of that reported in homogeneous grass stands in West Texas (Roberts et al. 1988), but was comparable to a summer headfire in a moderately grazed tallgrass prairie (Engle et al. 1988). The ten-fold difference we measured in ROS between fire types is consistent with the rate of spread in two grassland communities in west Texas (Roberts et al. 1988). Rate of spread and fuel consumption are the major variables in Byram's model of fireline intensity.

Although degree seconds at 30 cm was different between fire types, the difference at all strata was much less than the difference in fireline intensity and ROS between the two fire types. Degree seconds relate to the heat released over the entire combustion period whereas fireline intensity represents only the rate of heat energy released from the initial flaming front. Thus, the rate of heat released is greater in headfires, but the total amount of heat released is similar for both fire types.

Both fire types have been reported to be hotter above the herbaceous canopy (Fahnestock and Hare 1964, Bailey and Anderson 1980, Trollope 1984). In our study, maximum temperature was highest in both backfires and headfires at 30 cm, but maximum temperature declined more from 30 cm to 60 cm in the backfire. Maximum temperature above the herbaceous canopy is higher in headfires because the rate of energy release and convection is greater in headfires. Thus, differences between fire type in maximum temperature above the herbaceous canopy reflect the rate of energy release much like fireline intensity.

There is disagreement in the literature as to which fire type produces the hotter fire at the soil surface. McKell et al. (1962) found that backfires produced higher temperatures than headfires at the soil surface, but Daubenmire (1968) reported headfires were hotter than backfires at the soil surface. Maximum temperatures at the soil surface were not different in our study, although they were highly variable in both fire types.

Fire temperature in the combustion zone is primarily dependent upon the quantity of fine fuel consumed (Stinson and Wright 1969, Engle et al. 1988). Fine fuel load also has a pronounced effect on residence time, which increases proportionally to fuel load (Stinson and Wright 1969), especially with accumulation of mulch (Engle et al. 1988). The time required for active combustion was very near the same in both fire types in our study and we would expect a difference in residence time only with differences in fuel loading or fuel consumption.

Prediction Models

After fire type, fuel variables rather than weather variables were the primary fire environment variables related to fire behavior. Although fuel load was the first entered variable in just one of our models, fuel load accounted for 30-60% of the variation in fireline intensity in grassland fires in Africa (Trollope and Potgieter 1983). Fuel moisture was a more important variable than fuel load in both time-temperature and fireline intensity prediction models, possibly because of the extreme variability of the burns. Fuel moisture affects ignition and combustion more than any other environmental factor (Byram 1957, Brown and Davis 1973).

Fuel continuity variables were present in all but two models. Fuel continuity is a primary factor in fire behavior but is less important when heavy fuels are available or wind speed is high (Brown and Davis 1973). Wind speed is an important influence on fire behavior including rate of spread (Rothermel 1972, Albini 1976), but fuel discontinuity may alter the influence of wind so much that mathematical fire models become poor approximations of fire behavior (Brown 1982). Mathematical models assume uniform fuel which seldom occurs on tallgrass prairie (Brown 1982). Our study area contained dicontinuous fuels, and wind speed did not enter any of our fire behavior prediction models (Table 3).

CONCLUSIONS

Fireline intensity and rate of spread, measures of fire behavior that relate to behavior of the flaming fire front and rate of energy release, indicate that headfires are more intense than backfires. Time-temperature measures of fire behavior that account for energy released across the entire combustion zone indicate lesser differences between fire types. The behavior of backfires, however, is more variable than headfires in discontinuous fuels.

Other than fire type, fuel loading and fuel moisture are important variables in regression models of fire behavior because they determine to a large extent the energy available in the combustion process. Fuel continuity measures are important variables because they reflect the subtle fuelbed and microclimate differences associated with discontinuous fuels. Discontinuous fuels or disturbed patches form a mosaic that often results from spot grazing by large herbivores, soil disturbance from small mammals, soil heterogeneity, or natural spatial heterogeneity of tallgrass vegetation (Loucks et al. 1985). Thus, these environmental parameters together with fire type increase our understanding of fire environment effects on fire behavior and should allow us to achieve a greater understanding of the role of fire as an environmental factor in the native tallgrass plant community.

LITERATURE CITED

Albini, F. A. 1976. Estimating wildfire behavior and effects. USDA For. Serv. Gen. Tech. Rep. INT-30.

Alexander, M. E. 1982. Calculating and interpreting forest fire intensities. Can J. Bot. 60:349-357.

Bailey, A. W., and M. L. Anderson. 1980. Fire temperatures in grass, shrub, and open forest communities of Central Alberta. J. Range Manage. 33:37-40.

Britton, C. M., B. L. Karr, and F. A. Sneva. 1977. A technique for measuring rate of fire spread. J. Range Manage. 30:395-397.

Brown, J. K. 1982. Fuel and fire behavior prediction in big sagebrush. USDA For. Ser. Res. Pap. INT-290.

Brown, A. A., and K. P. Davis. 1973. Forest fire: control and use. McGraw Hill, New York.

