VEGETATION DYNAMICS AND LIVESTOCK

PRODUCTION ON RANGELANDS IN THE

SOUTHERN GREAT PLAINS

By

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PREFACE

       This dissertation contains four individual chapters to be submitted as separate manuscripts for publication. The first three chapters are applied ecology, drawing from theory to explain management and production strategies. The fourth chapter is more basic science, dealing with the invasion pattern and dynamics of *Lespedeza cuneata*. Chapter 1 is in the style and format of, and has been submitted to *Frontiers in Ecology and the Environment*. This chapter serves as an introduction to the concepts and applications examined in chapters two and four. Chapter 2 is a paper describing the invasion of *L. cuneata*, an exotic invasive forage legume, into rangelands managed with two fire and grazing regimes (traditional management and patch-burn management). This paper is in the style and format of, and has been published in *Rangeland Ecology and Management* (*Range Ecol Manage* 60: 253-260). Chapter 3 challenges the dogmatic use of herbicides for the control of forbs, and assumed increase in livestock production on semi-arid rangelands. This chapter focuses on vegetative community dynamics before and after herbicide applications. In addition, it follows livestock performance and production over a six year study period on rangelands in west central OK. This chapter is in the style and format of, and will be submitted to the *Rangeland Ecology and Management*. Chapter 4 builds on Chapter 2 to further describe *L. cuneata* invasion dynamics at two spatial scales from permanent modified Whittaker plots, and uses a grid coordinate system to map invasion dynamics. This chapter describes the effect of *L.*

cuneata invasion on plant species composition and attempts to identify the environmental influences on invasion. This chapter is in the style and format of, and will be submitted to the *Journal of Applied Ecology*.

The author is currently lead author on all four chapters. The information in Chapter 1 was a combination of literature review and concept development. This chapter originated from a grant proposal funded by the USDA-CSREES Biology of Weedy and Invasive Plants program. The author used the grant proposal as a backbone but further developed the literature review on exotic forages vs. invasive species, and large herbivore grazing behavior; and the conceptual model of altered grazing selectivity as a method of suppression for exotic forage invasions. Over one year of collaborative efforts went into the development and writing of the chapter.

Chapter 2 was completely written by the author, with appropriate collaboration from the co-authors throughout the revision process. The experiment though was in place before the author began research with the project. Fuhlendorf and Engle (2001, 2004) set the tone for the paper and further explained the experimental design. The author was present for over half of the data collection on the patch-burn study, and all of the data collection on the herbicide trials (1999-2002). All data analysis was conducted by the author, with advisement from co-authors. Interpretation was a combined effort between the author and co-authors.

The major portion of Chapter 3 was written by the author, with appropriate collaboration from the co-authors throughout the revision process. The experiment though was in place before the author began research with the project. O'Meilia (2003 Master's thesis, Oklahoma State University) set the tone for the paper and further

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scientist that I am. I hope to collaborate on many more occasions in the future with all of you.

Lastly, I would like to thank all of the technicians, station staff, other faculty, graduate students, and undergraduates for all of your assistance throughout my "tenure" here at OSU. Special thanks to Ken Nelson, Chris Stansberry, John Weir, Tim Tunnell, Ryan Limb, Jay Kerby, Dr. Karen Hickman, and mounds of undergraduates that have facilitated this research.

It is to all of you that I dedicate this volume, for without you it would be just paper on a shelf. With your help, I hope I have made it a meaningful, cohesive collection of information that can have a positive impact in Oklahoma, the US, and rangelands around the world.

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CHAPTER I

EXOTIC FORAGES OR INVASIVE SPECIES? FRIENDS, ENEMIES AND THE

CONUNDRM OF CONTROL

Exotic forages or invasive species? Friends, enemies, and the conundrum of control

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ABSTRACT

Exotic species intentionally introduced as forages have been a cornerstone of production agriculture for more than a century. However, these same forage species have been identified increasingly as among the most aggressive invaders in grazed ecosystems around the world because of their persistence under grazing, diverse mechanisms of reproduction, and rapid growth rate. Here, we conclude that exotic forage species be considered as special cases in invasion ecology. We propose a conceptual framework, with evolutionary patterns of disturbance and grazing preference, as the key to successfully limiting invasion of exotic forages in natural ecosystems. We also provide an example with *Lespedeza cuneata* and the fire-grazing interaction in tallgrass prairies of the central USA.

KEYWORDS: Altered grazing selectivity, foraging behavior, livestock, patch-burning, heterogeneity, spatial scale, vertebrate herbivory, shifting mosaic

Exotic Forages vs. Invasive Species

Deliberate introduction of exotic organisms by humans is the chief culprit of species invasions worldwide (Mack 2003). One of the central foci of agriculture for over 100 years has been the introduction, breeding and management of non-native plant species, typically referred to as improved, introduced, or tame forages, intended for use as livestock forage or production of hay. As a result, exotic forages have become dominant in grazed ecosystems throughout the eastern United States over the past 50

years (Barnes et al. 2003, Ball et al. 2002) and are invading rangelands and forests of the central and western US. The number of species of exotic forages brought into North America is unknown.

Throughout the past century, most land grant universities in the US developed forage breeding and management programs focused on breeding new cultivars and introducing these exotic species for sustainable forage production. Simultaneous to forage breeding, weed scientists have focused on understanding traits that make a species noxious and invasive (Rejmanek & Richardson 1996). It is ironic that most of the traits of a "successful" forage species are similar to traits that confer invasiveness (Baker 1974). For example germinability (Barnes et al. 2003, Yamashita et al. 2003), generation time (Newsome & Noble 1986), fitness (Edwards et al. 1998), and tolerance to disturbance (Volenec & Nelson 1995, Webster & Cardina 2004) (Table 1) are critical for successful introduction of forages as well as exotic invader success. As a result, invasive forage species differ from other invasive species in that forages were specifically introduced for desirable agronomic traits, including the ability to persist in grazed or hayed ecosystems (e.g., *Lespedeza* spp., Sollenberger & Collins 2003). Some examples of persistence mechanisms include high reproductive output and re-seeding ability, tolerance to repeated cutting or grazing to ground level, and resistance to disease and insect pests (Barnes et al. 2003). Therefore, the probability of successful invasion in grazed ecosystems for exotic forage species like *Bothriochloa ischaemum* (L.) Keng, *Festuca arundinacea* Schreb., and *Lespedeza cuneata* (Dum.Cours.) G. Don (Nomenclature from Diggs et al. 1999) could be higher than for other exotic plants which were not selected for persistence in a monoculture. Thus, we propose invasive forage

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species be distinguished from other invasive plant species because of this selection for persistence, and we consider the potential to manage invasive forage species through altering herbivore preference and grazing patterns.

In a nutshell:

o Exotic forage species have been deliberately introduced, and subsequently bred to exhibit specific persistence mechanisms, in grazed ecosystems around the world

o The same characteristics which make these species successful forages also make them excellent (and in many cases the most problematic) invasive plant species in natural areas, rangelands, and shrublands

o We propose that evolutionary disturbance regimes of fire and grazing which change large herbivore grazing selectivity from multiple spatio-temporal levels to that of the anthropogenically altered disturbance patch might limit the spread of exotic invasive forage species

Large Herbivores and Grazing Behavior

Grazing (by native herbivores, from invertebrates to large ungulates) is a pervasive disturbance in natural grassland and savannah ecosystems, and currently domestic livestock dominate the use of these lands globally. Many types of grassland evolved with grazing (Fuhlendorf & Engle 2004). In fact, ungulate grazing has been widely accepted as a keystone process associated with grassland ecosystems (Milchunas

et al. 1988, Knapp et al. 1999). Large herbivore selectivity is expressed at multiple

spatial scales. Herbivore grazing decisions are based on many factors including forage

nutritive value (or quality), forage biomass, and optimization of both biomass and

nutritive value (Pinchak et al. 1991, Pyke 1984). Large herbivore grazing can produce a

heterogeneous landscape, as a result of this selection at different scales (Senft et al. 1987;

Stuth 1991), however current grassland livestock management attempts to minimize this

variability, and promote a few key forage species by constraining grazing pressure,

duration, season, and/or distribution (Fuhlendorf & Engle 2001). However, typical large

herbivore grazing behavior is more complex.

We propose that altering the scale of grazing selectivity potentially could

overcome the persistence mechanisms of these invasive forages, decreasing their rate and

extent of invasion. In this paper, we provide a review of the grazing behavior of large

herbivores in managed ecosystems, and present a conceptual model for the use of altered

grazing selectivity to suppress exotic forage species invasions by anthropogenically

delineating disturbance patches within undisturbed landscapes.

Selective Foraging Behavior of Grazers

Herbivore grazing preference and selectivity are driven by a combination of

palatability and nutritional characteristics of available plants (Launchbaugh 1996),

nutritional requirements and physiological status of the herbivore (Huston & Pinchak

1991), and environmental stressors (Stuth 1991). Through repeated selection of the same

nutritious, palatable plants (those that express preferred flavor, and result in nutritional

gain or satisfaction) within the local plant community, patch preference is established (Figure 1). Preferred patches are structurally or compositionally distinct within the landscape because they are selectively grazed, and they offer attractive foraging habitat. The resulting plant responses lead to unbalanced competitive interactions between grazing tolerant and grazing intolerant species (Figure 2; Briske 1991). The unbalanced competitive interactions lead to modified resource acquisition by the plants, and in the end the potential for species replacement within the plant community. In the absence of invasive plant species, species replacement is a well known, often predictable process of plant succession in grazed ecosystems (Dysterhuis 1949, Briske et al. 2003). However, in the presence of invasive forage species, this replacement can be dominated by the single invasive forage. With rapid growth rates, prolific reproduction, and persistence mechanisms with disturbance, invasive forages can out-compete native plants in many management-based disturbance regimes, thus leading to dominance of the invasive forage in the area.

Heterogeneous landscapes present many opportunities and challenges to the herbivore, from changes in normal phenological development of species within the plant community, plant palatability and nutritive value, to environmental changes that require changes in foraging habit (McNaughton 1984). Heterogeneous landscapes can contribute to the formation of small grazing lawns (or patches), as animals repeatedly select accessible plant communities that include the most palatable plants or those that have the least chemical or structural defenses (Cingolani et al. 2005, Griffiths et al. 2003, McNaughton 1984). Plants with anti-herbivore defenses thrive; and increased animal density across the landscape leads to dominance of plants with defensive mechanisms, or

plants with a greater tolerance to herbivory (Launchbaugh 1996, Archer 1996).

Knowledge of large herbivore behavior might be useful for manipulating grazing to

decrease invasion by exotic forage species.

Plant-herbivore feedbacks also play a role in herbivore selectivity. Plant

characteristics that the herbivore associates with nutritious gain or gastro-intestinal

malaise (i.e. abdominal discomfort or illness), can dictate whether that plant is grazed in

the future. While some toxins can be physiologically or conditionally tolerated by

herbivores (Provenza et al. 1992), ingestion to the point of toxicity can have dangerous

effects if the mechanisms of tolerance fail (e.g. endophyte-fescue toxicity in cattle).

Herbivory defense mechanisms tend to enable the eventual dominance of the exotic

species in the plant community over native plants that lack defense mechanisms. For

ecologists interested in halting exotic plant invasions, this significant hurdle requires a

different model of managing grazed ecosystems.

The Altered Grazing Selectivity Hypothesis

A new model, based on evolutionary plant-herbivore interactions could be used to

minimize the invasion of exotic forages (Fuhlendorf and Engle 2001, 2004). By

changing the scale of the foraging decision from multiple spatio-temporal scales (Figure

3) to the scale of a large anthropogenically created patch, all foraging pressure (or

stocking density) from the landscape is focused on one patch. This patch shifts

throughout the landscape as additional anthropogenically disturbed patches are created

(e.g. prescribed fire, prescribed mowing, and chemical applications). Traditional

management for homogeneity actually results in ephemeral small grazing lawns across the landscape resulting from return foraging - which lead to perennial, uneven utilization of the entire landscape (Ganskopp & Bohnert 2006, McNaughton 1984). With altered grazing selectivity, the grazing lawns are focused in the disturbed area and large herbivores non-selectively forage on both native and exotic invasive plants within the recently disturbed area.

Fire-grazing Interaction: an Example of Altered Grazing Selectivity

An interaction of fire and grazing disturbances that create a shifting mosaic of plant communities in different stages of plant succession across the landscape has been proposed (Fuhlendorf & Engle 2001, 2004). Patch burning, or the application of the fire-grazing interaction model, uses fire disturbance as a mechanism to alter forage selectivity within an unburned landscape to the scale of the burned patch without manually herding the animals among patches or restricting movement with fences. Large herbivores spend over 70% of their grazing time on the most recently burned patch (termed focal grazing; Figure 4) (Fuhlendorf and Engle 2004). The absence of fences and manual herding allows herbivores the option of selecting plant communities or patches inside and outside the disturbance patch to fulfill nutritional or intake requirements. So, with fire, patch level selection increases and species-level selection decreases, while without fire, grazing animals select at multiple scales but tend to be highly selective of individual plant species, thus altering competition and causing some species to increase and others to decrease.

Focal grazing following burning has been shown to decrease the rate of invasion by the exotic nitrogen-fixing forage *L. cuneata* in the central Great Plains, USA (Cummings et al. 2007, Fuhlendorf & Engle 2004). The primary mechanism for invasion suppression by the fire-grazing interaction is that the scale of grazing selectivity is altered. Focal grazing on burned patches delays defensive mechanisms of plants (e.g. secondary chemical compounds, stem: leaf ratio, fungal associations) because of altered resource allocation to plant growth and survival. The production of plant defense chemicals, as products of secondary metabolism, is costly to the plant and relies on primary metabolites for substrates (Harborne 1991). If focal grazing continually removes forage from the plant, most if not all plant resources would be allocated to stem, leaf, and root production for survival (structures which are highly palatable to large herbivores) with minimal resource allocation to plant defenses.

Another possible mechanism of invasion suppression could be circumventing plant avoidance by the herbivores, permitting utilization of the invasive forage (Provenza et al. 1990, 1992). While typical foraging behavior results in different foraging preferences with changes in plant maturity (Figure 5), altering the scale of grazing selectivity to the large patch (Figure 4) causes herbivores to maintain a grazing lawn across the entire patch (i.e. focal grazing). The change in grazing selectivity could alter the plant-herbivore interaction in two ways. First, increased repetitive utilization could lead to positive post-ingestive feedbacks (i.e. increased usage due to perceived nutritional gain of the herbivore) toward invasive forages with minimal concentrations of secondary metabolites or other plant defenses (Burritt & Provenza 1989). Alternatively, the

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herbivore could develop physiological tolerance to the plant defenses, once the plant has

been deemed nutritious forage (Launchbaugh 1996, Provenza et al. 1992).

What does this mean for the exotic invasive forage?

One possible result is that sexual reproduction and plant defense mechanisms

within the focal grazing year could be decreased if not halted (Figure 5). Under minimal

foraging (or no foraging at all), plants in nutrient limited environments allocate excess

carbon to plant defenses (Figure 5; point 1) (Stamp 2003, Tuomi et al. 1991). In these

circumstances, the plant may progress to sexual reproduction (Figure 5; point 2), thus

leading to increased propagules for further invasion. Conversely, under focal grazing,

either the total carbon available to the plant may be decreased due to decreased

photosynthetic tissue from herbivory, or the herbivory may result in an increased need for

carbon in growth or storage tissue (Briske 1991), thus limiting the carbon available for

plant defense. An alternative circumstance could be the additive or synergistic effects of

the decreased available carbon and increased carbon allocation to growth (Figure 5; point

3). Herbivory has been shown to decrease reproductive effort in other invasive species

(Lewis et al. 2006), but the effect has not been documented in invasive forage species

with focused, periodic disturbance such as focal grazing.

Second, the typical germination release following fire in some invasive forage

species may facilitate the mortality of a multitude of seedlings by intense herbivory

following patch disturbance. This depletion of the seed bank is an additional mechanism

of invasion suppression with altered grazing selectivity over other grazing management systems (e.g., rotational grazing, and continuous, year-long grazing).

A third mechanism could be that native plants in grasslands exhibit a competitive advantage to invasive exotic forages following evolutionary disturbance patterns like the fire-grazing interaction. While exotic invasive forages may show some competitive advantage over native plants for one or several disturbance events (Figure 2), heavy disturbance patterns followed by secondary successional dominance might favor native grasses and forbs which evolved with these coupled events (Fuhlendorf & Engle 2001).

Conclusions

Exotic invasive forage species have a profound impact in grassland ecosystems; yet homogeneous grassland management often promotes the spread of invasive forages by allowing the full range of selectivity for free-ranging large herbivores. Foraging animals typically make decisions at multiple spatial scales ranging from the plant part to the plant community to the landscape, but grazing selectivity can be restricted to the disturbance patch created by the fire-grazing interaction. This form of heterogeneous grassland management has the potential to disrupt invasion by exotic forage plants which exhibit a broad range of anti-herbivore defenses.

Forage breeding has unintentionally resulted in a suite of exotic species capable of invading habitats well beyond that which could be possible with evolutionary time scale adaptations, thus leading to highly successful invaders once these species escape cultivation. For this reason, we propose that exotic invasive forages be considered as

special case invaders in invasion ecology and management. Management plans should address the key issues of persistence mechanisms, prolific reproductive output, and rapid growth rates, in addition to the other traits that make exotic forages highly invasive in grassland ecosystems.

By understanding large herbivore grazing behavior, evolutionary disturbance patterns like the fire-grazing interaction can be used to place the competitive advantage back on the native plants that have been naturally selected by this disturbance regime (Fuhlendorf & Engle 2001). The altered grazing selectivity hypothesis offers a framework for modifying the behavior of large herbivores in order to focus grazing pressure on a recently burned patch, thus limiting the invasion of exotic forage species.

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Table 1. Traits common to forage plants and invasive species expressed as either selection criteria for forage plants or characteristics of invasive types of plant species and examples of each plant type.

Selection criteria and species characteristic	Plant type			
	Forage species		Invasive species	
	Reference	Example	Reference	Example
Seed longevity in soil	Taylor 2005	*Trifolium* spp.	Van Clef & Stiles 2001	*Polygonum perfoliatum*
Minimal germination inhibition	Barnes et al. 2003	*Eragrostis* spp.	Yamashita et al. 2003	*Bischchofia javanica*
Short generation time	Barnes et al. 2003	*Medicago* spp.	Newsome & Noble 1986	*Bromus tectorum*
Wide tolerance range	Webster & Cardina 2004	*Desmodium tortuosum*	Larson et al. 2001	*Poa pratensis*
Rapid growth rate	Burton 1973	*Cynodon dactylon*	Baker 1974	*Pueraria montana*
Prolific seed production	Ward et al. 1985	*Lespededeza cuneata*	Edwards et al. 1998	*Lythrum salicaria*
Multiple means of reproduction	Schmidt & Hickman 2006	*Bothriochloa ischaemum*	Sakai et al. 2001	*Lespedeza cuneata*
Persistence under disturbance	Volenec & Nelson 1995	*Festuca arundinacea*	Webster & Cardina 2004	*Desmodium tortuosum*
Plant defenses to herbivory	Sollenberger & Collins 2003	*Lespedeza cuneata*	Schierenbeck et al. 1994	*Lonicera japonica*

Figure 1. Large herbivores typically create numerous patches, or grazing lawns, upon which they repeatedly forage, embedded within a matrix of ungrazed areas. The patch size and degree of use depends upon grazing pressure. Key factors including: topography, distance from water, and shelter result in small patches of heavy utilization within large management units of minimal foraging pressure.

Figure 2. The conceptual relationship between herbivory-induced competitive interactions and modified population structure as it might affect species composition within communities. Reproduced with permission from Timber Press.

Figure 3. The altered grazing selectivity hypothesis. Typical grazing behavior (-----) elicits decisions at multiple spatial scales, with the highest grazing selectivity at the feeding station and plant community scales. By anthropogenically creating a disturbance patch (e.g. fire, mowing) of highly nutritious forage, scale of preferential grazing can be shifted (—) to the scale of the disturbance patch, over-riding preferential selectivity at finer scales.

Figure 4. Anthropogenically altered grazing selectivity. By anthropogenically creating a recently disturbed patch (e.g. prescribed fire, mowing, or alternative means of structurally/physiologically altering the vegetation), over 70% of the foraging is concentrated within the disturbed patch resulting in focused grazing for the entire season or until another anthropogenically disturbed patch is created. Factors which typically drive foraging behavior (topography, distance from water, and shelter) become less important than evolutionary herbivore fidelity to the disturbance patch.

Figure 5. Conceptual models of physiology for exotic invasive forage plants over one growing season (top), and for exotic invasive forage plants over one growing season with anthropogenically altered grazing selectivity to the disturbance patch scale (bottom). At point 1 plant defenses increase to a threshold of decreasing palatability, herbivores avoid the plants leading to unrestricted production of plant defenses in the invasive plant. At point 2, without focused grazing pressure the plant is capable of reproducing. With focused grazing resulting from altered grazing selectivity, we hypothesize that the

forage plant palatability and nutritive quality will remain high throughout the growing season as a product

of focal grazing in the disturbance patch (point 3).

Figure 1.

Figure 2.