Byram, G. M. 1957. Some principles of combustion and their significance in forest fires. Fire Contr. Notes 18:47-57.

Byram, G. M. 1959. Combustion of forest fuels. p. 61-89. In: K. M. Davis (ed.). Forest fire: control and use. McGraw Hill, New York.

Daubenmire, R. 1968. Ecology of fire in grasslands. Adv. Ecol. Res. 5:209-266.

Engle, D. M., T. G. Bidwell, A. L. Ewing, and J. R. Williams. 1989. A technique for quantifying fire behavior in grassland fire ecology studies. Southwest. Nat. (in press)

Ewing, A. L., and D. M. Engle. 1988. Effects of late summer fire on tallgrass prairie microclimate and community composition. Amer. Midl. Nat. 120:212-223

Fahnestock, G. R., and R. C. Hare. 1964. Heating of tree trunks in surface fires. J. For. 62:799-805.

Hobbs, R. J., and C. H. Gimingham. 1984. Studies on fire on Scottish heathland communities. J. Ecol. 72:223-240.

Lindenmuth, A. W., and G. M. Byram. 1948. Headfires are cooler near the ground than backfires. Fire Contr. Notes 9:8-9.

Loucks, O. L., M. L. Plumb-Mentjes, and D. Rogers. 1985. Gap processes and large-scale disturbances in sand prairies. p. 71-83. In: S. T. A. Pickett and P. S. White (eds.). The ecology of natural disturbance and patch dynamics. Academic Press, New York.

McKell, C. M., A. M. Wilson, and B. L. Kay. 1962. Effective burning of rangelands infested with medusahead. Weeds 10:125-131.

Potter, R. L., D. N. Ueckert, and J. L. Peterson. 1983. Internal temperature of pricklypear cladophylls during prescribed fire in West Texas. Texas Agr. Exp. Sta. PR 4132.

Roberts, F. H., C. M. Britton, D. B. Wester, and R. G. Clark. 1988. Fire effects on tobosagrass and weeping lovegrass. J. Range Manage. 41:407-409.

Rothermel, R. C. 1972. A mathematical model for predicting fire spread in wildland fuels. USDA For. Serv. Res. Pap. INT-115.

Rothermel, R. C., and J. E. Deeming. 1980. Measuring and interpreting fire behavior for correlation with fire effects. USDA For. Serv. Gen. Tech. Rep. INT-93.

Stinson, K. J., and H. A. Wright. 1969. Temperature of headfires in the southern mixed prairie of Texas. J. Range Manage. 24:277-284.

Tangren, C. D. 1976. The trouble with fire intensity. Fire Technol. 12:261-265.

Trollope, W. S. W. 1984. Fire behavior. p. 199-217. In: P. de V. Booysen and N. M. Tainton (eds.). Ecological effects of fire in South Africa ecosystems. Springer-Verlag, New York.

Trollope, W. S. W., and A. I. F. Potgieter. 1983. Characteristics of fire behavior in the Kruger National Park. Res. Rep., Univ. Fort Hare, Alice, South Africa.

USDA Soil Conservation Service. 1981. Land resource regions and major land resource areas of the United States. Agr. Handb. 296, U.S. Government Printing Office, Washington, DC.

Van Wagner, C. E. 1973. Height of crown scorch in forest fires. Can. J. For. Res. 3:373-378.

Wright, H. A. 1970. A method to determine heat-caused mortality in bunchgrass. Ecology 51:582-587.

Wright, H. A. 1971. Why squirrel tail is more tolerant to burning than needle-and-thread. J. Range Manage. 24:277-284.

Wright, H. A., and A. W. Bailey. 1982. Fire ecology: United States and southern Canada. John Wiley, New York.

Table 1. Independent environmental variables used in multiple regression models for vegetation response prediction.

Variable	Code	Min	Max	Mean	SE
Relative humidity (%)	RH	18	51	34	2
Air temperature (^{o}C)	TMP	15	26	21	1
Wind speed (km hr^{-1})	WIND	3	24	10	1
Fuel load dry (kg ha^{-1})	FLD	2372	5584	3570	260
Fuel load fresh (kg ha^{-1})	FLF	2720	6576	4707	298
Fuel moisture (standing) (%)	FMS	5	59	28	4
Fuel moisture (fallen) (%)	FMF	13	148	48	9
Fuel moisture (total) (%)	FMT	12	60	31	4
Quadrat fresh weight STD[1]	QFFS	18	58	42	3
Quadrat dry weight STD[1]	QFDS	11	50	32	3
Quadrat fresh weight min.[1]	QFFMIN	15	122	69	8
Quadrat dry weight min.[1]	QFDMIN	12	100	54	26
Quadrat fresh weight CV	CVF	0.12	0.74	0.38	0.17
Quadrat dry weight CV	CVD	0.15	0.70	0.37	0.15

[1] All quadrat values in g $0.25m^{-2}$.

Table 2. Fire behavior variables used in regression models for relating fire environment to fire behavior on tallgrass prairie.

Variable	Code	Min	Max	Mean	SE
Fireline intensity (kW m^{-1})	BFI	31	2778	543	235
Rate of spread (m min^{-1})	ROS	1	35	6	3
Degree seconds 0 cm (^{o}CxS)	DS0	110	44765	10711	1870
Degree seconds 30 cm (^{o}CxS)	DS30	207	26851	8511	925
Degree seconds 60 cm (^{o}CxS)	DS60	63	10183	4446	464
Residence time 0 cm (S)	RT0	34	4144	561	141
Residence time 30 cm (S)	RT30	62	4314	1213	171
Residence time 60 cm (S)	RT60	60	4200	1072	191
Maximum temp. 0 cm (^{o}C)	MT0	17	750	210	29
Maximum temp. 30 cm (^{o}C)	MT30	24	618	283	26
Maximum temp. 60 cm (^{o}C)	MT60	24	423	171	22

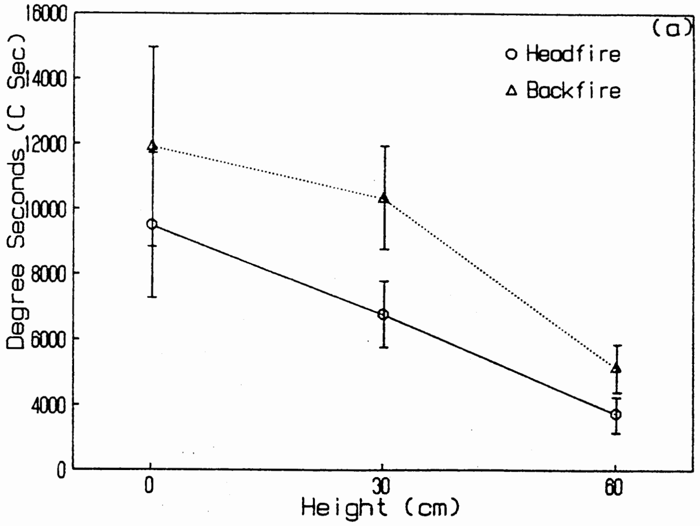
Table 3. Regression equations with environmental variables for predicting fire behavior of spring fires on tallgrass prairie.

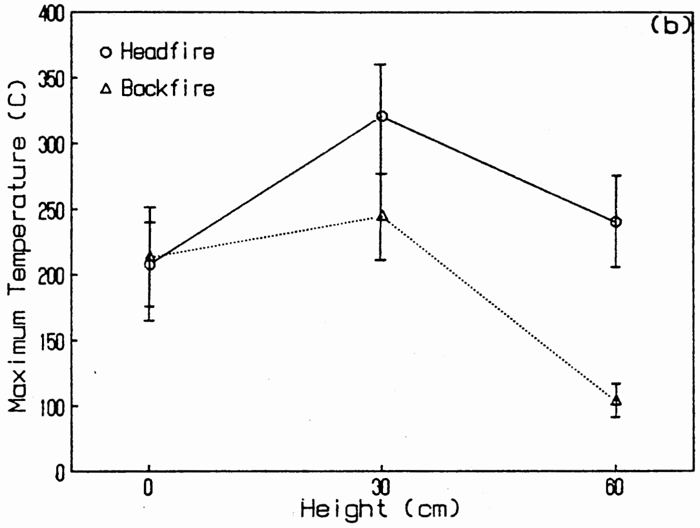
b_o	b_1	X_1	b_2	X_2	b_3	X_3	b_4	X_4	R^2	P>F
DEGREE SECONDS - 0 CM										
105244	-2356	TYPE	-1003	FMS	-661	QFDMIN	-74433	CVF	0.86	0.01
DEGREE SECONDS - 30 CM										
15408	4073	TYPE	41	FMM	-265	RH	-156	QFDS	0.83	0.01
DEGREE SECONDS - 60 CM										
-3873	-153	FMS	122	FMT	142	TMP	-19	QFFS	0.97	0.01
RESIDENCE TIME - 0 CM										
2039	-67	QFFS	128	QFDS	-19	QFFMIN	-3189	CVD	0.61	0.01
RESIDENCE TIME - 30 CM										
8641	0.86	FLD	-119	RH	-52	TEMP	-55	QFDMIN	0.83	0.01
RESIDENCE TIME - 60 CM										
1071	293	TYPE	-6	FMM	-45	RH	4084	CVD	0.78	0.01
MAXIMUN TEMPERATURE - 0 CM										
1467	-15	FMS	3	TMP	-10	QFDMIN	-1305	CVD	0.86	0.01

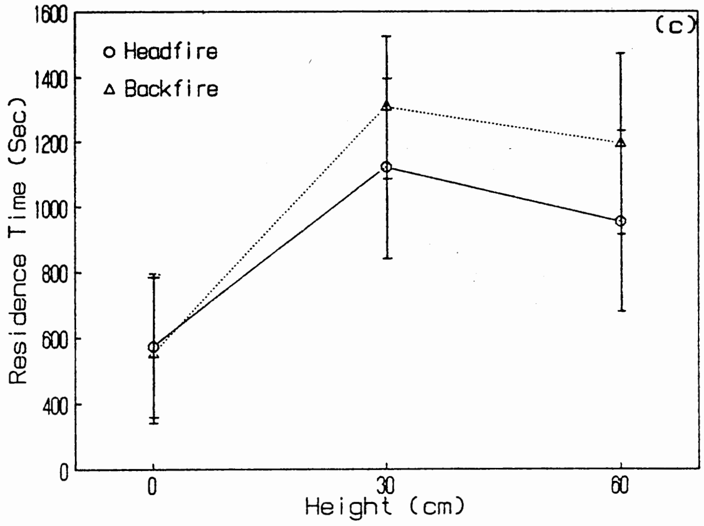
Table 3. Continued.