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        ┌─────────────────────────────┐
        │   Frequency/ Intensity and  │
        │   Seasonality of Herbivory  │
        └─────────────────────────────┘
          ↙                        ↘
┌──────────────────────────┐   ┌──────────────────────────┐
│ Differential Species     │   │ Differential Species     │
│ Utilization              │   │ Regrowth                 │
└──────────────────────────┘   └──────────────────────────┘
          ↘                        ↙
        ┌─────────────────────────────┐
        │   Unbalanced Competitive    │
        │   Interactions              │
        └─────────────────────────────┘
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        ┌─────────────────────────────┐
        │ Altered Plant and Population│
        │ Structure                   │
        └─────────────────────────────┘
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        ┌─────────────────────────────┐
        │   Modified Resource         │
        │   Acquisition               │
        └─────────────────────────────┘
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        │ Species Replacement within  │
        │ the Community               │
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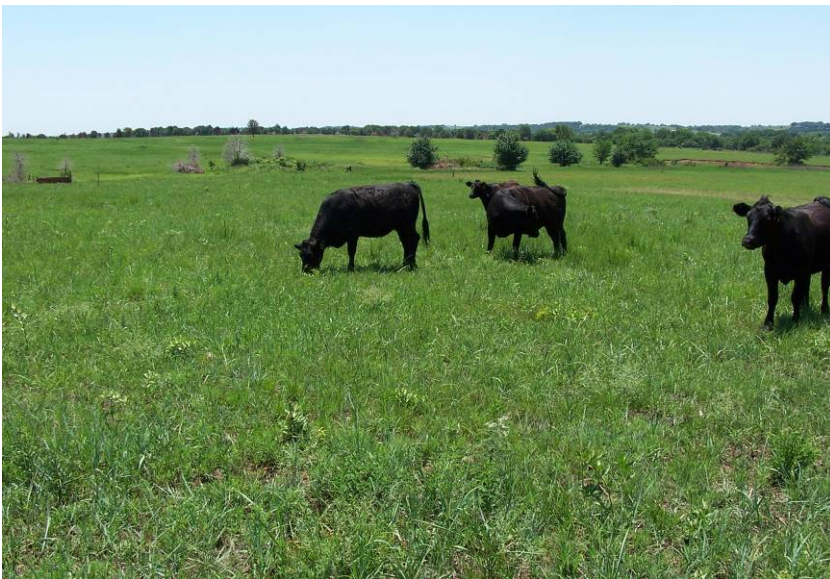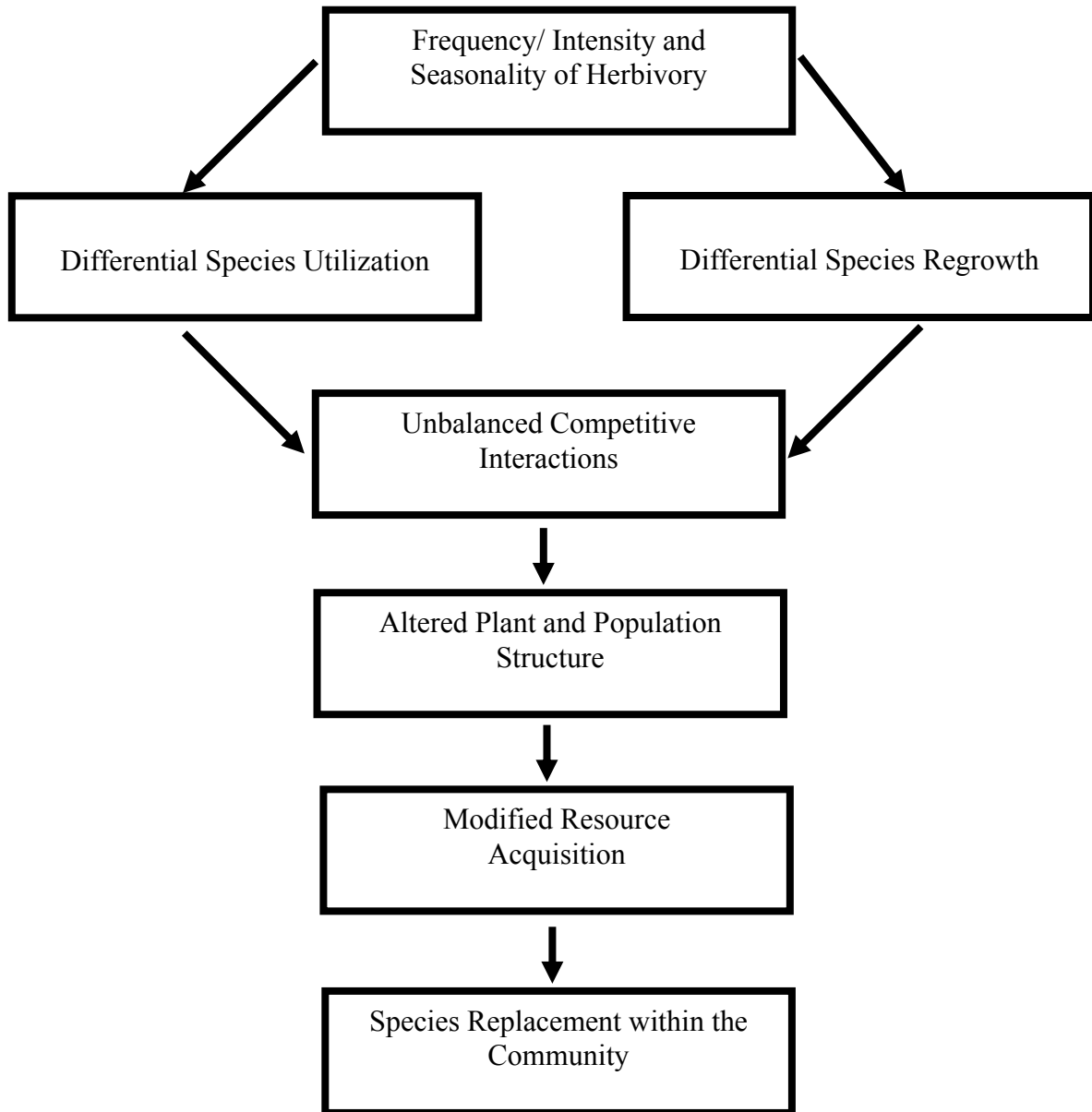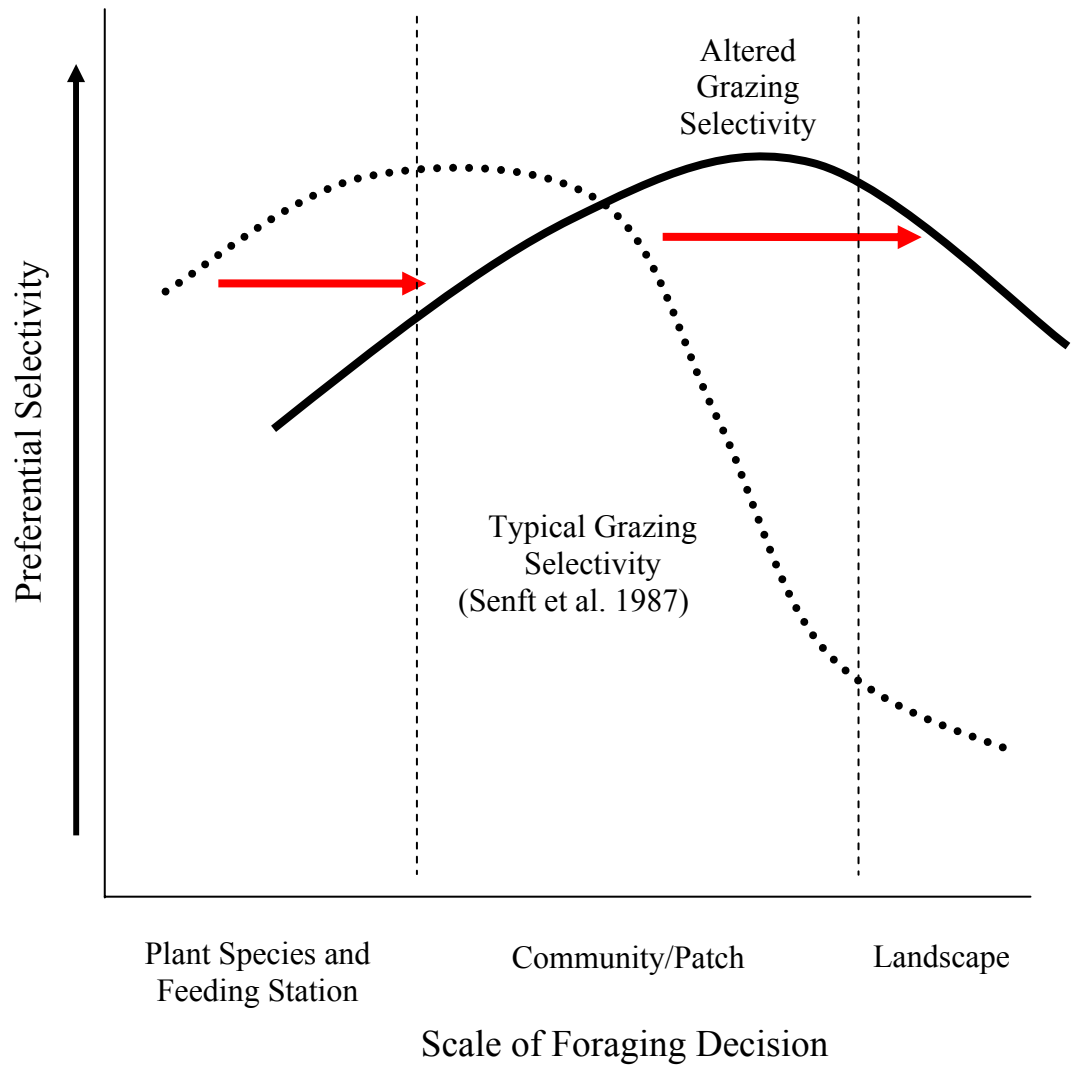
Figure 3

Figure 4.

Figure 5.
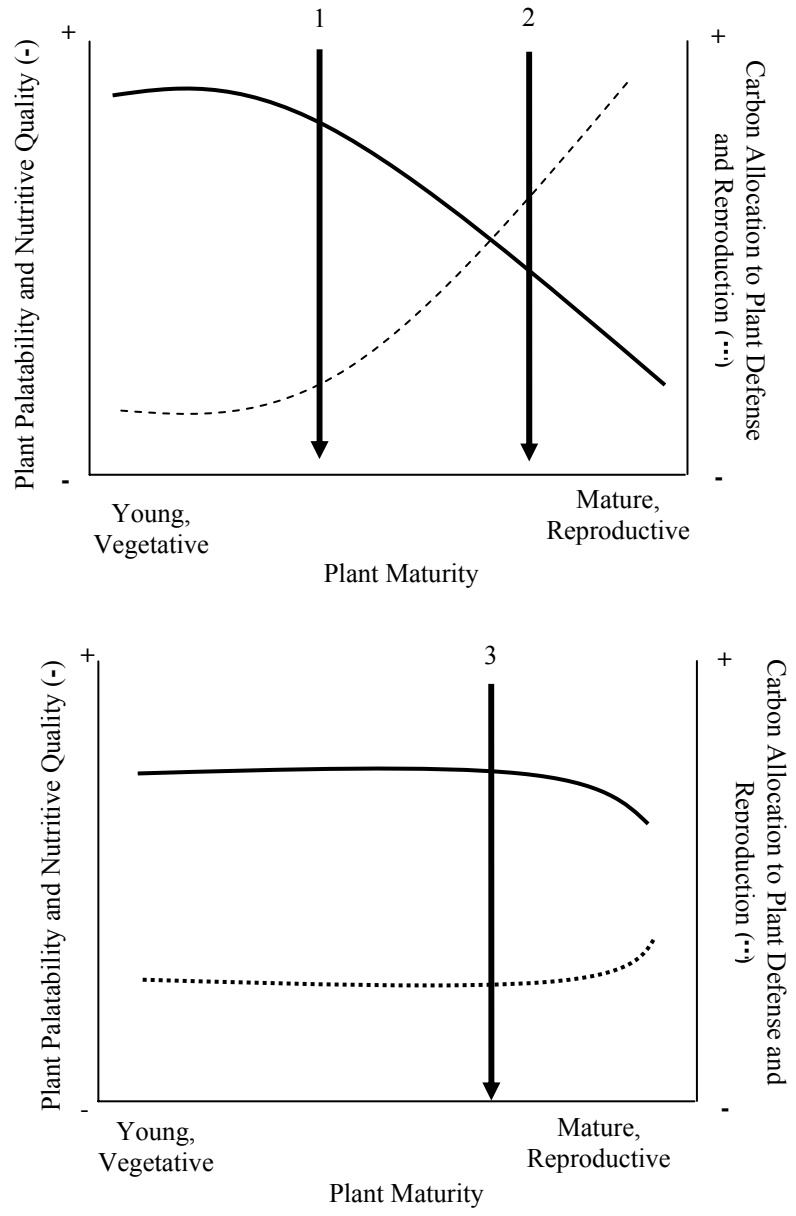
CHAPTER II

IS ALTERED GRAZING SELECTIVITY OF INVASIVE FORAGE SPECIES WITH

PATCH BURNING MORE EFFECTIVE THAN HERBICIDE TREATMENTS?

The following chapter chapter has been published in journal *Rangeland Ecology and Management* and appears in this dissertation with the journal's permission.

Is Altering Grazing Selectivity of Invasive Forage Species with Patch Burning More Effective than Herbicide Treatments?

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ABSTRACT

Invasion of rangeland by exotic forage species threatens ecosystem structure and function and can cause catastrophic economic losses. Herbicide treatments often are the focus of management efforts to control invasions. Management with the fire-grazing interaction (or patch burning) might suppress an invasive forage species that has grazing persistence mechanisms developed apart from the fire-grazing interaction. We studied tallgrass prairies invaded by sericea lespedeza [*Lespedeza cuneata* (Dum. Cours.) G. Don] to compare rate of invasion between traditional management and management with patch burning, to evaluate the effect of burn season on sericea lespedeza invasion within pastures managed with patch burning, and to correlate canopy cover of sericea lespedeza to canopy cover of other functional groups with and without herbicides. Sericea lespedeza canopy cover increased from 1999 to 2005 in both traditional and patch-burn pastures, but sericea lespedeza increased from 5 to 16% canopy cover in traditionally managed pastures compared to 3 to 5% in the patch-burn pastures. Rate of increase in canopy cover of sericea lespedeza was less in patches burned in summer (0.41% · year^{-1}) than in patches burned in spring (0.58% · year^{-1}) within patch-burn pastures. Most plant functional groups, including forbs, were weak negatively correlated with canopy cover of sericea lespedeza. Although herbicide application reduced mass of sericea lespedeza, other components of the vegetation changed little. Herbicide treatments temporarily reduced sericea lespedeza but would not predictably increase other plant functional groups. Patch burning reduced the rate of invasion by sericea lespedeza by maintaining young, palatable

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sericea plants in the burn patch, and could play a vital role in an integrated weed management strategy on rangelands.

Key words: Chinese bush clover, disturbance ecology, fire ecology, grazing management, heterogeneity, herbivory, invasion, macro-ecology

INTRODUCTION

Invasive plant species alter native plant communities and their rate of invasion depends upon the structure of native communities they invade (Woods 1993; Morgan 1998; Symstad 2000; Brandon et al 2004). In addition, the total area of rangelands in the U.S. decreased by 4.4 million ha from 1982 to 1997, while pasturelands decreased by 49 million ha during the same time period due to urbanization, erosion, and cultivation (National Resources Inventory 1997). Recently, invasive species in rangelands and other agricultural lands have cost U.S. agricultural production an estimated $33 billion each year and further threaten rangeland resources (Mack et al. 2000, Pimental et al. 2002). Given the loss of grasslands, and the economic costs of invasive species, it is especially important to study invasive species biology and ecology, and provide options to manage them.

Many exotic species have been deliberately introduced into the U.S. as forage species only to become aggressive invaders once they escape cultivation. Some examples include kudzu [*Pueraria montana* (Luor.) Merr.], Old world bluestem [*Bothriochloa ischaemum* (L.) Keng], and tall fescue [*Festuca arundinacea* Schreb.]. These species are unique from non-deliberately introduced, exotic invaders because they are selected for traits that promote establishment and persistence in grazed monocultures.

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These traits include aggressive growth rates, prolific seed production, multiple modes of reproduction (propagule and vegetative), and traits that encourage persistence in grazed ecosystems (e.g. chemical compounds, high stem-to-leaf ratio) (Barnes et al. 2003). As a result, exotic forage species are unique because they are selected for traits that assure their establishment and persistence in grazed monocultures; traits which also facilitate their invasion into diverse native ecosystems (Clubine 1995; Brandon et al. 2004).

Sericea lespedeza [*Lespedeza cuneata* (Dum. Cours.) G. Don] is an herbaceous, long-lived perennial legume introduced into the U.S. in 1896 from eastern Asia. Sericea lespedeza has been used extensively for forage production, erosion control, and land reclamation since the 1930s. The USDA introduced sericea lespedeza as a forage species, in part because it is persistent once established. This persistence in grazed ecosystems is due to non-preference by grazing animals later in the growing season. While highly nutritious and palatable early in its phenology, maturity leads to avoidance by grazers resulting from decreased digestibility (Clarke et al. 1939; Stitt and Clarke 1941; Donnelly 1954). Phenolic polymers called condensed tannins, located throughout the plant (Burns 1966; Mosjidis et al. 1990), also decrease digestibility and have been shown to cause gastro-intestinal malaise (or stomach discontent) in some ruminants (Provenza et al. 1990).

Control of sericea lespedeza has typically focused on using selective herbicides. These herbicides, such as metsulfuron-methyl (methyl 2-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]amino]sulfonyl]benzoate), triclopyr ([(3,5,6-trichloro-2-pyridinyl)oxy]acetic acid), and tank mixes of triclopyr and other herbicides, have been effective in season-long control of sericea lespedeza (Altom &

Stritzke 1992; Koger et al. 2002). However, chemical control does not provide permanent eradication of sericea lespedeza. Due to the prolific seed production (Stitt & Clarke 1941; Donnelly 1954) the soil seed bank provides new sericea lespedeza invaders for multiple years following herbicide treatment. Repeat application of selective herbicides for invasive species control is economically taxing and has profound negative impacts on native forbs and legumes in rangelands (Koger et al. 2002).

An alternative approach to managing invasive forages with persistence mechanisms, which maintain their dominance under grazing (i.e., secondary chemicals, growth form), is to alter the relationship between palatability and seasonality with intensive selectivity by grazing animals, and management that reduces the expression of persistence mechanisms (e.g. fire). An example of this alteration in grazing preference is patch-burning (Fuhlendorf & Engle 2001, 2004), which reduces selection on individual plants and increases selection of all species within a burned patch. Under patch-burned systems, portions of an individual pasture unit are burned in the spring and summer of each year (Figure 1) in an attempt to create a fire-grazing interaction. Cattle preferentially graze the recently burned patch following a prescribed burn and avoid other patches with greater times since fire (patch-burn treatment, in this study). The result is a shifting mosaic that includes unburned areas that are not likely to be grazed but have accumulated fuel, recently burned patches that attract livestock and are not likely to get burned, and several patches in transitional stages of succession. Grazing selectivity patterns are changed

from that of the individual species or feeding station to an entire burned patch, resulting in lower grazing preference of individual species across the burned area.

Therefore, we compared sericea lespedeza invasion under rangeland management based on patch-burning to invasion under traditional rangeland management. In addition to studying the fire-grazing interaction, we also wanted to evaluate the effects of traditional approaches to manage invasive species with herbicides. We compared the effect of standard rangeland herbicides on sericea biomass and the response of other plant functional groups to sericea control. Our specific objectives were to 1) confirm that sericea lespedeza invades rangelands and identify differences in invasion rate between traditional management and patch burning, 2) determine what effect season of burn has on sericea lespedeza invasion, and 3) compare the response of native plant functional groups to sericea invasion with the fire-grazing interaction and with herbicide applications. Our hypotheses are that sericea lespedeza will invade at a reduced rate in the patch-burn treatment compared to the traditional management treatment, and summer fires will be more effective at suppressing the sericea invasion than spring fires. In addition, all plant functional groups will be negatively affected by sericea lespedeza invasion, but these effects will be more pronounced with increased invasion.

METHODS

Study Regions

To address our objectives, we established multiple study locations in the southern Great Plains. One study location was used to address the first two objectives concerning the

invasion dynamics and impact of sericea lespedeza on rangeland vegetation. This study area (Experiment 1; see also Fuhlendorf & Engle 2004; Anderson et al. 2006; Fuhlendorf et al. 2006) utilized fire and grazing as management options to alter grazing patterns and selectivity of forage within experimental units. Nine additional study locations were used to address the third objective which investigated the relationship between sericea lespedeza biomass and native community biomass following herbicide application. These herbicide studies (Experiment 2) were located throughout central and southern Oklahoma over several years. Throughout the manuscript, the two types of studies will be explained separately for clarity.

For the patch-burn study (Experiment 1), the experimental area was located in north central Oklahoma on the Oklahoma State University Range Research Station (Lat 36°16'N; Long 97º09'W) located 21 km southwest of Stillwater, OK. The region is dominated by a continental climate with an average of 204 frost-free days and 846 mm annual precipitation, 65% of which falls from May to October. The vegetation matrix is tallgrass prairie with intermittent patches of cross timbers habitat on shallow uplands. Dominants of the tallgrass prairie in the area include little bluestem, *Schizacharium scoparium* (Michx.) Nash, big bluestem, *Andropogon gerardii* Vitman, Indiangrass, *Sorghastrum nutans* (L.) Nash, switchgrass. *Panicum virgatum* L., and tall dropseed, *Sporobolus asper* (Michx.) Kunth. Minor grasses include *Bouteloua curtipendula* (Michx.) Torr., and *Dicanthelium oligosanthes* (Schult.) Gould. The dominant forbs in the area are western ragweed, *Ambrosia psilostachya* DC., and common broomweed, *Gutierrezia dracunculoides* (DC.) S.F. Blake. The cross timbers communities are dominated by post oak, *Quercus stellata* Wang., blackjack oak, *Q. marilandica* Münchh.,

and hackberry, *Celtis* spp. The area is also invaded by eastern redcedar, *Juniperus virginiana* L. and sericea lespedeza. Initial sericea lespedeza invasion was light in the area, making up 0-7% of the plant composition. Prescribed fire was applied periodically to all study areas for eastern red cedar control prior to the experiment initiation.

The herbicide trials (Experiment 2) were located on private ranches across central Oklahoma (Koger et al. 2002). The general vegetation composition was similar to that of the patch-burn study explained above. The herbicide trials were located in southern and north central Oklahoma on tallgrass prairie that previously were managed with variable grazing and fire regimes and periodic broad spectrum herbicide applications. Initial sericea lespedeza invasion was heavy in all study areas, making up 35% of the plant composition on average. Nine herbicide trials in all were used in the initial data analysis. We used biomass means from the herbicide trials to evaluate the objectives of controlling sericea and increasing other grass and forb biomass. Unlike Koger et al. (2002) we analyzed a combined data set from nine herbicide trials, which compared similar herbicide treatments, to determine trends in the plant components following herbicide application.

Experimental Design

Experiment 1 - Patch Burning versus Traditional Grazing Management

In 1999, a completely randomized design (CRD) experiment was established to test the effects of patch-burning on vegetation dynamics (Fuhlendorf & Engle 2004). Six individual pastures (0.8 by 0.8 km) were assigned one of two treatments. The treatments were: 1) a patch burned treatment (the application of the fire-grazing interaction) and 2) traditional management for rangelands in the area (experimental design analogous to

Anderson et al. 2006, Fuhlendorf et al. 2006). The patch-burned treatment pastures (n=3, 0.8 by 0.8 km) consisted of six distinct patches within a pasture. Annually, one sixth of the pasture was burned in the spring and one sixth burned in the late summer which created a mosaic of plant diversity and structure across the pasture unit (Figure 1). As a result, patches of heavy disturbance were included within a landscape of patches that vary with time since focal disturbance (Fuhlendorf & Engle 2001, 2004). Traditional management pastures (n=3, 0.8 by 0.8 km) were prescribed burned every three years in the spring for *Juniperus virginiana* control. So, the only difference between treatments was the timing and pattern of the burns, with similar amounts of fire across the management units. From 1999 to 2005, both treatments were moderately grazed by mixed-breed cattle with a stocking rate of 0.83 ha AUM^{-1} (AUM = animal unit month) (Gillen et al. 1991). Annual vegetation cover of plant functional groups was measured by ocular estimation each summer beginning in 1999. Random sub-sampling with $30 - 0.1$ m^2 quadrats per patch monitored functional groups including tallgrasses, little bluestem, other perennial grasses, annual grasses, forbs, sericea lespedeza, other legumes, litter, and bare ground. Sericea lespedeza invasion was defined as the increase in percent vegetative cover over time.

Experiment 2 - Herbicide Studies

The herbicide trials (1997 through 2001) were designed as randomized complete blocks with three or four replications (n=3 or 4) and 15 to 18 different herbicide treatments and associated controls, depending on the study site. Herbicide treatments were made at various stages in sericea lespedeza development including the single stem, branched stem, and flowering stages (Koger et al. 2002). From 1997 to 2001 in some

cases, vegetative components were visually estimated for forage composition prior to hand clipping two 0.4 m² plots per experimental unit. Grass, forb, and sericea lespedeza biomass were determined as a percentage of the total biomass. A net change in component biomass was calculated for herbicide studies which had more than one year of forage data, by subtracting the first season biomass from the last season biomass. This approach addressed the broad hypothesis that herbicide applications were effective at managing sericea lespedeza to increase grass and other forb biomass. To identify relationships between changes in sericea lespedeza biomass and changes in native plant biomass, we used a macro-ecological approach. Each data point (n=251) represents the sericea lespedeza biomass (x-axis) and grass or forb biomass (y-axis) from one treatment in one of the nine herbicide trials. Since herbicide effectiveness is also a key issue, we analyzed the data in two separate methods. First, the entire data set was analyzed to identify any relationships between sericea lespedeza biomass and native plant biomass across treatments (including effective, non-effective, and no herbicide treatments). The second analysis included only the treatments which resulted in adequate control of sericea lespedeza (90% control or greater; *sensu* Koger et al. 2002) in our analysis.

Data Analyses

Experiment 1 – Patch-burn study

The rate of sericea lespedeza invasion in the patch-burn study (Experiment 1) was calculated two ways. First, means for invasion were generated from all 0.1-m² plots of each treatment per year (n=3 per year). Annual vegetative cover was regressed over year. Increased invasion was defined as an increase in sericea lespedeza cover for this study.

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Though we reported results from regression analysis, it should be noted that regression was only used to find rates of invasion (i.e. the slope of the trend line) and not strength of the relationship between year and annual sericea cover. The data were also analyzed with repeated measures analysis of variance (ANOVA) for means ($\alpha=0.05$ significant, $\alpha=0.10$ weakly significant) using PROC MIXED procedure in SAS (SAS 2000). Year was not treated as the related variable since new seedlings could have germinated each year. In addition, individual t-tests were run to compare each treatment at each year in sericea lespedeza cover.

Using only the patch-burn treatment pastures, the effects of burn season on invasion were tested. Each patch in the patch-burn treatment was designated as a spring or summer burn, depending on respective season of prescribed fire (Figure 1). The mean sericea lespedeza cover consisted of all patches within a given burn season for each year following a prescribed burn (n=3 per season per year). Least squared means were compared across years since fire for each burn season (PROC MIXED in SAS, $\alpha=0.05$).

To test the effect of increasing sericea lespedeza cover on the native functional groups, Pearson's correlation coefficients (PROC CORR procedure in SAS) were used to identify significant ($\alpha=0.05$, and 0.10) relationships with sericea lespedeza and other functional groups at the plot, patch, and pasture scales. It should be noted that these data are only for use as descriptive statistics to observe the effect of increasing sericea lespedeza on the native plant functional groups at multiple spatial scales. Individual experimental units were broken down into their component parts (sub-samples, time since fire, and season of fire) to observe the effects of invasion at each level since ecological

phenomena often have an associated inherent scale at which they occur (Turner et al. 1989).

Experiment 2 – Herbicide Studies

In the herbicide trials the data means of sericea lespedeza biomass, grass biomass, and forb biomass were compared using Pearson's correlation coefficients (PROC CORR procedure in SAS) to identify significant (α=0.05) relationships with sericea lespedeza. The first analysis included all herbicide treatments. The second analysis only included single applications of triclopyr, metsulfuron-methyl, or fluroxypyr (2-(4-amino-3,5-dichloro-6-fluoro-pyridin-2-yl)oxyacetic acid) herbicides at the rates depicted in Koger et al. (2002) to determine if herbicide effectiveness played some role in the relationship between sericea lespedeza cover and cover of native plants. Production from within treatment year, one year following treatment, and two years following treatment (where available) were used in the correlation analysis.

RESULTS

Experiment 1 - Patch Burning versus Traditional Grazing Management

Sericea lespedeza cover increased at a much greater rate in traditionally managed units than in the patch-burn treatment (Figure 2). Repeated measures ANOVA indicated significant year (p<0.001) and weakly significant treatment by year interaction (p=0.087). When looking at each treatment and year individually, at the initiation of the experiment in 1999, the two treatments did not differ significantly (p=0.11) in sericea lespedeza cover. By 2000, the traditionally managed treatment had increased significantly more than the patch-burn treatment (p=0.02) which showed signs of fluctuation rather than true

invasion with positive and negative annual changes. The divergence between treatments continued throughout the study period. Average sericea lespedeza cover increased in the traditionally managed pastures at a rate of 1.95% (r^2=0.997) per year, while patch-burned pastures only increased at 0.47% (r^2=0.676) each year (Figure 2). This is almost a four fold greater rate of increase in the traditionally managed pastures compared to the patch-burned pastures.

Within the patch-burn treatment, season of prescribed burn also had an effect on the invasion rate. Mean sericea lespedeza cover was statistically similar in summer and spring burn patches in the first and second year following burn, but became significantly higher (p=0.046) for spring burns in the third year suggesting that summer fires have decreased the rate of sericea lespedeza invasion more than spring fire. In addition, analysis of overall invasion rates indicated sericea lespedeza cover in the spring patch burns increased at almost twice the rate of summer patch burns from 1999 to 2005 (0.65 and 0.36 % cover increase per year, for spring burns and summer burns respectively). Annual invasion fluctuated from positive to negative rates of increase in cover for both burn seasons (data not shown). These fluctuations could result from areas of intensive sericea lespedeza utilization in the season following fire within the patch-burn units. Though neither season had a net negative rate of increase, large fluctuations in invasion rate indicate that this species may cycle with variable fire and weather patterns in the patch-burn treatment.

Experiment 1 - Response of Native Plant Functional Groups to Sericea lespedeza Invasion with the Fire-Grazing Interaction

The third objective was to determine the relationship between sericea lespedeza and the other functional groups in the patch-burn and traditionally managed treatments. Although not a specific part of our objectives, these relationships were analyzed at multiple scales of observation, because ecological phenomena often differ due to the scale of observation (Turner et al. 1989). Sericea lespedeza increases in cover resulted in decreased cover for most functional groups in our study, though some positive relationships also existed (Table 1). Recall that the experimental units (n=3 per treatment year^{-1}) were broken down into their component parts for these descriptive analyses. At the plot scale (0.1 m^2; n=3240 per treatment), weak negative correlations were found with tallgrass, little bluestem, other perennial grasses, and forbs for both treatments. In the patch-burn treatment, litter showed a slight positive correlation, while bare ground was negatively correlated. At the patch scale (0.1 km^2; n=108), functional groups in the traditional treatment showed more correlations with sericea lespedeza than the patch-burn treatment (Table 1). Tallgrass, little bluestem, and forbs showed negative correlations with sericea lespedeza in the traditionally managed treatment, while legumes, litter, and bare ground had positive correlations. The patch-burn treatment had only two significant (p<0.05) correlations at the patch scale. At the pasture scale (0.64 km^2; n=18), there was only one significant correlation for either treatment. In the traditional treatment, forbs showed a strong negative correlation (p=0.015) with sericea lespedeza, which increased in magnitude of the relationship (i.e. numerically greater correlation coefficients) as scale increased (Table 1). While these data indicate significant relationships (p<0.05) between sericea lespedeza cover and cover of the other functional groups, it should be noted that the relationships are extremely weak given the large sample size at the plot level

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(n=3240). Other factors, biotic and abiotic, appear to have a greater impact on the cover of forbs and grasses than sericea lespedeza.

Experiment 2 - Response of Native Plant Functional Groups to Sericea lespedeza Invasion with Herbicide Applications

When considering all data points in this broad scale study (Experiment 2), including both effective and ineffective sericea lespedeza control with herbicides applications, we found no clear relationship between sericea lespedeza biomass to either forb or grass production (Figure 3). The strongest relationship (r^2 =0.04; n=251) occurred between sericea lespedeza biomass and forb biomass but accounted for only four percent of the total variation. When we included only data from herbicide treatments, we found no relationship between grass or forb components and sericea lespedeza. This held true for herbicide treatments up to three years following herbicide application. In our studies across multiple sites on the southern Great Plains, we could not identify any meaningful relationships (linear or non-linear) between sericea lespedeza biomass and either grass or forbs.

For herbicide treatments in which we had more than one year of biomass data, the change in time in biomass of sericea lespedeza was also regressed by grasses and forbs to determine if successful sericea lespedeza control results in predictable increases of other functional groups (Figure 4). Using only the most effective sericea lespedeza herbicide treatments (Koger et al. 2002), there was a weak negative response in grass biomass (Figure 4a) to increasing amounts of sericea lespedeza biomass (n=23; a regression slope of -2.99; $r^2 = 0.50$). There was no relationship between change in sericea lespedeza

biomass and change in forb biomass over time (Figure 4b). In all, there was only one instance of biomass replacement by sericea lespedeza over time and it occurred within the grass component. In all other instances there was no predictable replacement of sericea lespedeza forage by grass or forb forage. This broad analysis of herbicide studies had similar conclusions to previous studies on non-fertilized and eroded sites (Koger et al. 2002) which reported minimal replacement of biomass when herbicides eliminated the existing sericea lespedeza invasion.

DISCUSSION

Given the prediction of vast economic costs and modification of native ecosystems by invasive species (Pimental 2002), it is especially important to study invasive species biology and ecology to understand the effects of invasion. We need a comprehensive understanding of invasion mechanisms and effects to provide land management options that efficiently deter invasion. Typically, the literature suggests that invasive plant species affect, and are affected by the plant communities they invade, correlating to major shifts in the existing plant community (Woods 1993; Morgan 1998; Symstad 2000; Brandon et al 2004). Sericea lespedeza has been suggested to invade old-field and cross timbers ecosystems (Eddy and Moore 1998; Brandon et al. 2004), but little data has been presented on the relationships between disturbances, such as fire and grazing, and sericea lespedeza invasion on prairies (Munger 2004). Sericea lespedeza invades rangelands at a rapid rate (2 % vegetative cover per year in our studies), and the invasion rate depends upon the fire and grazing management regime employed in the area. In addition, the invasion can have negative impacts on the cover of the other plant functional groups, and

herbicide application to reduce sericea lespedeza dominance did not result in increases in grass or forb biomass in our studies.

Patch Burning and Traditional Management

The term disturbance has positive and negative connotations depending upon the definition, but is accepted as a natural process in many ecosystems which depend on the regenerative effects of disturbance for their continued existence (Pickett & White 1985; Hobbs & Huenneke 1992). However, disturbance also facilitates the invasion of ecosystems by exotic plant species (Ewel 1986; Rejmanek 1989; Fuhlendorf & Engle 2004). The frequency and timing of the disturbance has a notable impact on the invasion potential, with the interaction of multiple disturbance types having the most profound effects on diversity in grassland plant communities (Collins 1987; Hobbs & Huenneke 1992). In our study, both treatments had the same level of grazing and overall the same amount of fire, but patch burning resulted in focal grazing followed by several years of rest. This fire-grazing interaction suppresses the increase in sericea lespedeza. Grazing animals that select for burned patches may be less likely to be selective at the species level.

In contrast, traditional rangeland management, with homogeneous, less focused disturbance (compared to patch-burning) appeared to provide opportunities for invasion (Figure 2), and the invasion by sericea lespedeza corresponded to decreases in cover of the native plant community (Table 1). Given the large sub-sample size, the relationships between sericea lespedeza cover and the cover of other functional groups should have been very strong. However, the weakness of the relationships indicates sericea lespedeza

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had very little impact on the plant community in our study, and other factors influenced the plant community dynamics.

Sericea lespedeza invasion rate remained constant in the traditional management treatment throughout the seven years, even following the pasture wide prescribed burn in 2003. Following this prescribed fire (see Figure 2) both treatments had the same amount of fire across the landscape with the only difference being the timing and pattern of fire. Though the application of fire across the landscape in the traditional management treatment provided new growth for livestock utilization, we propose the large extent of the burned area encouraged grazing selectivity at the species level. In contrast, patch burning led to significantly lower invasion rates (Figure 2), with summer burning actually reducing sericea lespedeza cover by the third year since fire compared to spring burning. This result is likely a product of focused grazing following a patch-burning event (Fuhlendorf & Engle 2004; Vermeire et al. 2004). Since cattle focused their grazing on recently burned patches, non-selective, repeated grazing led to consecutive feeding events on the most recently burned patch and equal avoidance of all species within the unburned patches. Regrowth of many unpalatable species is lower in secondary metabolites, because most plant energy is directed toward growth and reproduction instead of chemical defenses (du Toit et al. 1990; Rosenthal & Kotanen 1994). However, several studies found similar condensed tannin levels in all growth stages of sericea lespedeza plants (Burns 1966; Mosjidis et al. 1990). A likely alternative is that focused grazing following the patch-burn maintained sericea lespedeza plants at young maturity levels relative to other patches, thus maintaining utilization. The alteration of grazing preference, intensity, and duration by patch burning changes the level of grazing

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selectivity from the feeding station to the patch, and may be one limitation to sericea lespedeza invasion in rangeland ecosystems.

Biomass Replacement Following Herbicide Application

Although most weed control is conducted with the expectation of increased production of desirable species following herbicide application, our data did not consistently support this prediction. Standard broad-spectrum herbicides (i.e. 2, 4-D, dicamba, and picloram) do not provide adequate suppression of sericea lespedeza (Altom & Stritzke 1990; Koger et al. 2002). Thirty-nine percent of the sites in our studies indicated an increase in desirable biomass production following herbicide application. In over half of the studies, the predictable replacement of sericea lespedeza biomass by grass and forb biomass following herbicide application did not exist, or resulted in only slight change (Figures 3 & 4). While herbicide applications may have a utility in an integrated management program, chemical control of sericea lespedeza does not appear to be a viable means to increase desirable forage production in invaded rangelands. A weak relationship of increased sericea lespedeza and decreased grass production was present only with the most effective, and consequently most expensive, herbicide applications while forbs never showed this trend in our studies. However, the high amount of unexplained variance indicates other factors (biotic and abiotic) have a greater influence on grass and forb biomass than sericea lespedeza biomass.

While herbicide applications provided an effective control of the existing sericea lespedeza population, we suggest that a management option based on the entire plant community would allow continued suppression of the sericea lespedeza invasion. Swanton and Booth (2004) noted that invasive weed seed bank dynamics demand a

population approach for management when the weed is particularly problematic, but only require community management strategies if the plant invasion is not intensely problematic. We propose that in areas where sericea lespedeza populations are in the initial stages of establishment, management strategies like patch burning provide suppression of the invasion at the level of the recently burned patch thus managing the entire plant community rather than the individual invader populations. In areas where invasion has exceeded the initial establishment, a combination of sericea lespedeza population control with selective herbicides in an integrated framework with patch burning might provide the best management option.

MANAGEMENT IMPLICATIONS

Sericea lespedeza is invading rangelands of the southern Great Plains at rates approaching 2% increases in vegetative cover per year. The impact of invasion on the native plant community function is weakly negative, but more pronounced with traditional management. Focused grazing appears to limit the ability of sericea lespedeza to expand for several years following a prescribed burn, especially following summer fire. This might result from the maintenance of sericea lespedeza plants at young maturity levels due to the regrowth following the patch burn. We propose that historical disturbance regimes, like patch burning and grazing, could be the key for managing invasive forage species in ecosystems where invasion threatens sustainable function.

Modification of grazing selectivity patterns from species level to patch level decisions could limit invasion success without the loss of productivity or function.

Reduction of sericea lespedeza with herbicides is possible, but the associated increase in desirable forages was unpredictable. While other invasive plant species have been suppressed with herbicides in combination with other management techniques, our studies did not address the potential application of herbicides in an integrated management plan. A management approach which integrates herbicides and the fire-grazing interaction could be a viable option for long-term control, and future research should investigate this possibility.

ACKNOWLEDGEMENTS

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Table 1. Pearson's correlation coefficients (r) for significant (PROC CORR, p<0.05) linear relationships of functional group canopy cover with sericea lespedeza canopy cover at the plot ($0.1\ m^2$), patch ($0.1\ km^2$), and pasture ($0.64\ km^2$) scales of observation over seven years.

	Functional group *							
Treatment **	TG	LB	OTHPER	ANNGR	FORB	LEGUME	LITTER	BG
Plot (n=3240)								
Traditional	-0.161	-0.222	-0.110		-0.123			
Patch-burned	-0.064	-0.136	-0.124		-0.043		0.109	-0.096
Patch (n=108)								
Traditional	-0.331	-0.259			-0.313	0.344	0.192	0.314
Patch-burned						0.204	0.204	
Pasture (n=18)								
Traditional					-0.563			
Patch-burned								

* Functional groups: TG = tallgrass, LB = little bluestem, OTHPER = other perennial grasses, ANNGR = annual grasses, FORB = forbs, LEGUMES = leguminous plants other than sericea lespedeza, LITTER = litter, BG = bare ground.

** Correlation Coefficients are only listed for significant correlations (α = 0.05).

Figure 1. Prescribed burn treatment schedule for patches within the patch burned pasture units. Within each pasture small patches are burned in multiple seasons, followed by focused grazing disturbance of the burned patch.

Figure 2. Sericea lespedeza invasion over time in the traditional management and patch-burn treatments. Error bars indicate one standard error.

Figure 3. Regression analysis of sericea lespedeza biomass production and grass biomass production (A) or forb biomass production (B) in nine herbicide trials throughout central and eastern Oklahoma from 1997 to 2001.

Figure 4. Data from the most effective herbicide treatments with multiple years of biomass production data in central and eastern Oklahoma from 1997 to 2001. Points indicate the change in sericea lespedeza biomass production in relation to the change in grass (A) and forb (B) biomass production from the first year of data collection to the last year of data collection for only the best herbicide treatments in five herbicide trials (Koger et al. 2002).

Figure 1.

Pasture (Experimental Unit)

Spring 2000	Summer 1999
Spring 2003	Summer 2002
Spring 2006	Summer 2005
Summer 2000	Spring 2001
Summer 2003	Spring 2004
Summer 2006	Spring 2007
Spring 2002	Summer 2001
Spring 2005	Summer 2004
Spring 2008	Summer 2007

0.80 km

0.80 km
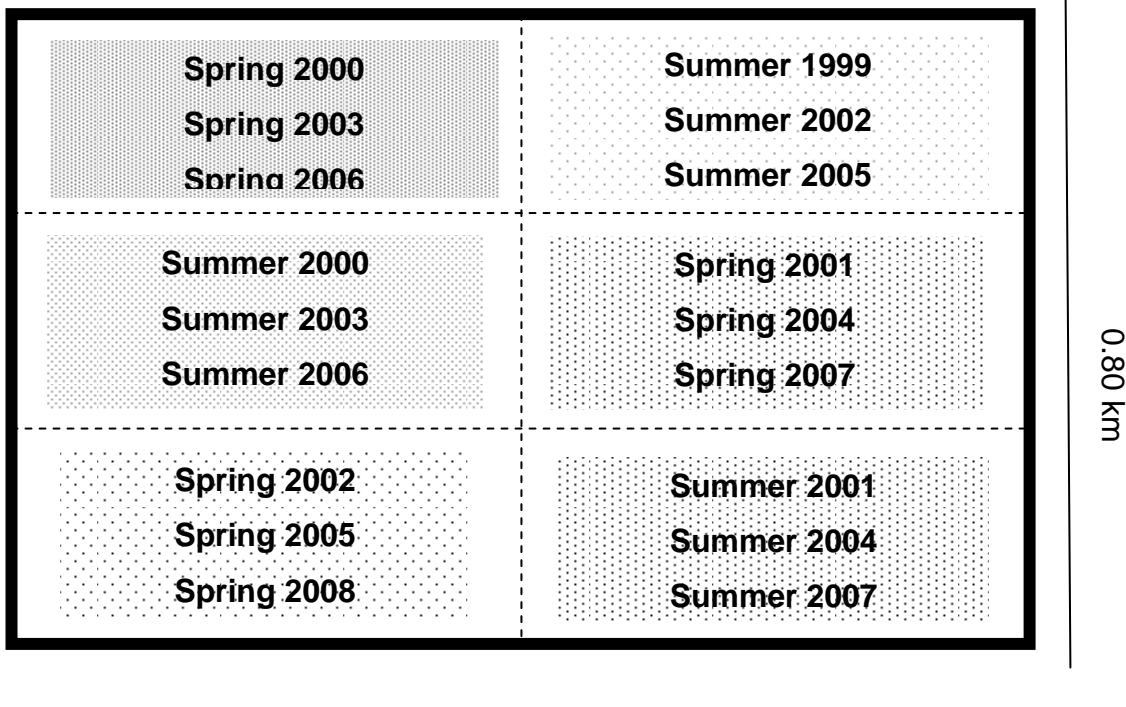
* The dark outline denotes the fence line enclosing an individual experimental unit. There are no interior fences within the pasture.