MAXIMUM TEMPERATURE - 30 CM										
924	-118	TYPE	-0.05	FLF	2	FMM	-10	RH	0.86	0.01
MAXIMUM TEMPERATURE - 60 CM										
267	-186	TYPE	2	FMM	-5	FMT	4	TMP	0.84	0.01
BYRAM'S FIRELINE INTENSITY										
2468	-1266	TYPE	10	FMM	-40	RH	2447	CVF	0.79	0.01
RATE OF SPREAD										
0.89	-0.22	TYPE	0.003	FMM	-0.01	RH	-0.004	QFFMIN	0.75	0.01

Figure 1. Time-temperature relationships in tallgrass prairie headfires and backfires for degree seconds (a), maximum temperature (b), and residence time (c).


(a)
Headfire
Backfire
Degree Seconds (C Sec)
16000
14000
12000
10000
8000
6000
4000
0
0
30
60
Height (cm)


(b)
Headfire
Backfire
Maximum Temperature (C)
400
350
300
250
200
150
100
0
0
30
60
Height (cm)


(c)
Headfire
Backfire
Residence Time (Sec)
1600
1400
1200
1000
800
600
400
0
0
30
60
Height (cm)

Chapter IV

PREDICTION OF FIRE EFFECTS ON TALLGRASS PRAIRIE HERBAGE PRODUCTION

Terrence G. Bidwell

Key Words: Fire behavior, fire environment, vegetation response

Abstract

The relationship of fire behavior to vegetation response has most often been studied in the context of forest and shrubland wildfire. Research on fire effects in grasslands has focused mostly on season of burning and has generally ignored the fire's characteristics. We constructed predictive models of herbaceous standing crop in tallgrass prairie using pre-fire measurements of environment and fire behavior parameters as independent variables. Spring headfires and backfires (n=16) were applied to 10 X 20 m plots on a moderately grazed, shallow prairie range site in good to excellent range condition. Environmental parameters included as independent variables were air temperature, wind speed, relative humidity, fine fuel loading, fine fuel moisture, and fuel continuity. Fire behavior parameters included in stepwise multiple regression were degree seconds, residence time, and maximum temperature derived from time-temperature traces, fireline intensity, and rate of spread. Fire type and fuel moisture were the pre-fire measurement variables most strongly related to standing crop in tallgrass prairie after late spring burning. Time-temperature parameters explained more of the variation of standing crop response to fire than fireline intensity or rate of spread.

INTRODUCTION

Environmental parameters form a matrix within which fairly broad prescriptions are written for rangeland fires. The environmental parameter bounds of fire prescription are broad because the objectives of vegetation manipulation are broad and sufficient fire containment measures are generally available for a fire of any intensity in many rangeland fuel types. The relationship of fire environment to fire behavior and to vegetation response has been studied largely in the context of high intensity wildfires in forest and shrubland because of potential economic loss of timber and danger to structures and humans (Byram 1959, Alexander 1982).

The same parameters of fire behavior used in forest wildfire ecology and behavior studies have been preferred to predict vegetation responses and to describe behavior in other wildland ecosystems (Alexander 1982, Albini 1984). However, research on fire ecology in grasslands has usually ignored fire environment and fire behavior. Fire intensity, related aspects of fire behavior, and environmental parameters may contribute greatly to fire effects on the ecosystem. The objective of this study is to construct predictive models of post-fire herbaceous standing crop in a tallgrass prairie based on variables of the fire environment and fire behavior.

STUDY AREA

Our study area is located at the Oklahoma State University Agronomy Research Range approximately 15 km west southwest of Stillwater, Oklahoma. Mean annual precipitation is 81 cm (Meyers 1982). The study area is a shallow prairie range site in the Central Rolling Red Prairies Land Resource Area (USDA Soil Conservation Service 1981). The soil is a Grainola clay loam with a clay B horizon and is a member of the fine, mixed thermic family of Vertic Haplustalfs. Dominant grasses include big bluestem (*Andropogon gerardii* Vitman), switchgrass (*Panicum virgatum* L.), indiangrass (*Sorghastrum nutans* (L.) Nash), and little bluestem (*Schizachyrium scoparium* (Michx.) Nash). The study area was grazed at a moderate to heavy stocking rate (2.4 AUM ha^{-1}) from mid-July to mid-November in 1985 and 1986 before the treatments were applied in the spring of 1986 and 1987.