Figure 2.
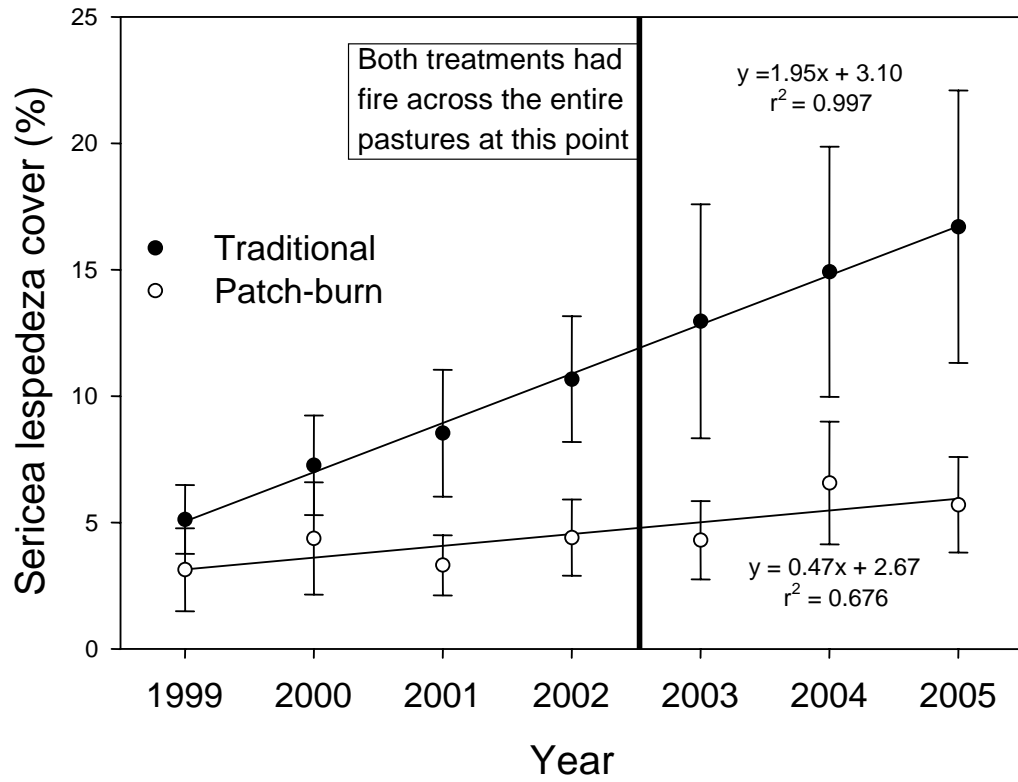
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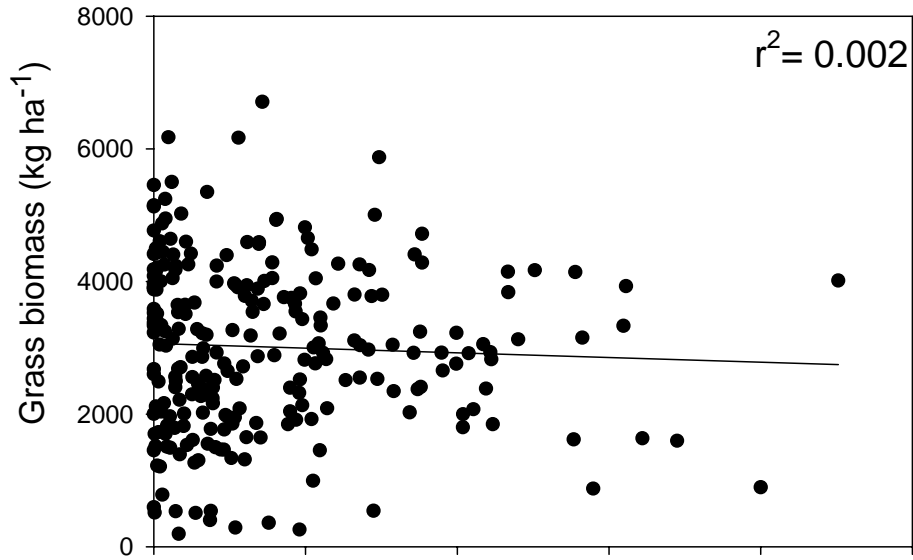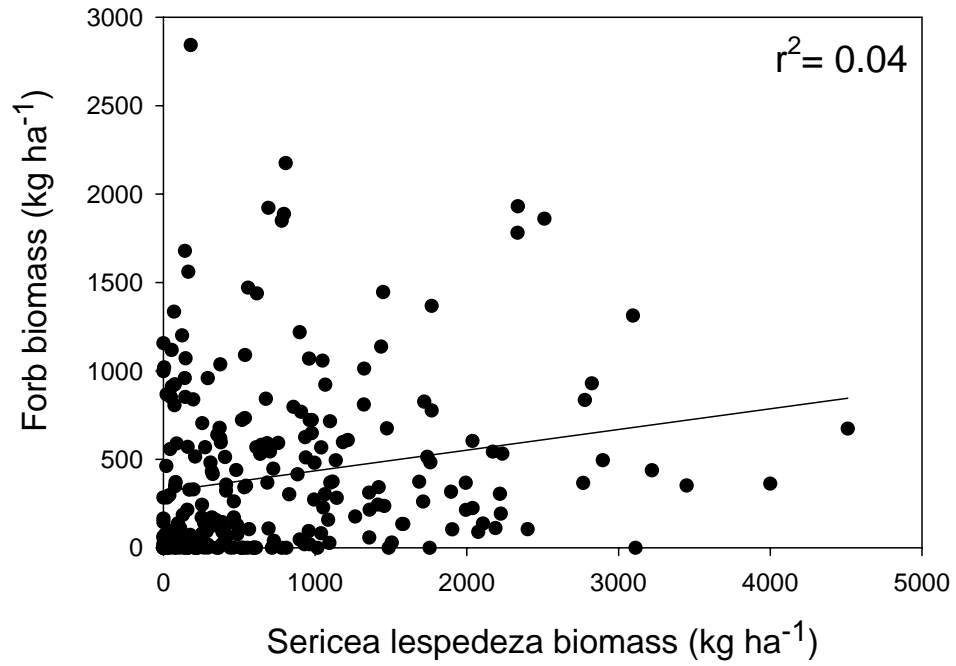
Figure 4.
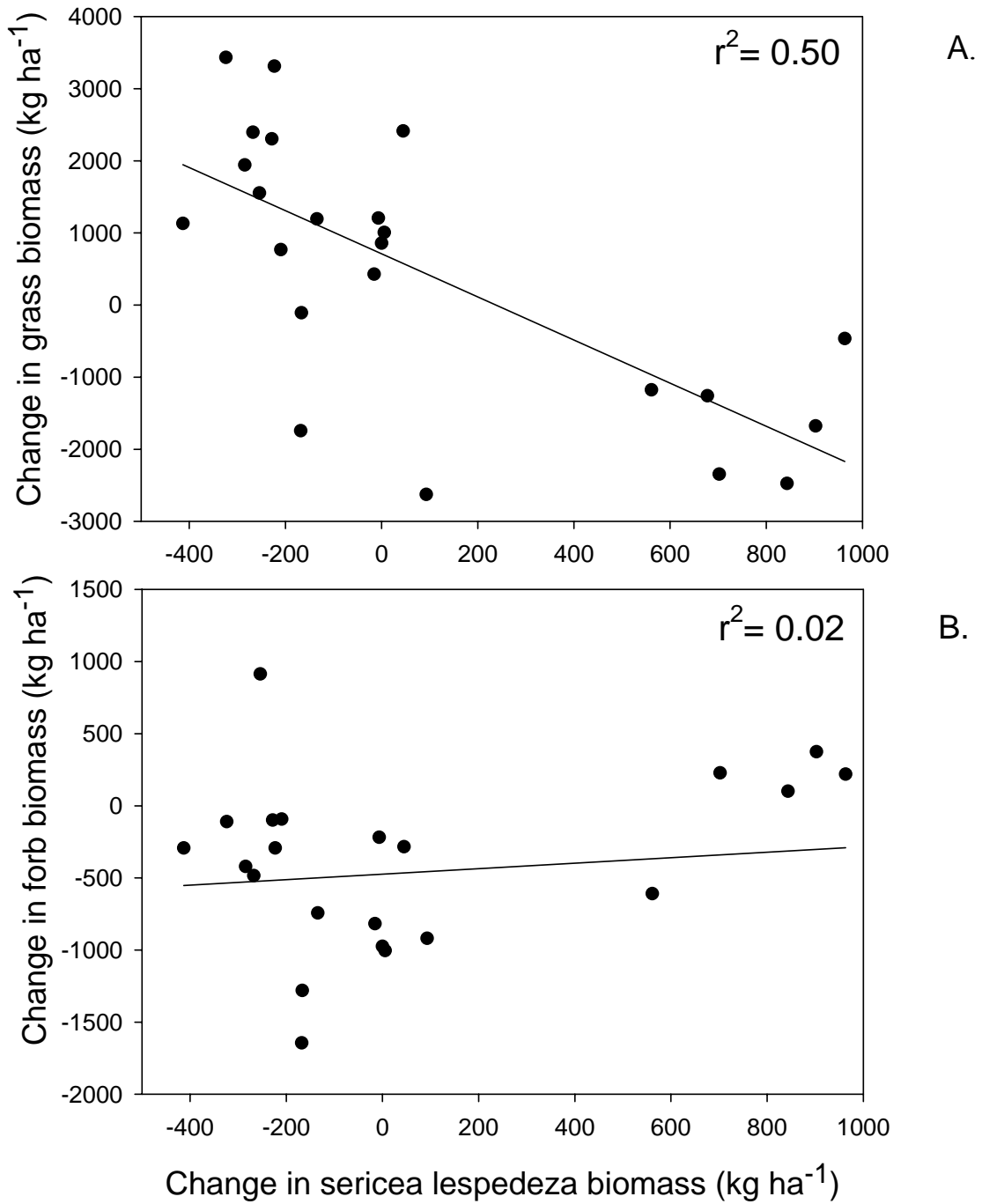
CHAPTER III

TO SPRAY OR NOT TO SPRAY: DO RANGELAND HERBICIDE APPLICATIONS

RESULT IN INCREASED LIVESTOCK GAINS?

To Spray or Not to Spray: Do Rangeland Herbicide Applications Increase Livestock Gains?

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ABSTRACT

Herbicides have been applied extensively on rangelands to eliminate undesirable plants. In return, an increase in production of desirable forage plants is thought to increase livestock gains or performance. While scores of research studies support the premise that weedy species suppression increases desirable forage, only a few studies have attempted to quantify the effects on livestock production within experimental units that are realistic in size to production pastures. For these reasons, we tested the effect of herbicide applications on vegetation response and livestock gain in a semi-arid rangeland. Two management units were aerially treated with 0.7 kg ae ha^{-1} picloram + 2,4-D in the spring of 2001 and spring of 2004, and compared to two untreated control units. Vegetation dynamics was observed in permanent plot areas from 2000 to 2005. In addition, stocker performance (average daily gain per head; ADG) and livestock production (kg ha^{-1}) were measured from 2000 to 2005. Herbicide treatment decreased ($P<0.05$) forb cover in the year of application, but the effect diminished by the year following treatment. Grasses varied more with annual precipitation than with herbicide treatment. Livestock ADG and gain ha^{-1} did not differ with treatment in any year or across years. Livestock production differed among years, responding to variation in growing-season precipitation. We conclude that herbicide application for weed control should not be based on the assumption that vegetation change will increase livestock production in semi-arid rangeland.

Keywords: cattle performance, average daily gain, weed grass trade-offs, plant species composition, weed control

INTRODUCTION

Rangelands throughout the Great Plains are managed to maximize the production

of desirable plant species for livestock production (Holecheck et al. 1998). In most cases,

vegetation and livestock manipulation reduces forage variability and increases utilization

(Vallentine 1990; Heittschmidtt & Taylor 1991; Holecheck et al. 1998). Management

efforts focus on fencing, water distribution, prescribed fire, specialized grazing systems,

and mechanical or chemical brush and weed control in an effort to maximize rangeland

productivity (Holecheck et al. 1989; Vallentine 1990).

Herbicides are typically used to reduce undesired herbaceous plants in rangelands

and other ecosystems (Thilenius et al. 1975; Miller & Stritzke 1995; New 1997;

DiTomaso 2000; Fuhlendorf et al. 2002a). Herbicides were applied to an estimated 1.2%

of the approximately 400 million ha of United States rangelands in 1987 (Bovey 1996).

Several states treated approximately 3% of their rangelands, including California, Idaho,

Nevada, New Mexico, Oklahoma, Kansas, and Florida (Bovey 1996). Herbicide

applications occurred on 25% of the 400 million ha of U.S. rangeland in 1997 (Bussan &

Dyer 1999). Broadleaf-selective herbicides are applied annually to about 20% of

Oklahoma's 9.3 million ha of rangeland to reduce weeds, increase forage production,

increase livestock performance, and improve aesthetics (New 1997). Many rangeland

managers operate under a largely untested assumption that a reduction of undesirable

weeds will facilitate management goals, including increased livestock performance.

There have been multiple studies that show an increase in desirable forage production

following the control of woody (Scifres & Koerth 1983, Bernardo et al. 1992), and

herbaceous weed species (Powell et al. 1982, Thilenius et al. 1975). However recent

studies indicate that this replacement does not always occur with herbaceous weed

control on rangelands (Cummings et al. 2007). In addition, there are no studies which

document an actual increase in livestock production following the removal of herbaceous

weeds.

The herbicide 2, 4-D [(2,4-dichlorophenoxy) acetic acid] is the most commonly

used herbicide in the United States for rangeland vegetation management (Rice &

Stritzke 1989; New 1997). Combined estimates of 2, 4-D use in croplands, pasturelands,

and rangelands for the United States range from 12.7-14.9 million kg annually

(Donaldson et al. 2002). Native and exotic dicots are primary targets of many herbicide

applications to rangelands in the central Great Plains (Gillen et al. 1987; Rice & Stritzke

1989; New 1997). However, these plants also comprise key structural, vegetative, and

nutritional elements of wildlife habitats (Koerth 1996), and livestock diets (Heitschmidt

& Taylor 1991).

Because there has been little direct research to address these issues, the goal of

this research was to evaluate ecological and economic sustainability of herbicide

applications on eroded rangelands. Our specific objectives were 1) to determine if

herbaceous weed control on southern rangelands results in increased desirable forage

cover, and 2) to determine if livestock production and performance increased following

herbicide application to the extent that economic gain was achieved by the application.

MATERIALS AND METHODS

Study Site

Livestock and vegetation community data were collected on the Marvin Klemme Range Research Station (35.4169°N, -99.0614°W, NAD 27) in southwestern Oklahoma, USA. The site is located approximately 15 km south of Clinton, Oklahoma and situated in the Western Redbed Plains Geomorphic Province of Oklahoma (Curtis & Ham 1972) within the mixed grass prairie of the southern Great Plains. Climate of the region is sub-humid with a mean annual temperature of 15°C (OCS 2003) and a mean annual precipitation of 774 mm (ranging from 529 to 1031 mm over the study period) (Table 1). The mean frost-free period is 210 days (OCS 2003). Less than 1% of the total land area of the county is enrolled in Conservation Reserve Program (FSA 2003). Soils are highly erosive and primarily classified as a Cordell silty clay loam with an average depth of 25-36 cm over solid siltstone (Moffatt & Conradi 1979; Gillen et al. 2000), including proportionally large amounts of bare ground and rock outcrops.

The plant community is indicative of historically cultivated croplands that have re-vegetated naturally in conjunction with intensive livestock use (Fuhlendorf et al. 2002b). Desirable plant species included: buffalograss (*Buchloe dactyloides*), silver bluestem (*Bothriochloa saccharoides*), hairy grama (*Bouteloua hirsuta*), blue grama (*Bouteloua gracilis*), sideoats grama (*Bouteloua curtipendula*), tall dropseed (*Sporobolus asper*) and western ragweed (*Ambrosia psilostachya*). Target species for the herbicide application included broom snakeweed (*Gutierrezia sarothrae*), curlycup gumweed (*Grindelia squarrosa*), Texas croton (*Croton texensis*), and white heath aster (*Symphyotrichum ericoides*). In addition, the native forb western ragweed (*Ambrosia*

psilostachya) was specifically monitored since this species composes at least a portion of cattle diets some times of the year, and provides wildlife food and habitat (Bidwell 2002).

Experimental Design

Four pastures, each approximately 40 ha, were selected as experimental units in a completely randomized design with two treatment pastures (herbicide; *n*=2) and two control (no herbicide) pastures (*n*=2). Pretreatment vegetation sampling in 2000 determined the mean forb composition on all pastures to be 23% of the total herbaceous cover. On the study pastures, the primary plant species targeted for control with herbicides included broom snakeweed, annual broomweed, and isolated patches of flame leaf sumac. On 24 April 2001, and 8 May 2004, a commercial applicator aerially applied 0.7 kg acid equivalent ha^{-1} of a commercial premix of 2, 4-D (2, 4-dichlorophenoxyacetic acid; Dow AgroSciences, L.L.C., Indianapolis, IN, USA) and picloram (4-amino-3, 5, 6-trichloropicolinic acid; Dow AgroSciences, L.L.C., Indianapolis, IN, USA) with 46.8 L ha^{-1} water to two of the four pastures (Herbicide treatment) as recommended by the Oklahoma State University Cooperative Extension Agents Handbook (OCES 2001). Weather data for application dates can be found in Appendix 1. The aerial application was assisted by GPS, to ensure accurate application of the treatment.

Vegetation Sampling

From 2000 to 2005, four-0.1 m^2 quadrats were sampled at each of 25 permanent points per pasture annually. Percent canopy cover by plant species and cover of bare ground and litter (Daubenmire 1959) were visually estimated during peak plant growth.

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For data analysis, we used all species data, and we also placed plant species into the functional groups of grasses, forbs, shrubs, and trees based on growth form (Fuhlendorf & Smeins 1998; Gillen et al. 2000). The year 2000 was pre-treatment, therefore the pre-treatment data served as a control to demonstrate any deviations once herbicide applications were made. Vegetation response data was not collected in 2003.

In addition to species composition, residual biomass was collected every two years throughout the study period. Thirty-0.1 m^2 subsamples were clipped from each treatment unit between mid November and mid December of 2002, 2004, and 2006, approximately 3 months following grazing termination. The addition of 2006 data to the study for residual biomass analysis served to quantify long term effects (2 years post treatment) on the biomass production following herbicide applications. The majority of the vegetation was dormant at the time of biomass sampling. The subsamples were dried for 7 to 10 days at 70°C and weighed.

Livestock Grazing

Season-long grazing was initiated annually during late April and terminated in late August. Each pasture was stocked with mixed breed yearling steers at a four-year mean (2000-2005) stocking rate of 0.63 AUM ha^{-1}. Steers were weighed individually with a 3-kg resolution electronic scale prior to stocking and at the time of removal each year. Changes in individual steer gain (ADG; kg head·day^{-1}) and total gain per hectare (kg ha^{-1}) were used to indicate the effect of herbicide application on livestock performance. Since 2000 was a pre-treatment year, the data served as a control to demonstrate any deviations once herbicide applications were made.

Statistical Analysis

We conducted repeated measures analysis of variance (PROC MIXED; α=0.05) and analysis of variance by year on a target plant species, broom snakeweed (*Gutierrezia sarothrae*), and desirable plant species including western ragweed (*Ambrosia psilostachya*), sideoats grama (*Bouteloua curtipendula*), and blue grama (*Bouteloua gracilis*), and on plant functional groups (grass, forbs, litter, bare ground) to monitor changes in vegetation composition following herbicide application. The functional groups were sampled within years to specifically evaluate the effects of herbicide applications in 2001 and 2004. Vegetation data and livestock performance data were both intensively sampled in space (between 20 & 30 sub-samples rep·year^{-1}) and time (2000 to 2005), which maximize the statistical power of the experimental design given the replication constraints. Herbicide treatment served as the fixed effect, and random effects were replication by treatment. Tests of differences in mean plant cover for functional groups and individual species and mean residual biomass (g 0.1m^{-2}) relied on probability differences (α=0.10, weak significance; α=0.05 strong significance).

We also used analysis of variance (PROC MIXED SAS 9.01; SAS Institute 2000) to determine if livestock production and performance were affected herbicide treatment over the six year study. Herbicide treatment served as the fixed effect, while random effects included replication by treatment and sub-sample. Differences in mean ADG and mean gain ha^{-1} were determined using probability differences (α=0.10, weak significance; α=0.05 strong significance).

RESULTS

Vegetation Response

Herbicide applications dramatically decreased some key target species, but little to no effect on the others. The perennial forb broom snakeweed did not change with the herbicide application, but rather had cyclic population fluctuations which peaked in 2000 (7.5% cover) and again in 2004 (3.5% cover), resulting in a significant ($P<0.05$) year effect but no treatment effect (P=0.74) or significant treatment by year interaction ($P=0.93$) (Table 1). Western ragweed on the other hand a significant treatment effect ($P=0.0387$), and highly significant year effect ($P<0.0001$) and treatment by year interaction (Table 1). This was the only plant species of the four that showed more dependence on herbicide application than on other environmental factors (Figure 1).

Selected grass species experienced little to no effect from the herbicide application, but showed a strong influence from the annual environmental variation (Figure 2). Neither sideoats grama nor blue grama exhibited significant treatment or treatment by year interaction effect (Table 1). However both species experienced significant ($P<0.05$) annual variation in cover (sideoats grama ranged from 5 to 30 % cover; blue grama ranged from 1 to 21% cover), which seemed to follow variation in precipitation throughout the study period (Table 2).

There was no treatment, or treatment by year interaction effect indicated by repeated measures ANOVA for any plant functional group. Repeated measures ANOVA of each functional group indicated only significant linear ($P<0.001$) and quadratic ($P<0.001$) year effects for forbs, grass, litter, and bare ground. Analysis of variance for individual years indicated significantly lower cover for forbs in 2001 ($P=0.01$), 2004

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($P<0.001$), and 2005 ($P=0.02$) in the herbicide treatment compared to the control. In addition, cover for grass was significantly greater in the herbicide treatment compared to the control in 2002 ($P=0.078$), 2004 ($P=0.03$), and 2005 ($P=0.01$). In all cases these responses resulted in the year of, or the year following herbicide applications.

Livestock Performance and Production

Stocking density was similar between treatments for the duration of the study (Table 2). From 2000 to 2005, there were no differences between treatments within any year ($\alpha=0.05$) for average daily gain ($P=0.881$; Figure 3) or gain ha^{-1} ($P=0.921$). Within treatments, there were significant differences between years for ADG ($P=0.001$) and gain ha^{-1} ($P<0.001$), which followed directly with growing season precipitation differences (Table 3, Figures 4 and 5). Herbicide applications in 2001, and again in 2004 had essentially no effect on livestock performance. By far the majority of the variability was due to precipitation patterns. In fact, the control treatment had greater production and greater ADG in 50% of the years during the study. High precipitation years in 2002, 2004, and 2005 resulted in years with the greatest mean livestock production with 61, 72, and 62 kg ha^{-1}, respectively (Figure 5).

Residual Biomass

There were no significant differences between the treatments within any sampling year for residual biomass production ($P=0.601$). There was a significant year effect ($P=0.02$) with the greatest residual biomass production in 2004 (34 g 0.1m^{-2}) and the least residual biomass in 2006 (23 g 0.1m^{-2}) (Figure 6). Residual biomass aids in

adjustment of stocking density and duration in proceeding years. In this study, residual

biomass indicated that stocking density was appropriate throughout the study period.

DISSCUSSION

Herbicide applications are one cornerstone of land management in grazed

ecosystems throughout the Great Plains and around the world (Baldwin & Santelmann

1980, Holechek et al. 1998), but what are their true benefits and consequences? In

Oklahoma (in 1995), approximately 20 % of the rangelands are treated with herbicides

suggesting that over 3-5 years the majority of Oklahoma rangelands potentially could be

treated. In Texas, 90% of the ranchers believed that fairly intensive vegetation

management is necessary to maximize forage production (Hanselka et al. 1990). While

increased desirable forage production from small plot studies has been reported in studies

following herbicide application (Powell et al. 1982, Borman et al. 1991), other studies

suggest that the increase in desirable forage production is short-term or non existent

(Torrell et al. 2005, Cummings et al. 2007). In this study, we found that forbs decreased

with herbicide applications in the year of treatment and one year post treatment, but these

effects diminished by the second year, and did not significantly differ ($P>0.05$) from the

control after the second application (Figure 3). Also, herbicide effectiveness appeared to

be highly dependent on growing season precipitation, with the most effective herbicide

application occurring in the wettest year. In addition, some forb species actually

decreased episodically in the control pastures the year of herbicide application to

treatment pastures (Figure 1). On average, desirable grass species were highly variable

with variable growing season precipitation and herbicide treatments had minimal influence across a rangeland landscape.

Cattle derive at least a portion of their diet from the very forbs that many herbicide applications target. Forbs comprise up to 20% of domestic livestock diets on rangelands (Heitschmidt & Taylor 1991), and recently have been shown to comprise 31% of cattle diets in forest ecosystems (Walburger et al. 2007). Without these components in the ecosystem, larger herbivore nutrient requirements may not be met by desirable grass species in some seasons or for certain physiological requirements (Stuth 1991, Huston & Pichak 1991). The relative portion of forbs and grasses in cattle diets depends upon their relative abundances in rangeland landscapes and livestock production did not benefit from herbicide treatment (Thelinius et al. 1975). Our study supports this conclusion from both the individual animal performance and the livestock gain per area. Neither ADG nor gain ha^{-1} were significantly different between herbicide and control treatments (Table 3).

One unique caveat to our study is the fact that we observed vegetation patterns at the same scale at which we observed livestock performance. Scale of observation has been shown to significantly affect vegetation dynamics results in rangelands (Fuhlendorf & Smeins 1996). Previous studies concerning trade-offs between undesirable forbs and desirable plant species observe these phenomena at very fine (small) scales <0.1 ha (Aarssen & Epp 1990; Rice et al. 1997) which might not be applicable to the grazing animal. Our study accounts for the vegetation patterns at a scale similar to the scale which livestock must utilize. In this respect, the vegetation dynamics can be applied directly to changes in livestock performance. In this study, no change in livestock

performance was observed indicating the livestock did not respond to slight changes in the vegetation composition which resulted following herbicide applications. Instead the animals seemed to gain better in wet years and less in dry years, following a trend of increased herbage production and/or quality in wet years (Figures 4 & 5).

The implications for this lack of livestock benefit extend well beyond the management unit. From both economical and ecological aspects, herbicide applications which decrease forb abundance and diversity without increasing animal production could have detrimental effects. Economically, herbicide applications provide little to no benefit unless forb populations comprise a substantial portion of the landscape. In fact, economic thresholds of plot level studies can only be reached when utilization of grass forage is sufficiently large to justify the investment of herbicide (Powell et al. 1982, Dahl et al. 1989, Rice & Stritzke 1998). At these animal densities, forb cover could again increase as a result of over grazing desirable forages, thus negating any benefit from the herbicide application. In addition, the negative environmental effects of heavy grazing have been shown to persist for nearly half a century in these semi-arid rangelands (Fuhlendorf et al. 2002b).

Ecologically, the detrimental effects of forb decrease could be realized at many trophic levels and potentially in impaired ecosystem function. Biodiversity has been proposed as one source of stability in managed ecosystems (Tilman & Haddi 1992, Tilman & Downing 1994). Decreasing forb diversity with the use of phenoxy herbicides like 2,4-D can decrease arthropod habitat and diversity, which could in turn effect higher trophic levels (Taylor et al. 2006). The decrease in forb abundance and diversity beyond that observed here by episodic dynamics (Figure 1) could be detrimental to wildlife

because these plants also comprise key structural, vegetative, and nutritional elements of wildlife habitats (Koerth 1996).

In summary, the dogmatic application of broad spectrum herbicides like 2,4-D to rangelands in expectation of increased livestock gains has no basis in semi-arid rangelands. While the significant decrease in forb cover resulted in an increase in desirable forage cover following these applications, our study showed no subsequent increase in livestock production compared to the control treatment over the six year study with two separate herbicide applications. In our study, desirable grass cover and livestock production responded more to annual fluctuations in precipitation, peaking in wet years and decreasing in dry years. Due to the complexity of native ecosystems, quantifying non-target effects from herbicide applications is difficult, but the potential negatives far outweigh the negligible livestock benefits in many cases.

MANAGEMENT IMPLICATIONS

We have shown that broad spectrum herbicide applications to control forb species do not result in increased livestock performance or livestock production on semi-arid rangelands in the southern Great Plains. Herbicide applications are warranted in some circumstances for specific management objectives (e.g. specific brush removal, invasive plant species management, or aesthetics). However, in many cases the application of broad-spectrum herbicides provides no economic benefit to livestock production, and might be detrimental to native ecosystem structure, function, and stability by removing vital parts of the plant community. Therefore, caution should be taken to critically evaluate objectives for broad spectrum herbicide applications in these diverse

ecosystems. The potential ecological benefits of not applying herbicides appear to far

exceed production benefits from livestock grazing on rangelands.

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Table 1. Results of analysis of variance comparing the effect of treatment (herbicide or no herbicide) on canopy cover of selected plant species (two undesirable forbs and two desirable forage grasses) from 2000 to 2005. Values in the table represent P values which were derived from repeated measures analysis of variance (α=0.05; SAS Inst. 2000).

	Forbs		Grasses	
Effect	Broom snakeweed	Western ragweed	Sideoats grama	Blue grama
Treatment	0.74	0.04	0.16	0.24
Year	0.001	<0.001	0.001	<0.001
Trt x Year Interaction	0.93	<0.001	0.47	0.69

Figure 1. Herbicide treatment effects on broom snakeweed (**top**) and western ragweed (**bottom**) vegetative cover from 2000 to 2005 on the Marvin Klemme Range Research Station near Clinton, OK. Herbicide applications were made in April 2001 and May 2004 to the herbicide treatments. Asterisks indicate significant differences (* $P<0.1$; ** $P<0.05$) between treatments within a year.

Figure 2. Herbicide treatment effects on sideoats grama (**top**) and blue grama (**bottom**) vegetative cover from 2000 to 2005 on the Marvin Klemme Range Research Station near Clinton, OK. Herbicide applications were made in April 2001 and May 2004 to the herbicide treatments. Asterisks indicate significant differences (* $P<0.1$; ** $P<0.05$) between treatments within a year.

Figure 3. Herbicide application effects on forbs (**top**) and grass (**bottom**) functional groups from 2000 to 2005 at the Marvin Klemme Range Research Station in west central OK. Error bars indicate 1 SEM. Asterisks indicate significant differences (* $P<0.1$; ** $P<0.05$) between treatments within years.

Figure 4. Average daily gain from stocker cattle on the Marvin Klemme Range Research Station from 2000 to 2005. Herbicide applications were made in April 2001 and May 2004 to the herbicide treatments. There were no significant differences between treatments in any year.

Figure 5. Gain and growing season precipitation data (March to October) for stocker cattle on the Marvin Klemme Range Research Station from 2000 to 2005. Herbicide applications (picloram + 2,4-D) were made in May 2001 and May 2004 to the herbicide treatments. Error bars indicate one standard error for the gain data. No error bars were include for the precipitation data due to $N=1$.

Figure 6. Residual biomass (g 0.1 m^{-2}) in the herbicide and no herbicide treatment units. Livestock were typically removed in September of each year. Residual biomass was collected between mid November and mid-December of each year. Biomass means + 1 SE.

Figure 1.
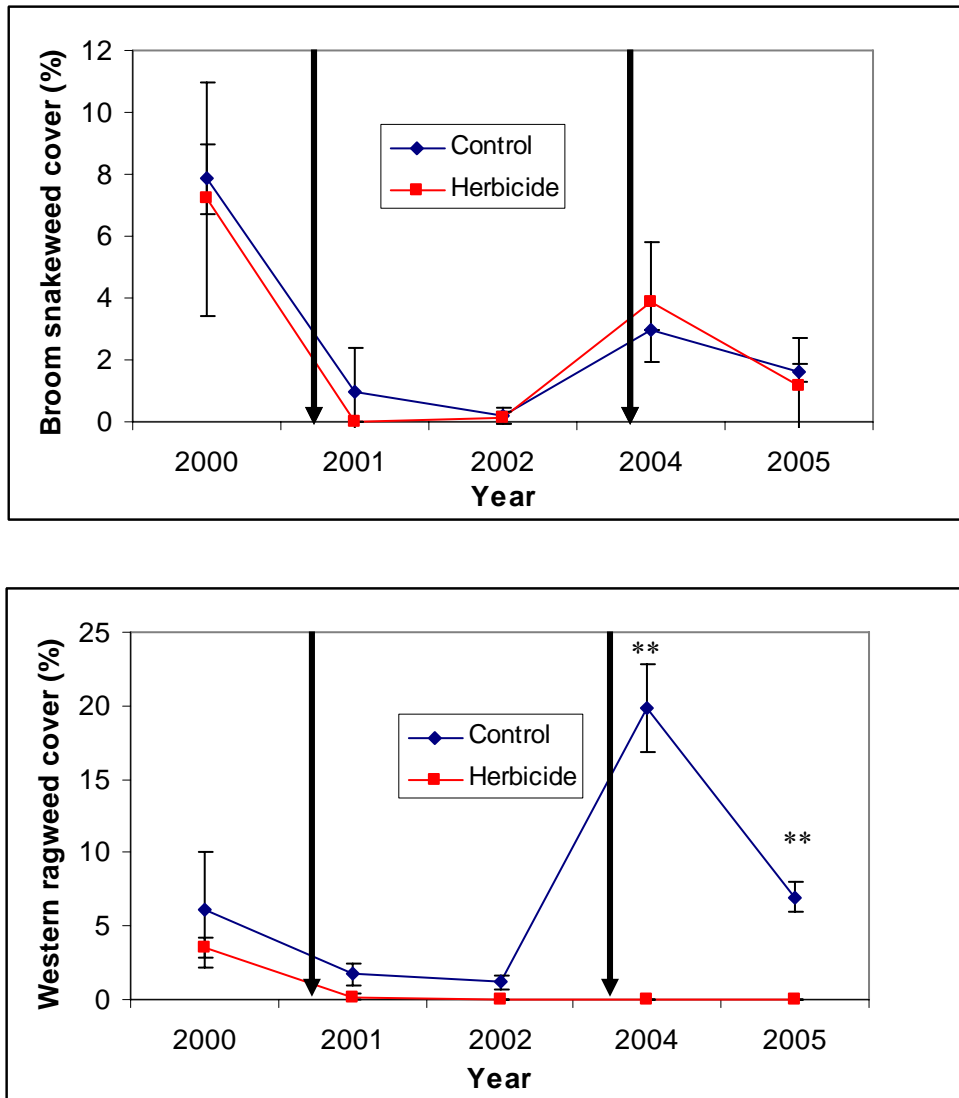
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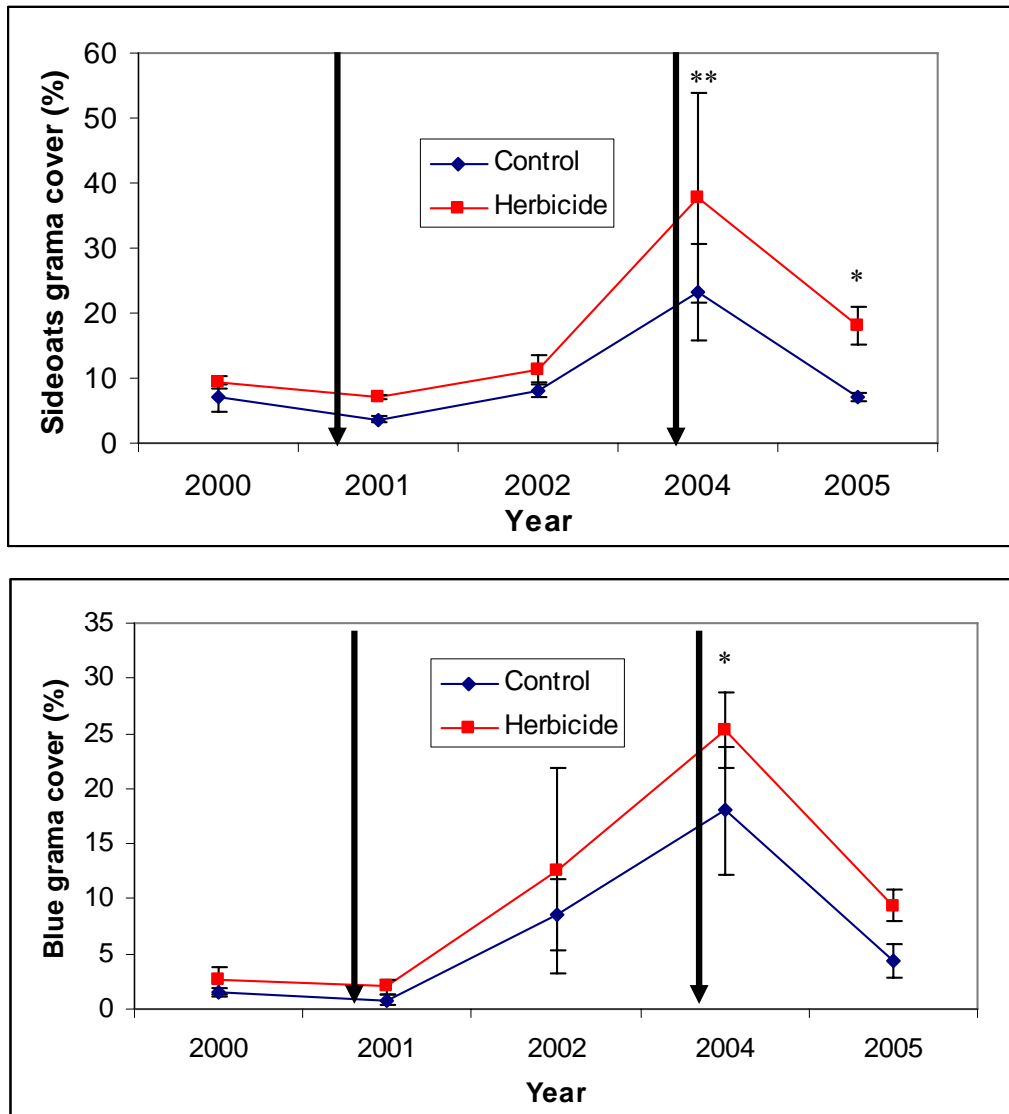
Figure 3.
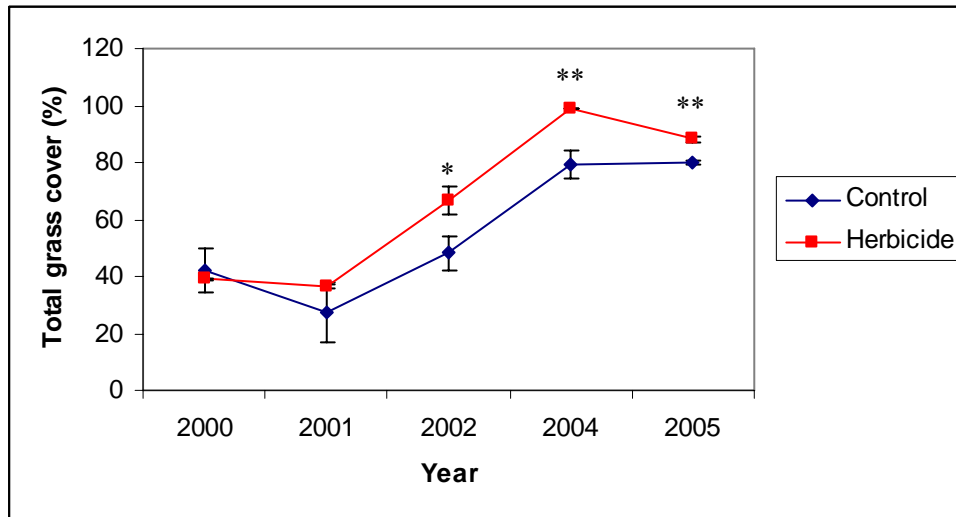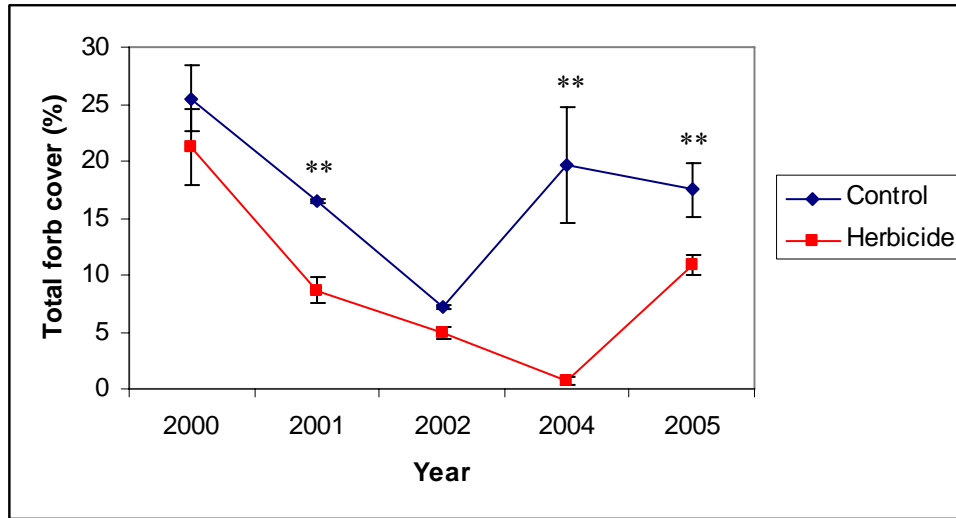
Table 2. Stocking density, annual precipitation, and growing season precipitation for the study period on the Marvin Klemme Range Research Station in west central Oklahoma. Precipitation data were derived from the Oklahoma Mesonet site (BESSIE) located on the research station.

Year	Stocking Density (ha head^{-1})		Precipitation (mm)	
	Herbicide	Control	Annual	Growing Season
			(Jan. to Dec.)	(Mar. to Oct.)
2000	2.0	2.0	862	755
2001	2.0	2.0	592	438
2002	2.1	2.1	850	712
2003	2.0	2.0	529	479
2004	2.0	2.0	1031	740
2005	2.0	2.0	783	691
2006	2.0	2.0	715	594

Table 3. Means for gain per area and average daily gain (ADG) on the Marvin Klemme Research Range Station in southwestern Oklahoma, USA. Letters represent significant differences ($P<0.05$) in means among years within a treatment. There were no significant differences between treatments in any year for either gain per area or ADG.