METHODS AND MATERIALS

We replicated treatments four times in a randomized complete block design on 10 X 20 m plots located on almost level land (<2% slope), and oriented southeast to northwest to correspond to the southeast winds which prevail during the spring. Each replication consisted of a headfired plot, a backfired plot, and an unburned plot. Beginning in March and ending in April, 1986 and 1987, we set line headfires and backfires at plot borders with a drip torch. Each replication was burned the same day in a 4 hour burning period.

Fuel loading and several weather variables were sampled immediately before each fire (Table 1). Measures of continuity of fuel loading such as standard deviation (SD), standard error (SE), and minimum fuel loading were included as regression model variables. Weather variables were measured using a belt weather kit at 2 m above the ground and included ambient air temperature, relative humidity, and wind speed. Fuel load was measured by clipping herbaceous material in five quadrats (0.5 X 0.5 m) per plot immediately before each fire. Clipped herbage was separated into standing and fallen (litter and mulch). Fuel moisture, expressed on a dry weight basis, was determined after samples were oven dried at $70^{o}C$ for 72 hrs.

Parameters of fire behavior included fireline intensity, rate of spread (ROS), and various time-temperature relationships (Table 2). Byram's (1959) fireline intensity was calculated as the product of fine fuel loading, heat yield, and ROS (Bidwell and Engle 1988). Heat yield (low heat of combustion) was determined by bomb calorimetry for the total fuel sample (standing and fallen) as described in Bidwell and Engle (1988). Time-temperature measurements follow that described by Bidwell et al. (1988) and Engle et al. (1988a).

Response of the post-fire standing crop was measured by clipping five 0.5 X 0.5 m quadrats per plot in June and August as previously reported by Bidwell et al. (1988). The MAXR option in the SAS regression procedure was used to construct predictive models of standing crop response to fire and establish relationships between fire behavior, fire type, and standing crop response (SAS Institute 1985). The use of 4 independent variables in the stepwise regression procedure yielded high R^2 values for most models. In examining many equations using variable entries limited by probability values of $P \leq 0.05$ (SLENTRY=0.051 option, SAS Institute 1985) and by requesting maximum R^2, the addition of the 5th variable seldom increased the explanatory power of an equation.

RESULTS AND DISCUSSION

Prediction of Fire Effects from Environmental Parameters

Fire type was the first entered variable in 4 of 10 models of vegetation response (Table 4). Although season of burn is considered the overriding factor in standing crop response to burning (Towne and Owensby 1984, Owensby 1985), fire type also affects standing crop response (Bidwell et al. 1988). Fire type can be specified in the fire prescription because it is a function of wind direction and point of ignition in the fuelbed.

Fuel load variables entered as the first variable in only two of the regression models and totaled 4 entries out of the 40 possible entries (Table 4). This is somewhat surprising because fuel load, the mass of fuel available for combustion per unit area (Luke and McArthur 1978), is an important component of fire intensity (Ewing and Engle 1988) as well as fireline intensity (Byram 1959, Trollope and Potgieter

1983). In practical terms, however, minimum thresholds of fuel load are required for various management objectives (Clark 1983, Wright and Bailey 1982). For example, to prevent encroachment of small eastern redcedar (*Juniperus virginiana* L.) into the tallgrass prairie, fuel load must be sufficient only for the fire to carry across the burn unit. However, higher fire intensity and heavier fuel loading is required to control larger trees (Bernardo et al. 1988, Engle et al. 1988b). Fuel continuity variables were present in 13 of the 40 possible model entries indicating that fuel continuity may be more important than average fuel load.

Precipitation before spring burns is an influential factor affecting herbaceous plant responses (Wright 1974, Towne and Owensby 1984). Our models indicate that fuel moisture, which reflects precipitation, is also important. Moisture content of fallen fuel was the first entered variable in three models and fuel load (fresh weight) was the first entered variable in one model. One of these two variables occurred in all but two of the ten models. Fuel moisture is critical in the combustion process because as fuel moisture increases the available fuel energy decreases (Byram 1957). As as fuel moisture approaches 30%, a substantial portion of the fuel bed will not burn (Clark 1983). Moisture of cured (i.e. dead) fine fuels is directly related to relative humidity (Frances 1973, Trollope 1984) and equilibrates rapidly with the atmosphere (Albini 1984). However, if green material is present, which is the case of prescribed fires in the spring in the tallgrass prairie, relative humidity is a poor estimate of fuel moisture (Clark 1983). This is because fuel load (fresh weight) includes both intra- and extra-cellular moisture (standing dead and green). The first entry of fuel load (fresh weight) was into the little bluestem (June) model, and as a later entry variable in other models.

Fuel moisture may also be an important predictor of tallgrass prairie response to fire because heat penetration into plant tissue exponentially increases with increase in intra-cellular moisture (Wright 1970). Variation in phenological stage of herbaceous plants results in the variation of reported lethal temperatures (Wright and Bailey 1982). In our study, moisture content of fallen fuels was very high in some burns because of recent heavy precipitation and a saturated soil surface. Relative humidity, the only weather variable to enter first in any model, may be less important in late spring fire effects models because of the high moisture content of fallen fuels and the considerable amount of new green growth present in the fuelbed.