Year	Gain per area (kg ha^{-1})		ADG (kg head·day^{-1})	
	Herbicide	Control	Herbicide	Control
2000	50.1 c	52.9 y	0.69 bc	0.72 yz
2001	37.3 d	34.2 z	0.62 bc	0.57 z
2002	60.0 b	61.7 wx	0.83 a	0.84 x
2003	48.9 c	52.9 y	0.61 c	0.66 z
2004	73.7 a	69.8 w	0.84 a	0.80 xy
2005	63.9 b	60.7 xy	0.80 ab	0.75 yz
Mean	55.6	55.4	0.73	0.72

Figure 4.
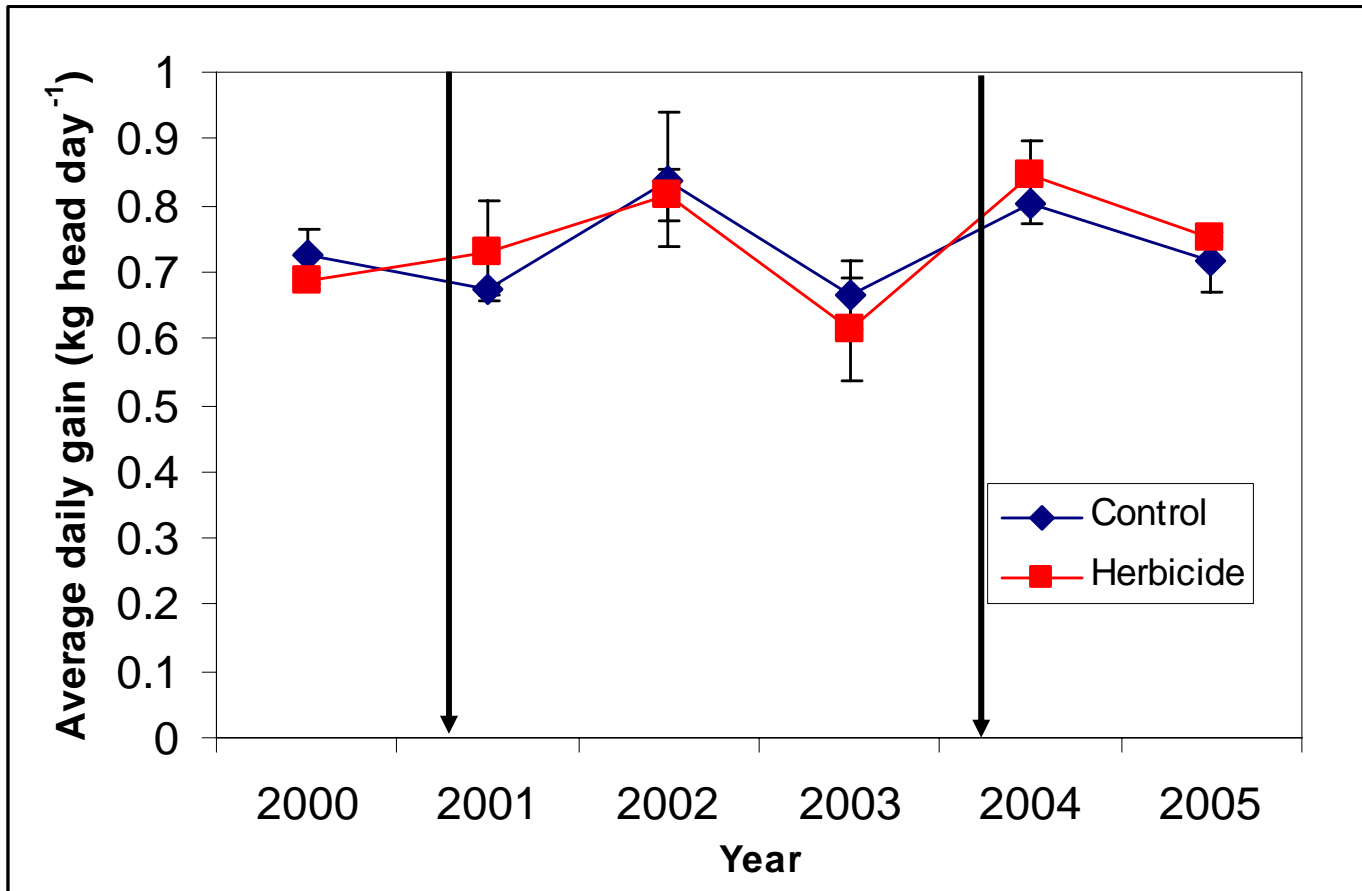
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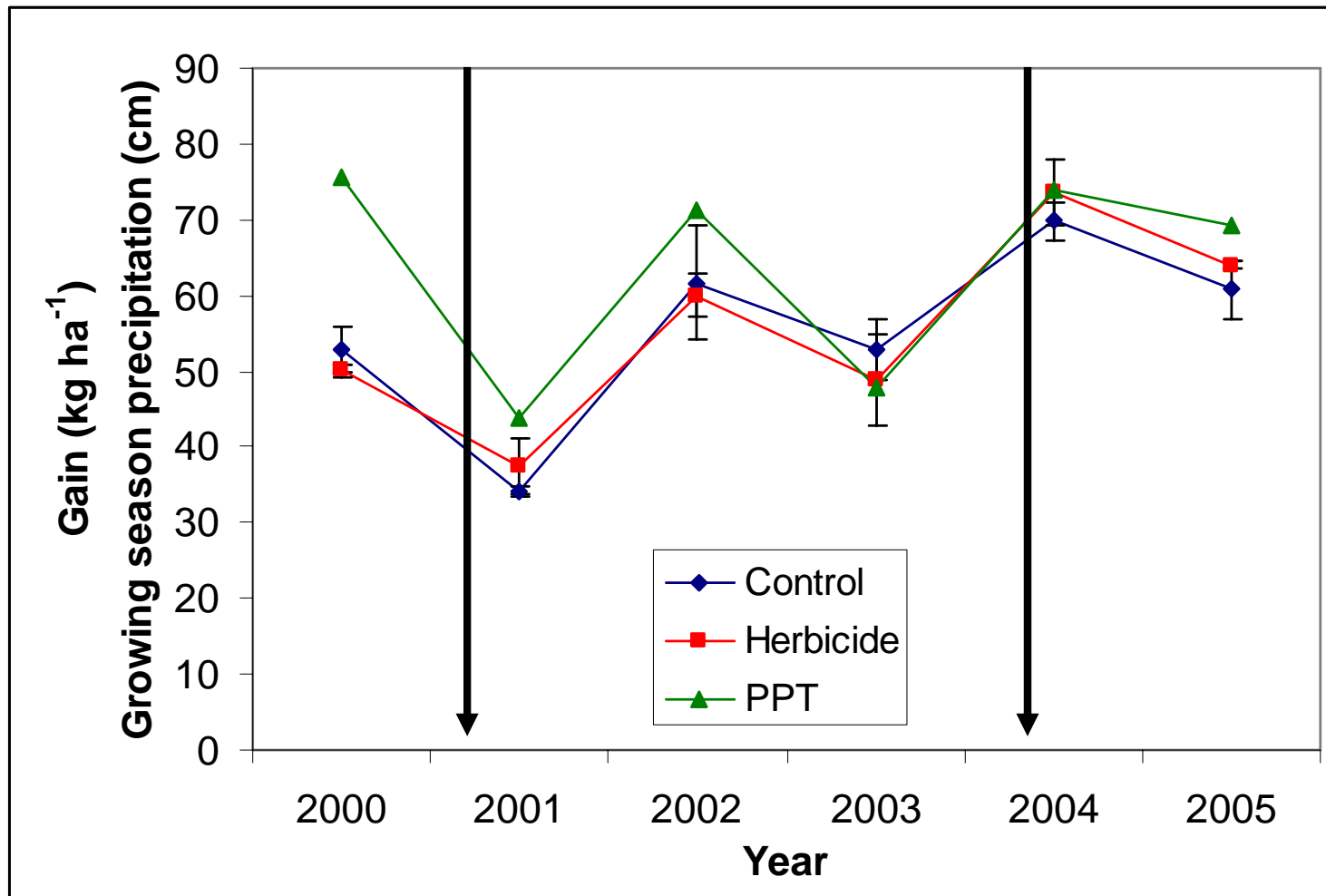
Figure 6.
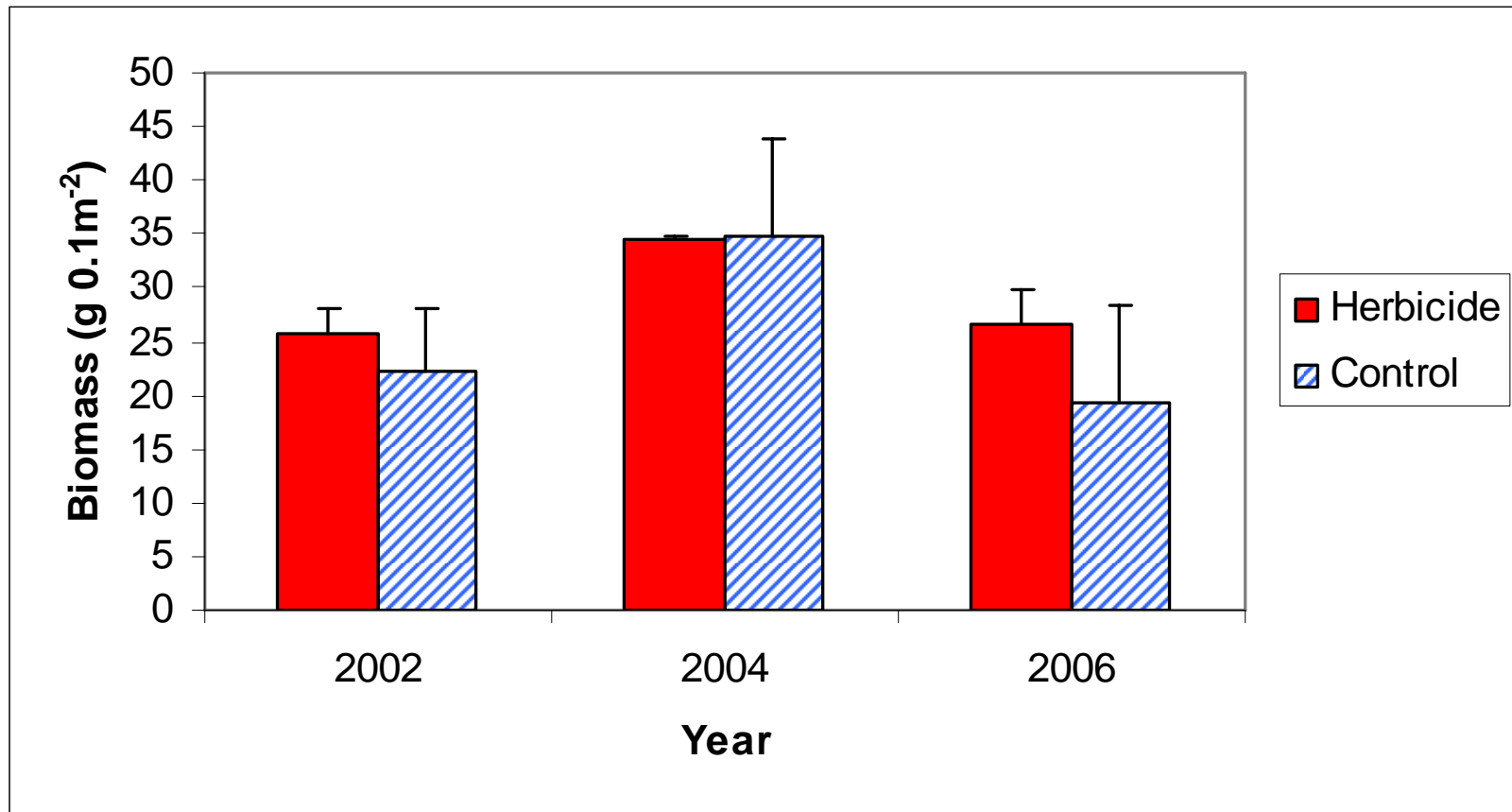
Appendix 1. Weather conditions on herbicide application dates from the Oklahoma
Mesonet site (BESSIE) on the Marvin Klemme Range Research Station. Precipitation
(Precip.), average (avg.).

Variable	24 April 2001		8 May 2004	
	Min	Max	Min	Max
Air temp. (°C)	6.1	21.7	16.7	29.4
Relative humidity (%)	21	83	46	94
Wind speed (m s^{-1})	2.7 avg.	7.7	7.5 avg.	14.6
Soil temp. (°C)	13.9	22.8	20	27.2
Previous 7 day precip. (mm)	3.3		0.0	

CHAPTER IV

THE ROLE OF ECOSYSTEM HISTORY AND CURRENT MANAGEMENT ON

RATE AND PATTERN OF EXOTIC SPECIES INVASION

The Role of Ecosystem History and Current Management on Rate and Pattern of Exotic Species Invasion

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Summary

1. Exotic forage species invasions result in ecological and economical losses to rangelands in the Great Plains; however their rate, pattern, and determinants of invasion are not well understood, thus long-term invasion management cannot be implemented.

2. We tested management treatment effects on 1) *L. cuneata* invasion rate and pattern over time, and 2) proximate determinants of invasion, and 3) species composition in sites with and without *L. cuneata* invasion.

3. The experiment is located in north central Oklahoma (36º16'N; 97º09'W), 21 km southwest of Stillwater, OK. The vegetation matrix is tallgrass prairie with intermittent patches of cross timbers habitat on shallow uplands. Traditional management for the region included grazing at moderate stocking rates and burning the pasture entirely every three years. Patch-burn grazing included burning small patches across landscape in the spring or summer every three years and grazing at moderate stocking rates. Floristic species composition was collected from 36 permanent Whittaker plots (500 m^2; 18 per treatment). In addition, *L. cuneata* invasion was mapped as vegetative cover using a coordinate grid mapping system. In 2005, soil samples were taken to quantify environmental variability among the sites.

4. Invasion rates did not differ between treatments with an annual increase in *L. cuneata* cover of between 0.7 and 1.1%. Change in proportion of area invaded showed increasing trends in both treatments, however, rates were 5 to 6 times higher with traditional management treatment than patch-burning. *L. cuneata* invasion at the fine scale was most influenced by *L. cuneata* invasion at the broad scale, while *L. cuneata* invasion at the broad scale was a product of treatment, site differences, and year. The probability of

invasion for a coordinate grid cell increased directly with the increase in adjacent cell invasions.

5. *Synthesis and analysis.* Examining the rate, pattern and proximate causes of invasion have elucidated some key features of exotic forage invasions in rangelands. Traditional management regimes appear to facilitate high rates of invasion. Patch-burn grazing appeared to be more resilient to invasion due to increased floristic spatial variation across the landscape.

Keywords: sericea lespedeza, Chinese bush clover, fire-grazing interaction, prescribed fire, invasive species ecology, non-native plant dynamics, detrended correspondence analysis

Nomenclature: Diggs et al. 1999

Introduction

Invasive species in rangelands, pasturelands, and croplands cost U.S. agriculture producers an estimated $33 billion annually and contribute to the loss of natural rangelands (Mack et al. 2000, Pimental et al. 2002). Invasive plant species affect, and are affected by the plant communities they invade, correlating to major shifts in the native plant community (Brandon et al 2004, Morgan 1998, Symstad 2000, Woods 1993). Given the loss of rangelands and pasturelands, and the economic and environmental costs of invasive species, it is especially important to study invasive species biology and ecology to provide rangeland management options that deter biotic invasions.

Invasion rate and pattern have been investigated for many exotic species at fine and broad spatio-temporal scales (Pysek & Prach 1995, Shigesada & Kawasaki 1997, DiVittorio et al. 2007). Several studies have investigated environmental variability in relation to these invasion patterns, indicating that both biotic (Stohlgren et al. 2005), and abiotic (Manning et al. 2007) environmental variation may determine the rate, pattern, and success of plant invasions. In addition, invasion of many plant species is patchy, due in part to propagule dispersal, and environmental patchiness which leads to differences in community invasibility (Eriksson & Ehrlen 1992). However, these factors have not been examined in detail under differing management regimes which may affect the invasion determinants. Research is also lacking on invasive herbaceous plants which exhibit similar life history to native plants in managed grazing ecosystems.

Sericea lespedeza [*Lespedeza cuneata* (Dum. Cours.) G. Don] is an invasive, herbaceous, long-lived perennial legume invading rangelands in central and eastern U.S. Introduced into the U.S. in 1896 from eastern Asia, *L. cuneata* has been used extensively

for forage production, erosion control, and land reclamation since the 1930s. To date, *L. cuneata* is only listed on the U.S. Dept. of Agriculture noxious plants list for two states, Colorado and Kansas, though the plant is still planted for soil conservation and forage production across the southern and eastern U.S. (USDA, NRCS 2005). While extensive research has been conducted on the species as an agronomic crop, few studies document the ecological characteristics of *L. cuneata* as an invasive species (Altom & Stritzke 1993, Brandon et al. 2004, Fuhlendorf & Engle 2004, Cummings et al. 2007). Herbicides have been used to effectively control *L. cuneata* in the year after application (Koger et al. 2002), but these applications can be costly to both the rangeland manager and the other plant species that occur concomitantly in invaded ecosystems.

Other prairie management options have shown some potential for increasing diversity and possibly suppressing the invasion of *L. cuneata*. Fire and grazing can be used in concert to increase complexity in pattern across the landscape, while maintaining high rangeland productivity (Fuhlendorf & Engle 2001, Masters 1993, Vermeire et al. 2004). The fire-grazing interaction model includes feedbacks that create a shifting mosaic of distinct habitat patches. This shifting mosaic is achieved by burning small patches within the pasture, or landscape (Figure 1). Fuhlendorf & Engle (2004) noted that cattle preferentially grazed the recently burned patch following a prescribed burn, allowing the other areas within the pasture to grow and recover (patch-burn treatment, in this study). Researchers are now addressing the benefits of management based on pre-European settlement disturbance regimes like patch burning.

Because invasive species threaten rangeland integrity under any management regime, it is important to assess the role of invasive species in these ecosystems. For this reason,

our goal in this research was to evaluate *L. cuneata* invasion under rangeland management based on the fire-grazing interaction (patch-burn treatment), compared to traditional rangeland management practices. Specifically, we examined treatment effects on 1) *L. cuneata* invasion rate and pattern over time at two spatial scales, 2) proximate determinants of *L. cuneata* invasion, and 3) species composition in sites with and without *L. cuneata* invasion.

Materials and Methods

STUDY REGION

The experimental area is located in north central Oklahoma on the Oklahoma State University Range Research Station (Lat 36º16'N; Long 97º09'W) located 21 km southwest of Stillwater, OK. The region is dominated by a continental climate with an average of 204 frost-free days and 843 mm annual precipitation, 65% of which falls from May to October (81% in this study period). The vegetation matrix is tallgrass prairie with intermittent patches of cross timbers habitat on shallow uplands. Dominants of the tallgrass prairie in the area include *Schizacharium scoparium* (Michx.) Nash, *Andropogon gerardii* Vitman, *Sorghastrum nutans* (L.) Nash, *Panicum virgatum* L., and *Sporobolus asper* (Michx.) Kunth. Minor grasses include *Bouteloua curtipendula* (Michx.) Torr., and *Dicanthelium oligosanthes* (Schult.) Gould. The dominant forbs in the area are *Ambrosia psilostachya* DC., and *Gutierrezia dracunculoides* (DC.) S.F. Blake. The cross timbers communities are dominated by *Quercus stellata* Wang., *Q. marilandica* Münchh., and *Celtis* spp. The area is also invaded to various extents by *Juniperus virginiana* L. (eastern red cedar) and *L. cuneata*. Prescribed fire was applied periodically to all study areas for *J. virginiana* control prior to the experiment initiation.

EXPERIMENTAL DESIGN

In 1999, a completely randomized design experiment was established to test the effects of patch-burning on vegetation dynamics. At the time of experiment initiation, *L. cuneata* invasion was not an objective for study. Initial *L. cuneata* invasion was light in the area, making up 4% of the species composition (ranging from 0 to 7% across all units). As the study progressed, noticeable increases in *L. cuneata* cover prompted additional study and observation of invasion dynamics.

In 1999, three individual experimental units (*n*=3; 0.8 by 0.8 km) were assigned as a patch-burned treatment (the application of the fire-grazing interaction) and three other experimental units (*n*=3) were traditionally managed for rangelands in the area (this treatment served as the control). The patch-burned treatment consisted of six distinct patches within a pasture unit. Each year burn crews prescribed burned one sixth of the pasture and one sixth burned in the late summer, creating a mosaic of plant diversity and structure across the pasture unit (Fuhlendorf & Engle 2001, 2004). The resulting landscape included patches of heavy disturbance within a matrix of patches that vary with time since focal disturbance. Traditional management treatment pastures (*n*=3, 0.8 by 0.8 km) were burned every three years for *J. virginiana* control, but unlike the patch-burned treatment, in the traditional management treatment the entire pastures were prescribed burned as a whole. This resulted in more homogenous structure and composition across the landscape compared to patch-burn pastures. From 1999 to 2006, both treatments were moderately stocked by mixed-breed cattle (Gillen et al. 1991).

DATA COLLECTION

Vegetation composition and cover were collected each summer beginning in 2002. Data were collected from one Whittaker plot (Shmida 1984) established in each patch of each treatment pasture (n= 3 pastures treatment^{-1}; 18 sub-samples treatment^{-1}). The Whittaker plots were modified for space limitations with the smallest nested sub-plots being 0.5m^2, intermediate plots being 2.5m^2, and 50m^2, and the largest plot 500m^2 (Figure 1a). Species composition (species presence and cover estimated visually) were collected for the 10 individual 0.5m^2 sub-plots. For each higher order plot size (2.5m^2, 50m^2, and 500m^2) only additional plant species abundance – those not already detected in smaller plots - was recorded. Some authors have cited problems, including plot shape and autocorrelation, with the original Whittaker design as a sampling method (Stohlgren et al. 1995, Stohlgren 1994). Our modifications overcome the problem of plot shape, since all plots become rectangular, and we averaged the ten smallest sub-plots into one mean in analysis procedures.

In addition to species composition, we also monitored *L. cuneata* invasion using visual grid mapping. Each summer *L. cuneata* cover extent was mapped on a 2.5- by 5-m coordinate grid at peak growth (Figure 1b). *L. cuneata* patches were identified as being at least 0.5 m from the nearest neighbor patch. Total patch size and patch number were then recorded for each of 40 cells per Whittaker plot. We ran analysis procedures on the annual mean number of *L. cuneata* invasion patches per Whittaker plot, and the proportional change of *L. cuneata* invaded plot area over time.

In depth analysis on the probability of invasion given the status of adjacent grid cells was also performed. For this analysis the coordinate grid cells 12 to 19 and 22 to 29

(Figure 1b) were identified as either invaded or naïve for each year (2003 to 2006). The total number of adjacent cells (possible 8 for each cell) was also quantified for each of the 16 grid cells per Whittaker plot. In addition, each year the total number of naïve cells which were invaded that year and invaded cells which lost *L. cuneata* from the past year were calculated. This data were used to further quantify invasion dynamics, and identify population fluctuations of invaded areas.