Prediction of Fire Effects from Fire Behavior Parameters

Degree seconds, a time-temperature parameter related to fire intensity (Albini 1976) and fire effects on herbaceous plants (Wright 1970), was the first fire behavior variable to enter in 9 of 10 models (Table 5). Measurement with thermocouples at 30 and 60 cm were better than soil surface measurements which contradicts our expectation that thermocouple proximity to herbaceous plant meristems is paramount for relating time-temperature measurements to vegetation response. Degree seconds from elevated thermocouples may have more power as predictive variables because they are affected less by the variation associated with discontinuous fuel beds (Bidwell and Engle 1988). We attribute the variation in the fuel bed to multiple plant species with different moisture contents, different fuel architecture among species, and previous grazing patterns.

Fireline intensity and ROS together in a two variable model were weak predictors of vegetation response in regression models ($R^2<0.36$, $P>0.14$). Fireline intensity entered the four variable prediction models in only 3 of 40 selection opportunities and then only as the third or fourth variable (Table 5). Fireline intensity was a poor predictor of grass response to fires in west Texas (Roberts et al. 1988). Other measurements of fire behavior related to fire intensity, such as time-temperature relationships, appear to be more valuable for relating fire behavior to tallgrass standing crop. However, fireline intensity is an equally important parameter for predicting crown scorch height of shrubs (Roberts et al. 1988).

Residence time was the first variable entry selected in the regression model for tallgrass standing crop in August and in all but two of the remaining regression models as the second or third variable (Table 5). Residence time, which should relate well to fire effects on grassland plants, can be estimated from time-temperature data but not from fireline intensity, or other fire behavior measurements (Alexander 1982). Residence time, like degree seconds and unlike fireline intensity, is a measure of the relative amount of energy released throughout the depth of the combustion zone and in proximity to the vegetation (Alexander 1982, Engle et al. 1988a).

Management Suggestions

Degree seconds estimates at ground level and 30 and 60 cm above ground level proved to be the best set of fire behavior variables for explaining the variation in vegetation response to fire. On the other hand, using prefire environmental measurements to predict vegetation response can serve to better define fire prescriptions. For example, a commonly used prescription to improve livestock forage quality in the tallgrass prairie is to initiate a headfire in late spring at the time of resumption of growth of the warm-season tallgrasses (Launchbaugh and Owensby 1978). The prescription would call for 10 to 16 km h^{-1} wind speed, approximately 40% relative humidity, and an air temperature of approximately 16^{o} C. To predict tallgrass standing crop (kg ha^{-1}) in August, the environmental regression model is $Y = -197 - [244(Type)] + [0.17(FLF)] + [25.9(RH)] - [10.8(QFDMIN)] = 954$ kg ha^{-1}, where Type is 1 (headfire), FLF is 2875 kg ha^{-1}, RH is 40%, and QFDMIN is 12 g 0.25 m^{-2}. By changing the fire type (X_1) from a headfire (dummy variable =

1) to a backfire (dummy variable = 2), the model output suggests that tallgrasses would be reduced by 26% (244 kg ha^{-1}) to 710 kg ha^{-1}.

A common fire prescription for increasing forb and legume production is to burn during the winter. However, by selecting a backfire instead of a headfire, forb and legume standing crop can be increased in late spring burning (Bidwell et al. 1988). To predict forb and legume standing crop in August, the environmental model is $Y = 104 + [75(Type)] + [0.05(FLF)] - [6.7(RH)] + [313(CVD)] = 367$ kg ha^{-1}, where Type is backfire (dummy variable = 2), FLF is 2875 kg ha^{-1}, RH is 40%, and CVD is 0.70. Headfiring instead of backfiring would reduce forbs and legumes by 20% (75 kg ha^{-1}) to 292 kg ha^{-1}.

Other burning prescriptions are possible provided the environmental variables remain within the range of data used to construct these models. Spring fire prescriptions for tallgrass prairie are broad. Environmental extremes, especially wind and fuel moisture, truncate fires for either safety or flammability reasons (Wright and Bailey 1982). Prediction equations should thus be used judiciously, well within the extremes.

LITERATURE CITED

Albini, F. A. 1976. Estimating wildfire behavior and effects. USDA For. Serv. Gen. Tech. Rep. INT-30.

Albini, F. A. 1984. Wildland fires. American Scientist 72:590-597.

Alexander, M. E. 1982. Calculating and interpreting forest fire intensities. Can J. Bot. 60:349-357.

Bernardo, D. J., D. M. Engle, and F. T. McCollum. 1988. An economic assessment of risk and returns from prescribed burning on tallgrass prairie. J. Range Manage. 41:178-183.

Bidwell, T. G., D. M. Engle, and P. L. Claypool. 1988. Effects of spring headfires and backfires on tallgrass prairie. J. Range Manage. (in review).