In 2005, soil samples were collected from all Whittaker plots (*n*=18 treatment^{-1}) for analysis of soil characteristics. Fifteen-2.5 by 10 cm soil sub-samples were collected from the soil surface to 10 cm depth with a standard soil probe from each individual plot (6 plots per experimental unit, or pasture). These sub-samples were then combined and homogenized thoroughly for analysis. The samples were packaged and sent (within 24 hrs.) to the Soil, Water, and Forage Analysis Laboratory at Oklahoma State University, Stillwater, OK. Soil structural and compositional components were used in regression analysis including soil texture and soil organic matter. Means and ranges for soil environmental variables are displayed in Appendix 1.

Annual precipitation also was monitored for the study area over the eight year study. A central Oklahoma mesonet station monitored monthly precipitation for the duration of the study. This station was centrally located among the experimental units with a mean distance of 1.23 km from any unit. A summary of the precipitation data from the eight year study is provided (Appendix 2).

DATA ANALYSIS

To test for differences in *L. cuneata* invasion rate and pattern over time between treatments, linear regression and analysis of variance (ANOVA) (SAS Inst. 2000) were

used to detect differences in the pattern and extent of *L. cuneata* invasion at both fine and broad spatial scales (0.5 m^2 and 500 m^2, respectively). We regressed change in *L. cuneata* cover with time (years) for each treatment to determine general trends in invasion. Regressions were performed, not to determine the strength of the relationship of cover with time, but to find the slope of the resulting trend line to determine the rate of invasion (% cover increase each year) for the two treatments. Within the patch-burn treatment, we regressed change in *L. cuneata* cover with individual time since fire (years) and season of prescribed burn (spring vs. summer) to observe differences in invasion dynamics. Proportion of total plot area invaded, number of invasion patches, and change in invaded area over time were subjected to the repeated measures ANOVA using the MIXED procedure (α =0.05) to identify differences in invasion dynamics between the two treatments.

In addition, the status of adjacent cells (invaded vs. naïve), and environmental variables were used to determine influences of invasion severity and environmental variability on invasion patterns and rate.

Multiple regression analysis (PROC REG, SAS) and principal components analysis (PCA; PROC PRINCOMP, SAS) were performed on the species composition, *L. cuneata* invasion, and environmental variables to address objectives two and three concerning proximate influences of treatment differences on invasion, and the effect of invasion on plant species in burned and grazed rangelands. For these analyses the plant species were placed in functional groups including: tallgrasses, *S. scoparium*, other grasses, legumes (excluding *L. cuneata*), *Symphoricarpos orbiculatus* (buckbrush), and all other woody plants. Percent vegetative cover of each functional group was included

in analysis. *L. cuneata* vegetative cover at two spatial scales (fine or 0.5m^2, and broad or 500 m^2) was also included only in the PCA, as including it in the regression analysis would have confounded the interaction between variables. Environmental variables including: cover of litter and bare ground (%), soil organic matter (%), and sand (%), and growing season precipitation (mm) were evaluated to determine their influence as proximate causes of invasion. Since there were multiple variables with differing units of measurement, all variables were log transformed prior to multiple regression analysis.

Results

INVASION DYNAMICS

Previous analysis has suggested that *L. cuneata* invasion was more extensive in the traditional treatment units compared to the patch-burn treatment units but little is known about the detailed rates and patterns of invasion at multiple scales (Fuhlendorf & Engle 2004). In our study with 18 permanent plots for each treatment (6 per replication by 3 replications), there was at least detectable *L. cuneata* invasion in 72% and 33% of the permanent plots in the traditional management and patch-burn treatments, respectively. In addition, *L. cuneata* cover never exceeded a treatment mean of 8% for either the traditional or patch burn treatment at the fine scale. However, individual sample sites increased to as much as 75% cover in the traditional treatment by the end of the study, while other sites lacked *L. cuneata* invasion completely.

Fine spatial scale (0.5m^2). Extent of invasion at fine spatial scales was highly variable in space and time throughout the study. Grazing and fire treatments began in the summer of 1999 so this study was started three years after treatment initiation. The invasion

followed similar trends in both treatments at the fine scale with an average annual

increase of 1.4 % cover in the traditional management treatment and an annual decrease

in the patch-burn treatment of 0.29 % cover (Figure 3). There were no significant

differences (α=0.05) in invasion rate for any year between the two treatments, or over the

four years of study (P=0.502) at this scale due to the high variability between units in the

extent of invasion. The rate of invasion for *L. cuneata* is similar to that noted in Brandon

et al. (2004) for the northern Great Plains and previous studies at this site (Fuhlendorf &

Engle 2004, Cummings et al. 2007).

Broad spatial scale (500 m²). At the broad spatial scale, *L. cuneata* invasion also

increased over time in both treatments. Gradual increases in the frequency of individual

L. cuneata patches (Figure 3), and the proportion of total plot area covered by these

patches (Figure 4) occurred each year of the study. While *L. cuneata* invaded both

treatments, the annual number of individual patches ranged from five to six times greater

in the traditional management treatment (Figure 3). Repeated measures analysis of

variance indicated a significant difference in the mean frequency of invaded cells

between traditional and patch-burn managed treatments. Both treatments experienced a

significant increase (P<0.05) in patches by 2005 compared to the initial invasion in 2003.

The total proportion of invaded area also increased dramatically from 2003 to 2006 in

both the traditional management and patch-burn treatments (Figure 4). Drought

conditions in the summer of 2006 lead to decreased *L. cuneata* cover in both treatments

(Figure 4). While there were no statistically significant differences between treatments in

the proportion of invaded area (P=0.13), only one of the three patch-burn treatment units

experienced discernible increase in *L. cuneata* invasion. This experimental unit was

somewhat of an outlier and hence shrouded the dynamics of the other two patch-burned experimental units which showed little to no net increase in proportion of invaded area from 2003 to 2006 (0.01 to 0.1% increase; data not shown). In the other two patch-burn units, *L. cuneata* invasion was minimal. In addition, there was little change over time. Those patches which had no initial population remained relatively resilient to the invasion, or lacked sufficient dispersal sources for invasion even at the broad scale (data not shown).

In contrast, all three traditional management units increased in proportion of invaded area from 2003 to 2006 (3.5 to 17% increase; data not shown). The removal of aboveground litter, and detritus from the soil surface in areas adjacent to the invasion could have facilitated the rapid expansion of the *L. cuneata* invasion. There was no localized heavy grazing pressure (as in the patch-burn treatment) in these traditionally managed units following the burn to counteract the availability of open niches. As a result, *L. cuneata* invaded many new niches and its competitive ability allowed it to establish in those areas.

PROXIMATE DETERMINANTS OF INVASION

Probability of invasion. Analysis of the coordinate grid data indicated that the probability of invasion increased linearly (traditional), and in polynomial fashion (patch-burn) as the proportion of adjacent cells increased in both treatments (Figure 5). Invasion was not exponential in the traditional management treatment like has been reported in previous studies of other invasive plant species (Pysek & Prach 1993, Shigesada & Kawasaki 1997). Instead the *L. cuneata* appeared to gradually invade naïve cells (Figure

1). This could be a result of the ebb and flow that individual plants or clones of the

invader exhibit. Further analysis indicated that each year *L. cuneata* in some cells was

lost, while additional cells were gained in both treatments (from 1 to 3% lost annually,

and from 2 to 5% gained annually). The number of invaded cells lost was never

significantly different between treatments at any annual interval, or over the four year

study. The number of invaded cells gained showed one year in which the gain was

higher in the traditional management treatment than in the patch-burn treatment (2004 to

2005, *P*=0.04). In all other cases, the periodic invasion, and loss of invasion was similar

between treatments.

Multiple regression at fine spatial scale (0.5m^2). Of the variables included in the

regression analysis, only *L. cuneata* at the broad scale stayed in the linear regression

model at α=0.10 as the determinate in a stepwise regression. Therefore the best

predictive linear model for *L. cuneata* cover at the fine scale was:

$$y = -2.0 + 4.5(\text{TRT}) - 3.7(\text{OM}) - 1.1(\text{PATCH})$$

(1.1)

where *y* is the cover of *L. cuneata* at the fine scale, *TRT* is treatment, *PATCH* is the

treatment patch (sub-sample), and *OM* is percent organic matter (r^2=0.18).

Multiple regression at broad spatial scale (500m^2). Of the variables included in the

regression analysis, four variables at the broad scale stayed in the linear regression model

at α=0.10 as the determinate in stepwise linear model development. Therefore the best

predictive linear model for *L. cuneata* cover at the fine scale was:

$y = 8.99 + 6.4(TRT) -1.8(PATCH) - 4.22(CLAY) + 1.5(REP) + 1.5(YEAR)$ **(1.2)**

where *y* is the cover of *L. cuneata* at the broad scale, *TRT* is the treatment (traditional vs.

patch burn), *PATCH* is the treatment patch (or sub-sample), *CLAY* is the percentage clay

content of the soil, *REP* is replication, and *YEAR* is the data collection year (r^2=0.48).

The regression coefficient for treatment indicates the difference in magnitude of *L.*

cuneata cover in the traditional management treatment over the patch-burn treatment.

Soil organic matter (SOM) should also be noted here, since omitting replication from the

analysis resulted in the inclusion of this variable. Correlation analysis indicate that SOM

was highly correlated to replication (*r*= -0.72), far greater than any other variable (data

not shown). Soil organic matter appeared to be inversely related to *L. cuneata* cover (*r*=-

0.64), with less *L. cuneata* cover in higher SOM soils (Figure 6). Soil organic matter did

not differ significantly between treatments (*P*=0.24) indicating the variation in *L. cuneata*

cover with SOM may have indicated some affinity for lower SOM soils, or greater

competitive effects from native plants in higher SOM soils.

INVASION AND FLORISTIC SPECIES COMPOSITION

Floristic composition in the treatment units included nearly 150 vascular species

over the four year study. Co-dominants of the tallgrass prairie ecosystem were common

in all plots (see Study Region above). *Schizacharium scoparium* (Michx.) Nash,

Andropogon gerardii Vitman, and *Sporobolus asper* (Michx.) Kunth were the most common C_4 grass species (27.5, 11.5, and 10.2% cover, respectively). *Ambrosia psilostachya* DC., and *Gutierriezia dracunculoides* (DC.) Blake were the most common C_3 forb species (7 and 3% cover, respectively) across sites and years. Surprisingly, the third most common forb was *L. cuneata* (3.5% over the five years), accounting for 6 to 500 times the average composition of the indigenous legume species (data not shown).

Principal components analysis indicated that *L. cuneata* cover at both the fine and broad scales were highly correlated with the first axis of the PCA when plant species were placed into functional groups pooled between both treatments (Table 1). Legumes other than *L. cuneata* were correlated with the second and third axis, while *Symphoricarpos orbiculatus*, a ubiquitous small sub-shrub, was correlated with the third axis. These trends indicate a dominant effect from the *L. cuneata* invasion within these plant communities.

Past studies indicate a decrease in the rate of invasion with patch-burning as opposed to traditional management regimes (Fuhlendorf & Engle 2004). However, other authors have found that invasion rates increased with increased disturbance (Brandon et al 2004, Morgan 1998). Our data indicate that species richness had little effect on *L. cuneata* invasion (Figure 7). Studies in Minnesota with non-native invaders, New England with invasive *Lonicera tatarica* L., and in Illinois with multiple invaders all indicate that invasion in other ecosystems occurs at decreased rates with higher plant diversity (Symstad 2000, Woods 1993, Yurkonis et al. 2005). The difference in our data set might indicate the aggressive nature of this particular invasive forage species, and possibly exotic invasive forages in general.

Discussion

Patch-burning and grazing at moderate stocking rates provides many benefits to the traditional management regimes in the area, including decreased *L. cuneata* invasion area and greater biodiversity at the landscape scale (Fuhlendorf & Engle 2004). Additional evaluation of the invasion patterns in this study indicate that the rates and patterns of invasion are similar between treatments in most cases (Figure 2) and differ only in magnitude of the invasion (Figures 3 & 4). The similarities in invasion pattern appear to be driven more by abiotic variation (Figure 6) than biotic variation of plant species composition (Figure 7). Our results agree with previous studies which pointed to spatial environmental variability as one proximate cause of increased invasion severity (Manning et al. 2007).

The proximate causes of the differences in the extent of invasion between treatments are largely unanswered. The status of adjacent cells, or plant communities within a landscape, soil properties, and the naïve plant community itself might all play a part in the determination of rate and extent of invasion, but their inter-relationships appear too complex to identify to date. Further investigation into these inter-relationships between biotic and abiotic components of these prairie ecosystems could elucidate the causes of invasion. Here we have demonstrated that treatment, and in particular patch burning, appears to have the greatest influence on the rate and pattern of invasion in rangelands (Equations 1.1 and 1.2), however the proximate causes of this suppression are still unknown. The suppression of *L. cuneata* invasion is not the only benefit to heterogeneous management like patch burning.

The caveat with patch-burned prairie ecosystems is that multiple disturbance histories occur within the same pasture unit. As a product of focal disturbance by fire and grazing, local areas are heavily disturbed and other areas within the unit recover through post-disturbance succession. This heterogeneity, with disturbances occurring in different seasons and years has been shown to provide landscape stability (Fuhlendorf & Engle 2001) and significantly decreased *L. cuneata* invasion compared to traditional management (Cummings et al. 2007).

Although the increase in invasion was less in the patch-burn treatment, there was at least a slow increase in *L. cuneata* coverage area for both treatments over time. Focused grazing, as a product of patch burning in multiple seasons, appears to limit the ability of *L. cuneata* to expand for several years following a prescribed burn. *L. cuneata* appears to be less associated with early successional, xeric sites. However, as seed dispersal via intentional plantings (to prevent soil erosion, aide in soil reclamation, or for forage production; USDA, NRCS 2005) expands the species westward, the general impact of low precipitation ecosystems on invasion will be observed. In highly productive areas, this exotic invasive forage establishes quickly and dramatically influences species composition. With patch-burning, the rate of invasion at broad spatial scales is minimized by the altered grazing selectivity (Cummings et al. 2007) compared to traditional homogeneous rangeland management. For this reason, we suggest patch burning and grazing at moderate stocking rates could be used as a management alternative to traditional rangeland management in the Great Plains region, where invasive *L. cuneata* threatens sustainable rangeland function.