Bidwell, T. G., and D. M. Engle. 1988. Relationship of fire environment to fire behavior on tallgrass prairie. J. Range Manage. (in review).

Byram, G. M. 1957. Some principles of combustion and their significance in forest fires. Fire Contr. Notes 18:47-57.

Byram, G. M. 1959. Combustion of forest fuels. p. 61-89 In: K. M. Davis (ed.). Forest fire: control and use. McGraw Hill, New York.

Clark, R. G. 1983. Threshold requirements for fire spread in grassland fuels. Ph.D. Thesis, Texas Tech Univ., Lubbock. 86p.

Engle, D. M., T. G. Bidwell, A. L. Ewing, and J. R. Williams. 1989a. A technique for quantifying fire behavior in grassland fire ecology studies. Southwest. Nat. (in press).

Engle, D. M., J. F. Stritzke, and P. L. Claypool. 1988b. Effect of paraquat plus prescribed burning on eastern redcedar (_Juniperus virginiana_). Weed Tech. 2:172-174.

Ewing, A. L., and D. M. Engle. 1988. Effects of late summer fire on tallgrass prairie microclimate and community composition. Am. Midl. Nat. 120:212-223.

Frances, W. H. 1973. Effective heating of fuel ahead of spreading fire. USDA For. Serv. Res. Pap. INT-140.

Launchbaugh, J. L., and C. E. Owensby. 1978. Kansas rangelands: their management based on a half century of research. Kansas Agr. Exp. Sta. Bull. 622., Kansas State Univ., Manhattan.

Luke, R. H., and A. G. McArthur. 1978. Brushfires in Australia. Australian Gov. Publ. Serv., Canberra.

Meyers, H. R. 1982. Climatological data of Stillwater, Oklahoma 1893-1980. Okla. Agr. Exp. Sta. Res. Rep. P-821.

Owensby, C. E. 1985. Fire and tallgrass prairie. p. 252-270. _In_: L. D. White, D. E. Guynn, and T. R. Troxel, (eds.). Proc. International Ranchers Roundup, Texas A & M Univ. and Texas Agric. Res. and Ext. Center, Uvalde.

Roberts, F. H., C. M. Britton, D. B. Wester, and R. G. Clark. 1988. Fire effects on tobosograss and weeping lovegrass. J. Range Manage. 41:407-409.

SAS Institute Inc. 1985. SAS user's guide: statistics. Version 5 ed. SAS Institute Inc., Cary, NC.

Towne, G., and C. Owensby. 1984. Long-term effects of annual burning at different dates in ungrazed Kansas tallgrass prairie. J. Range Manage. 37:392-397.

Trollope, W. S. W. 1984. Fire behavior. p. 199-217 In: P. de V. Booysen and N. M. Tainton (eds.). Ecological effects of fire in South Africa ecosystems. Springer-Verlag, New York.

Trollope, W. S. W., and A. I. F. Potgieter. 1983. Characteristics of fire behavior in the Kruger National Park. Research Report, University of Fort Hare, Alice, South Africa.

USDA Soil Conservation Service. 1981. Land resource regions and major land resource areas of the United States. Agric. Handb. 296, USDA Soil Cons. Serv., U.S. Government Printing Office, Washington, DC.

Wright, H. A. 1970. A method to determine heat-caused mortality in bunchgrass. Ecology 51:582-587.

Wright, H. A. 1974. Effect of fire on southern mixed prairie grasses. J. Range Manage. 27:417-419.

Wright, H. A., and A. W. Bailey. 1982. Fire ecology: United States and southern Canada. John Wiley and Sons, New York.

Table 1. Independent environmental variables used in multiple regression models for prediction of vegetation response.

Variable	Code	Min	Max	Mean	SE
Relative humidity (%)	RH	18	51	34	2
Ambient air temp. (^{o}C)	TMP	15	26	21	1
Wind speed (km hr^{-1})	WIND	3	24	10	1
Fuel load dry (kg ha^{-1})	FLD	2372	5584	3570	260
Fuel load fresh (kg ha^{-1})	FLF	2720	6576	4707	298
Fuel moisture (standing) (%)	FMS	5	59	28	4
Fuel moisture (fallen) (%)	FMF	13	148	48	9
Fuel moisture (total) (%)	FMT	12	60	31	4
Quadrat fresh weight STD[1]	QFFS	18	58	42	3
Quadrat dry weight STD	QFDS	11	50	32	3
Quadrat fresh weight minimum	QFFMIN	15	122	69	8
Quadrat dry weight minimum	QFDMIN	12	100	54	26
Quadrat fresh weight CV	CVF	.12	.74	.38	.17
Quadrat dry weight CV	CVD	.15	.70	.37	.15

[1] Values are from individual samples in quadrats (g 0.25 m^{-2}).

Table 2. Fire behavior variables used in regression models for relating fire environment to fire behavior in tallgrass prairie, 1986 and 1987.

Variable	Code	Min	Max	Mean	SE
Fireline intensity (kw m^{-1})	BFI	31	2778	543	235
Rate of spread (m min^{-1})	ROS	1	35	6	3
Degree seconds 0 cm (^{o}CxS)	DS0	110	44765	10711	1870
Degree seconds 30 cm (^{o}CxS)	DS30	207	26851	8511	925
Degree seconds 60 cm (^{o}CxS)	DS60	63	10183	4446	464
Residence time 0 cm (S)	RT0	34	4144	561	141
Residence time 30 cm (S)	RT30	62	4314	1213	171
Residence time 60 cm (S)	RT60	60	4200	1072	191
Maximum temperature 0 cm (^{o}C)	MT0	17	750	210	29
Maximum temperature 30 cm (^{o}C)	MT30	24	618	283	26
Maximum temperature 60 cm (^{o}C)	MT60	24	423	171	22

Table 3. Dependent vegetation response variables (kg ha^{-1}) for which multiple regression equations were derived for prediction, 1986 and 1987.

Variable	Minimum	Maximum	Mean	SE
Tallgrasses, June	260	1020	636	53
Tallgrasses, August	880	2570	1692	127
Little Bluestem, June	150	740	368	46
Little Bluestem, August	300	1620	761	89
Other Grasses, June	700	1620	1091	62
Other Grasses, August	1580	3960	2278	150
Forbs and Legumes, June	140	730	323	38
Forbs and Legumes, August	150	580	325	30
Total Standing Crop, June	1700	3580	2530	138
Total Standing Crop, August	4170	6890	5103	193

Table 4. Regression equations with environmental variables for predicting standing crop after spring fires on tallgrass prairie, 1986 and 1987.

b_0	b_1	X_1	b_2	X_2	b_3	X_3	b_4	X_4	R^2	P>F
TALLGRASSES, JUNE										
908	-1.8	FMF	-6.0	TMP	18.7	QFFMIN	-19.9	QFDMIN	0.74	0.01
LITTLE BLUESTEM, JUNE										
1907	-0.08	FLF	-10.8	RH	8.1	WIND	-12.9	TEMP	0.60	0.01
OTHER GRASSES, JUNE										
722	133	TYPE	-2.3	FMF	18.9	RH	-947	CVF	0.37	0.01
FORBS AND LEGUMES, JUNE										
96	-2.5	FMF	15.3	QFFS	-13.1	QFDS	1.8	QFFMIN	0.40	0.01
TOTAL STANDING CROP, JUNE										
1471	-11.1	FMF	26.7	FMT	38.7	RH	-1461	CVD	0.81	0.01
TALLGRASSES, AUGUST										
-197	-244	TYPE	0.17	FLF	25.9	RH	10.8	QFDMIN	0.73	0.01
LITTLE BLUESTEM, AUGUST										
3271	-26.1	RH	-18.2	TEMP	-11.2	QFFMIN	6.7	QFDMIN	0.53	0.01
OTHER GRASSES, AUGUST										
2134	357	TYPE	-6.7	FMS	10.0	FMF	-1905	CVD	0.81	0.01
FORBS AND LEGUMES, AUGUST										
104	75	TYPE	0.05	FLF	-6.7	RH	313	CVD	0.57	0.01
TOTAL STANDING CROP, AUGUST										
2646	0.15	FLD	35	RH	-65.7	WIND	19.9	QFFMIN	0.76	0.01

Table 5. Regression equations with fire behavior variables for prediciting spring fire effects on tallgrass prairie, 1986 and 1987.

b_0	b_1	X_1	b_2	X_2	b_3	X_3	b_4	X_4	R^2	P>F
TALLGRASSES, JUNE										
661	0.06	DS30	-0.09	DS60	-1.3	MT0	0.66	MT60	0.65	0.08
LITTLE BLUESTEM, JUNE										
484	-0.04	DS60	-0.03	RT0	0.74	MT0	-0.55	MT60	0.88	0.01
OTHER GRASSES, JUNE										
1534	-0.02	DS60	0.27	RT30	-0.34	RT60	-0.97	MT30	0.50	0.24
FORBS AND LEGUMES, JUNE										
579	-0.03	DS30	-0.20	RT0	-0.20	RT30	-0.09	BFI	0.85	0.01
TOTAL STANDING CROP, JUNE										
3944	-0.45	DS60	-0.28	RT60	-1.1	MT0	-0.45	BFI	0.85	0.01
TALLGRASS, AUGUST										
1830	0.58	RT0	-0.64	RT60	3.7	MT60	-44	ROS	0.66	0.07
LITTLE BLUESTEM, AUGUST										
569	-0.07	DS0	-0.07	DS60	0.25	RT60	4.1	MT0	0.78	0.02
OTHER GRASSES, AUGUST										
2280	0.10	DS30	-0.39	RT0	-0.23	RT60	-1.7	MT0	0.88	0.01
FORBS AND LEGUMES, AUGUST										
168	0.03	DS0	-0.01	DS30	0.06	DS60	-1.5	MT0	0.76	0.02
TOTAL STANDING CROP, AUGUST										
5277	0.14	DS60	-0.57	RT60	1.6	BFI	-156	ROS	0.71	0.05

VITA

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