Acknowledgements

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Figure 1. Whittaker plot design a) and coordinate grid overlay b) used in the experiment. One Whittaker plot was established in each patch of each pasture in both the traditional management and patch-burned treatment pastures. Species composition and percent cover were recorded for each of the ten 0.5 m^2 sub-plots. At the higher resolution plots (2.5, 50, and 500 m^2) only additional species presence was recorded, unless the species composed a substantial portion of the entire plot area, at which time a percent cover value was also recorded for that species. *L. cuneata* patch size and number dynamics were mapped for each Whittaker plot from 2003 to 2005.
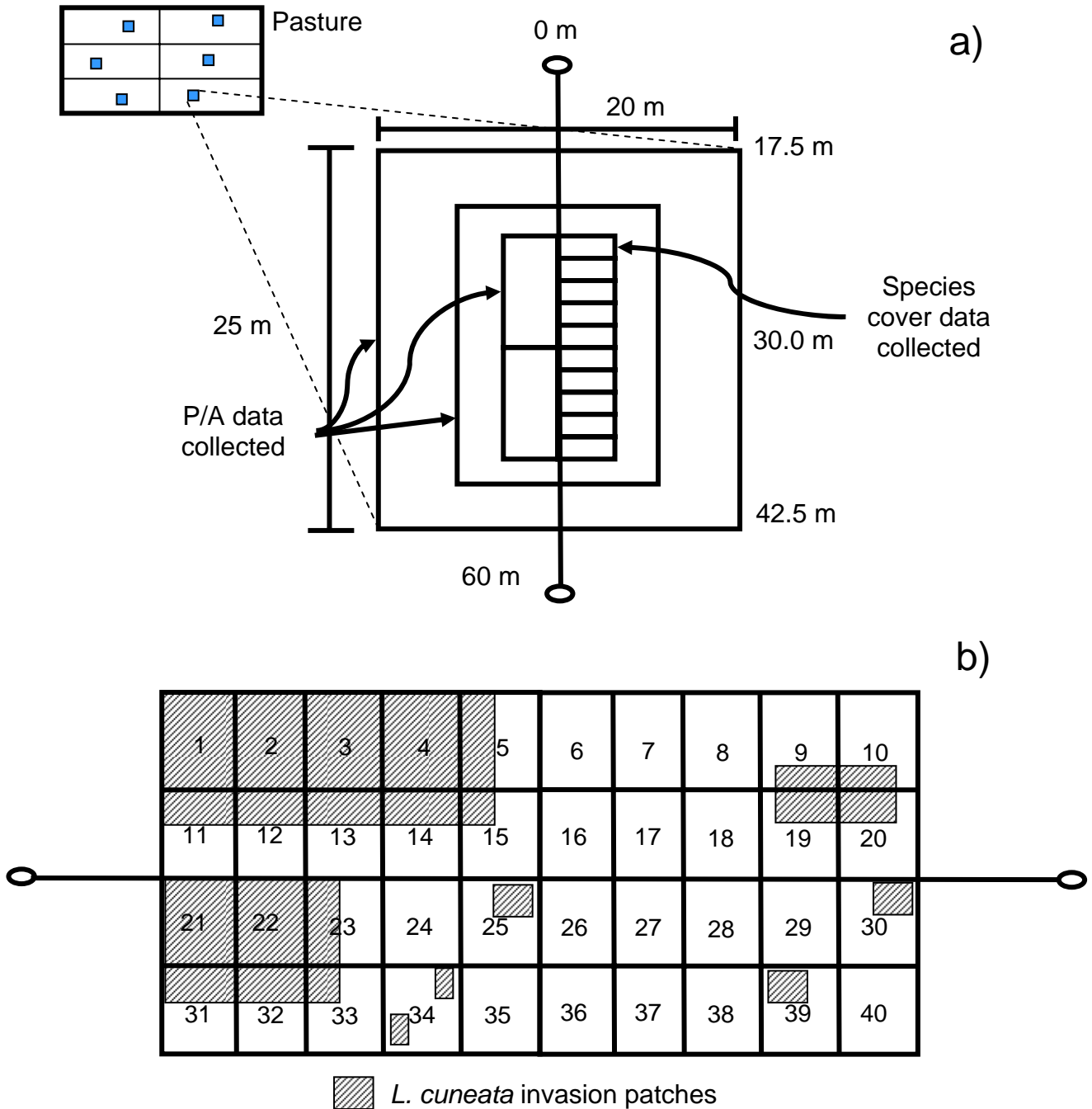
Figure 2. *L. cuneata* invasion in traditional management (♦) and patch-burned (■) treatments over the five year study at the 0.5m^2 scale. Regression analysis was not used to determine the strength of relationship between cover and time, but to find the slope of the resulting trend line which we use as a rate of invasion (% cover change per year). *L. cuneata* invasion did not differ between treatments in any year at this scale. *L. cuneata* cover in the plot areas was highly variable (ranged from 0 to 75%; mean=3.5%), however all plots with at least one population increased in cover over time.
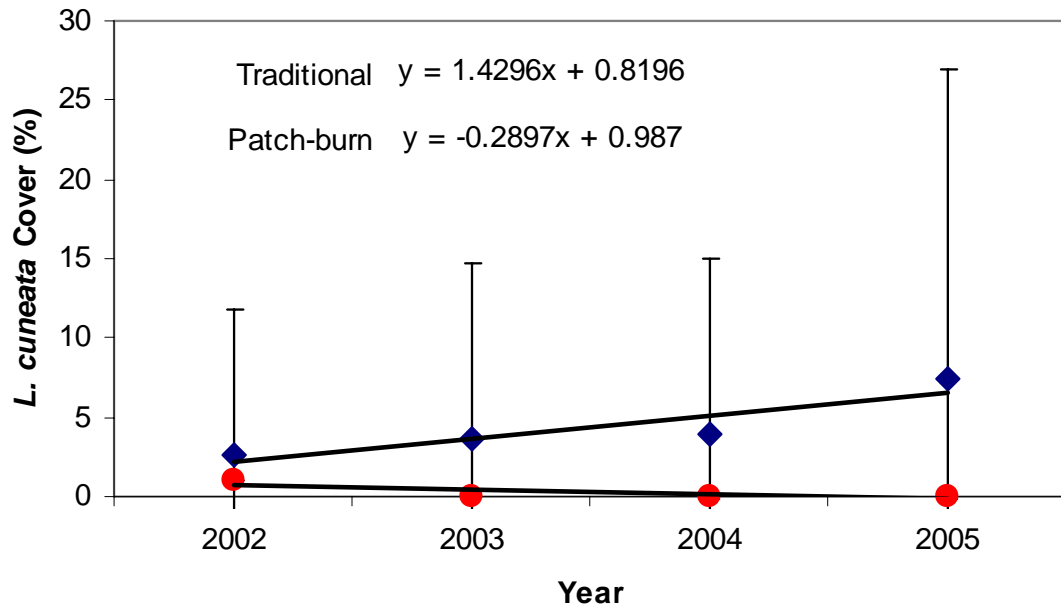
Figure 3. Mean frequency of *L. cuneata* patches (±1 SEM) in Whittaker plot coordinate grids from 2003 to 2006 for traditional management and patch-burn treatments (spring and summer patch-burn patches shown independently). Means represent the average number of cells with *L. cuneata* invasion out of a possible 720 cells treatment·year^{-1}.
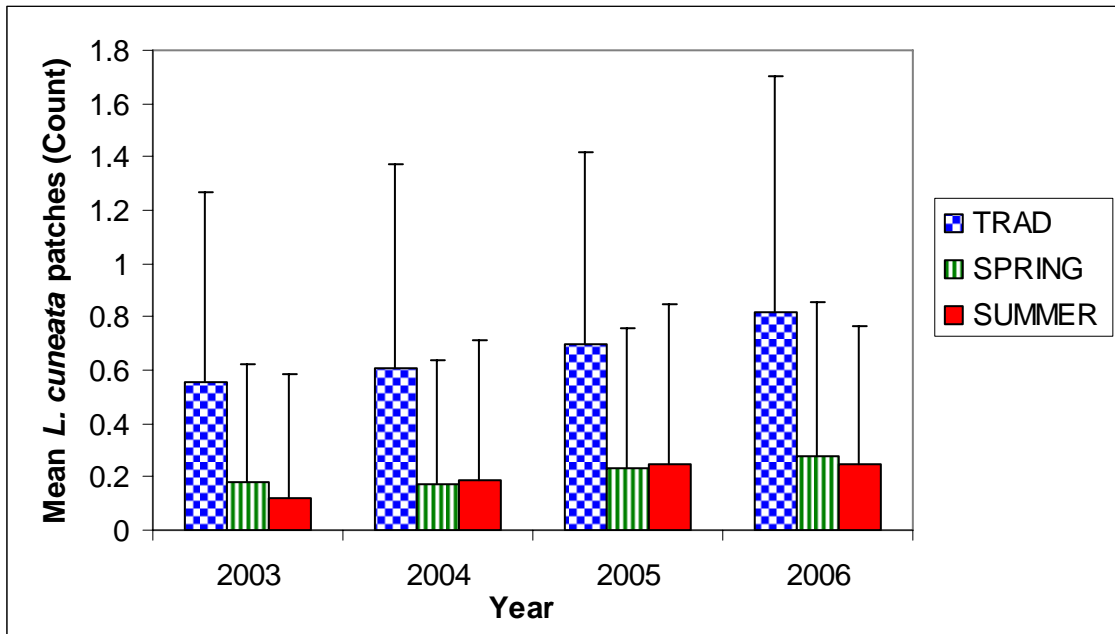
Figure 4. Mean *L. cuneata* invasion (+ 1 SEM) in traditional management and patch-burn Whittaker plot (500 m^2) areas over time. Spring and summer patch-burn means are shown independently. Values indicate the proportion in total plot area covered by *L. cuneata* vegetation from 2003 to 2006. Proportional change was net positive for both treatments over time, indicating *L. cuneata* invades new land area regardless of treatment.
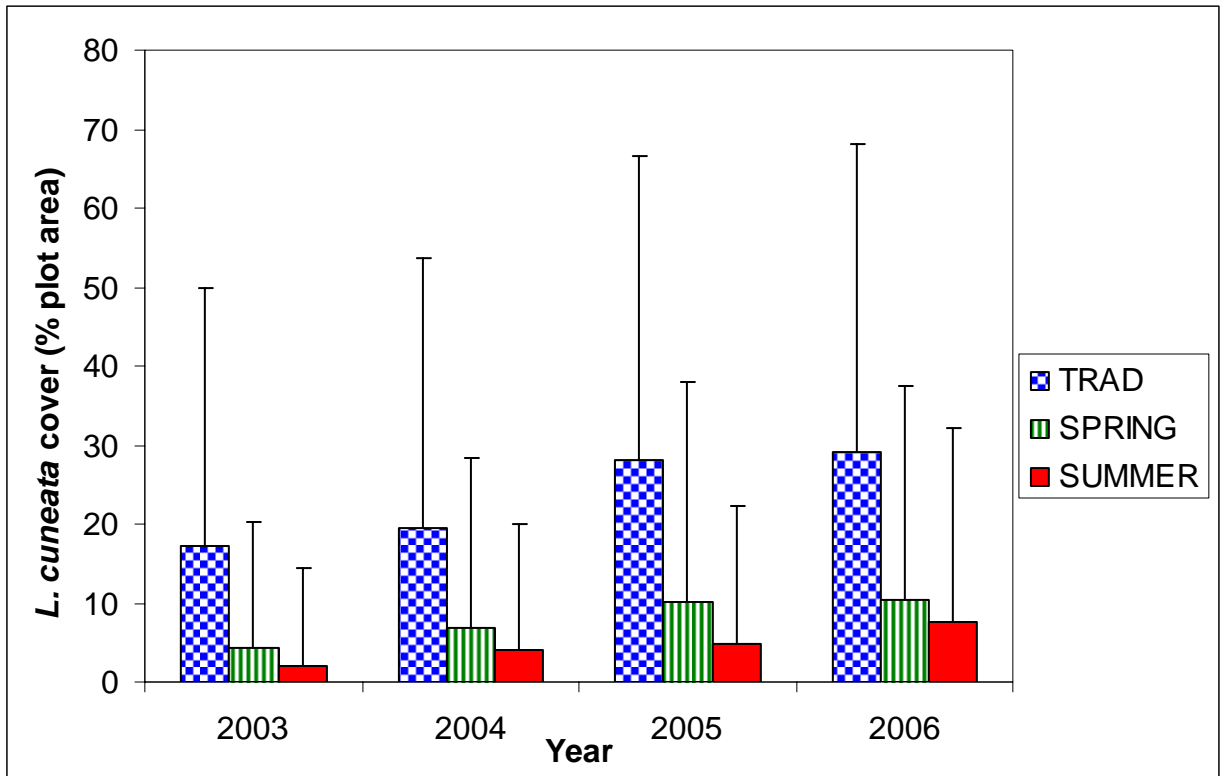
Figure 5. Effect of adjacent grid cells on the invasion status in traditional (**top**) and patch-burned (**bottom**) treatments from 2003 to 2006.
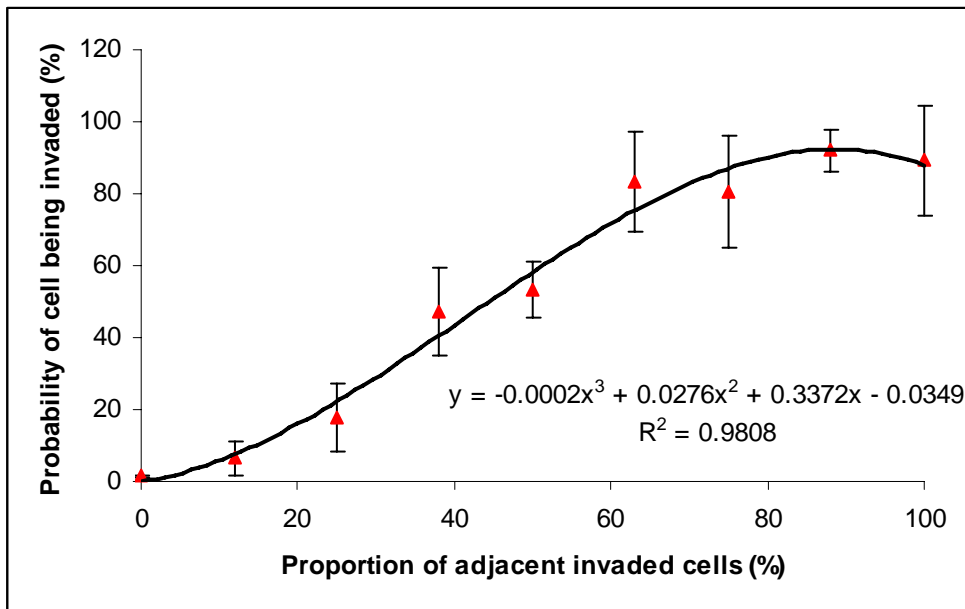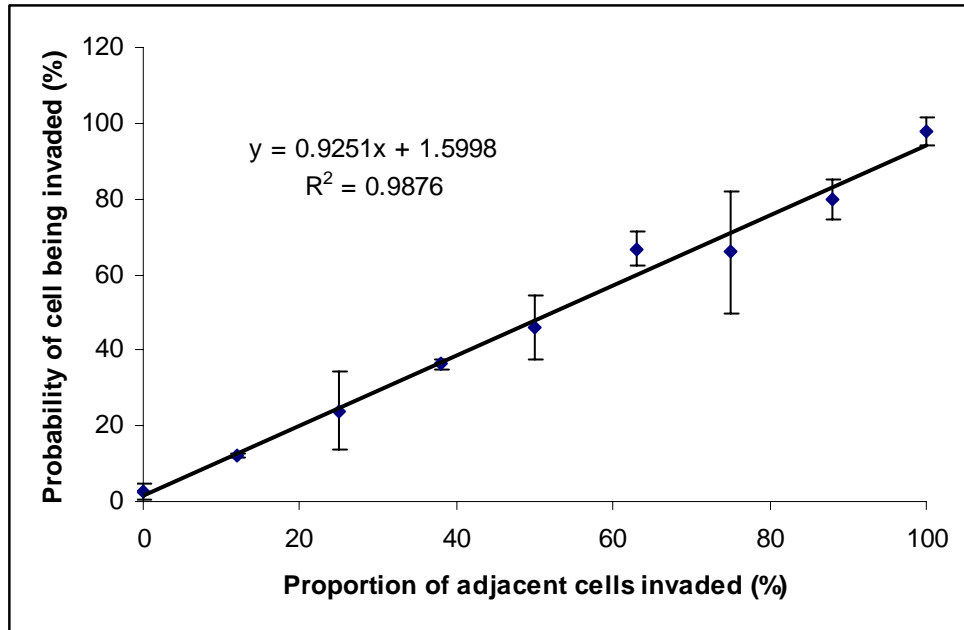
Table 1. Principal components analysis of the species composition and environmental variation within Whittaker plots from 2003 to 2006.

	PCA Axis 1	**PCA Axis 2**	**PCA Axis 3**
Eigenvalue	39.12	17.52	15.22
Proportion of variation	0.40	0.18	0.15
Cummulative variation	0.40	0.58	0.73
Associated variables Eigenvector	*L. cuneata* cover at the fine scale	*Symphoricarpos orbiculatus* cover	Legume cover
	0.78	-0.75	0.75
	L. cuneata cover at the broad scale		
	0.61		

Figure 6. Regression of soil organic matter on *L. cuneata* invasion in patch burn (●) and traditional management (▲) treatments Soil organic matter and *L. cuneata* cover are from the 2005 data collection period.
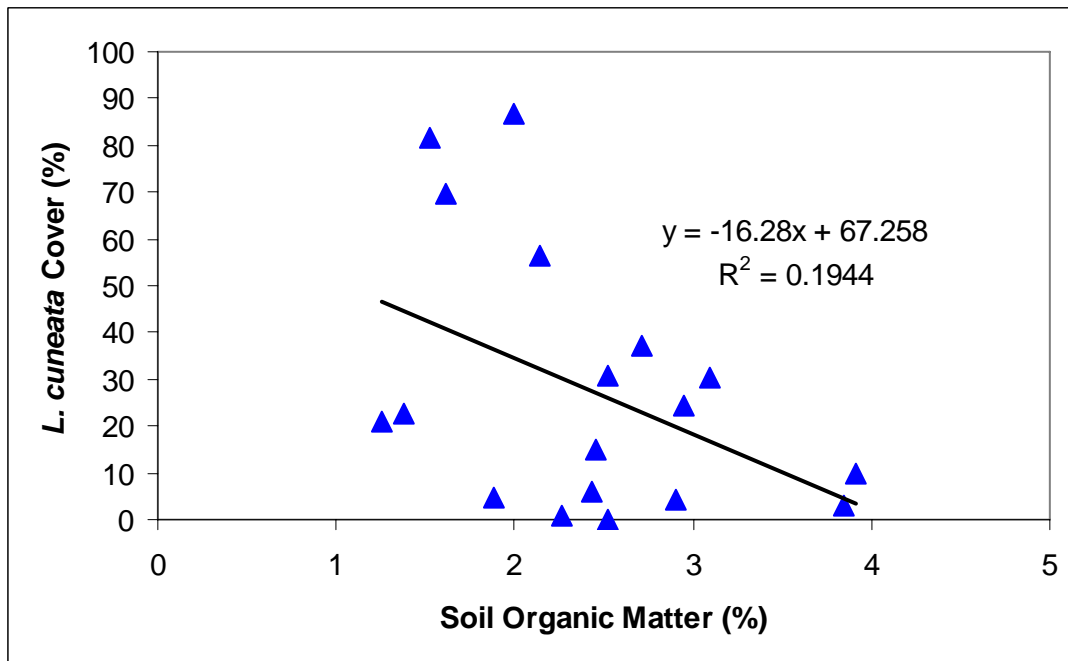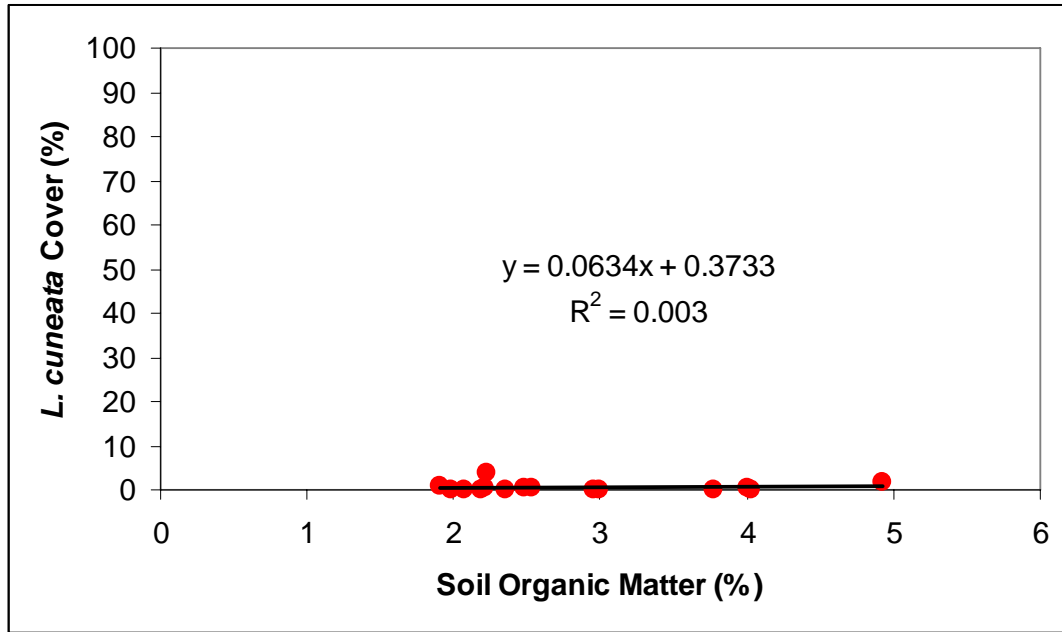
Figure 7. The effect of *L. cuneata* invasion on floristic composition pooled across treatments over the four year study. *L. cuneata* invasion had minimal influence on species richness in both management treatments.

$$y = -0.0182x + 45.576$$
$$R^2 = 0.0031$$
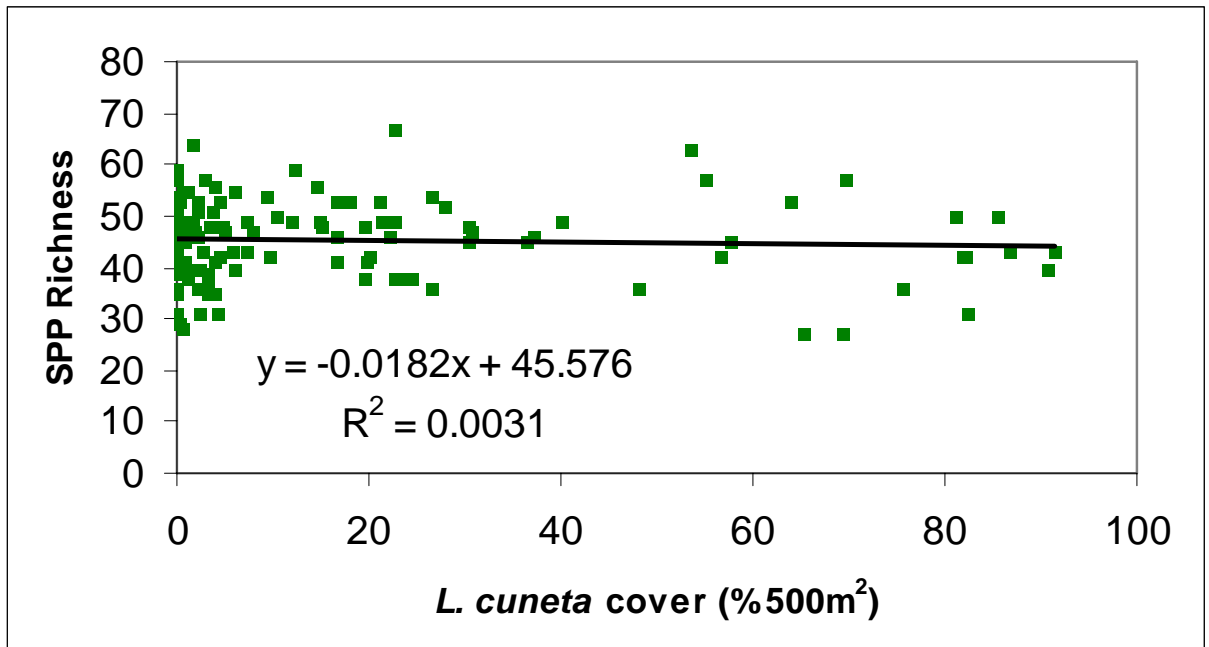
Appendix 1. Descriptive statistics for 2005 Whittaker plot soils variables and *L. cuneata* cover at fine (LECUFINE) and broad (LECUBRD) scales. Standard deviation (SD), minimum (Min) and maximum (Max) values included for each treatment. Significant differences for each variable between treatments are indicated (*).

| Variable | Treatment | | | | | | | | |
| | Patch-burn | | | | Traditional | | | | |
	Mean	SD	Min	Max	Mean	SD	Min	Max	p<0.05
Soil organic matter (%)	2.7	0.9	1.8	4.9	2.4	0.8	1.3	3.9	
Soil pH	6.7	0.5	6.0	7.7	6.5	0.6	5.9	7.9	
NO3-N	6.3	4.6	1.0	19.0	5.9	4.2	1.0	13.0	
P	11.6	4.7	9.0	30.0	10.2	1.0	9.0	13.0	
K	256.6	57.3	160.0	378.0	252.6	71.9	151.0	456.0	
Sand (%)	36.9	11.7	17.5	52.5	42.4	10.8	20.0	57.5	
Silt (%)	39.2	10.9	27.5	65.0	35.5	8.8	17.5	50.0	
Clay (%)	23.9	5.7	17.5	37.5	22.1	5.6	15.0	37.5	
LECUFINE (%)	5.0	14.3	0.0	55.3	7.3	17.7	0	75.7	
LECUBRD (%)	7.5	19.2	0.0	75.5	28.0	28.0	0.2	86.8	*

Appendix 2. Annual precipitation data and growing season precipitation data from the Marena (MARE) site of the Oklahoma Mesonet system from 1999 to 2006. The mesonet station was centrally located among the experimental units. NA=not available.

Year	Jan.-Dec. Total	Mar.-Oct. Sub-total
	(mm)	(mm)
1999	1122.9	974.9
2000	899.7	757.2
2001	698.5	515.1
2002	946.9	784.1
2003	648.2	554.5
2004	947.9	659.4
2005	860.0	756.4
2006	621.0	507.7
8 year mean	843.2	688.7
30 year mean	944.9	NA

Appendix 3. Plant species list for the Patch-burn Study at the Oklahoma State University Range Research Station in Stillwater, OK. Only plant species found in the Whittaker plots described above from 2002 to 2006 are included.

Code	Scientific Name		Common Name	Season of Growth	Origin	Life	Source
SCSC	*Schizachyrium scoparium* (Michx.) Nash	G	Little Bluestem	Warm	Native	Perennial	NARP 3rd
Big Three							
ANGE	*Andropogon gerardii* Vitman	G	Big Bluestem	Warm	Native	Perennial	NARP 3rd
PAVI	*Panicum virgatum* L.	G	Switchgrass	Warm	Native	Perennial	NARP 3rd
SONU	*Sorghastrum nutans* (L.) Nash	G	Indiangrass	Warm	Native	Perennial	NARP 3rd
Other Grasses							
AGAL	*Agrostis alba* L.	G	Red Top	Warm	Native	Perennial	IFNUS
ALOCA	*Alopecurus carolinianus* Walt.	G	Carolina Junegrass	Cool	Native	Annual	USDA
ANTE	*Andropogon ternarius* Michx.	G	Splitbeard Bluestem	Warm	Native	Perennial	IFNUS
ANVI	*Andropogon virginicus* L	G	Broomsedge	Warm	Native	Perennial	NARP 3rd
ARLO	*Aristida oligantha* Michx.	G	Annual Threeawn	Warm	Native	Annual	NARP 3rd
ARPU	*Aristida pupurea* Nutt.	G	Purple Threeawn	Warm	Native	Perennial	Weeds
BOTCA	*Bothriochloa caucasica*	G	Caucasian Bluestem	Warm	Intro	Perennial	IDOKPL
BOTIS	*Bothriochloa ischaemum*	G	Plains Bluestem	Warm	Intro	Perennial	IDOKPL
BOTSA	*Bothriochloa saccharoides* (Sw.) Rydb.	G	Silver Bluestem	Warm	Native	Perennial	NARP 3rd
BOCU	*Bouteloua curtipendula* (Michx.) Torr.	G	Sideoats Grama	Warm	Native	Perennial	NARP 3rd
BOGR	*Bouteloua gracilis* (H.B.K.) Lag. Ex Steud.	G	Blue Grama	Warm	Native	Perennial	NARP 3rd
BOHI	*Bouteloua hirsuta* Lag.	G	Hairy Grama	Warm	Native	Perennial	NARP 3rd
BRJA	*Bromus japonicus* Thunb.	G	Japanese Brome	Cool	Intro	Annual	Weeds
BUDA	*Buchloe dactyloides* (Nutt.) Engelm.	G	Buffalograss	Warm	Native	Perennial	NARP 3rd

Code	Scientific Name		Common Name	Season of Growth	Origin	Life	Source
CHVE	*Chloris verticulata* Nutt.	G	Tumble Windmill Grass	Warm	Native	Perennial	Weeds
COCY	*Coelorachis cylindrica*	G	Rattail Grass	Warm	Native	Perennial	NRCS hbk
CYDA	*Cynodon dactylon* (L.) Pers.	G	Bermudagrass	Warm	Intro	Perennial	NARP 3rd
DIOL	*Dicanthelium oligosanthes* Schultes	G	Scribner's Panicum	Cool	Native	Perennial	NRCS hbk
DICO	*Digitaria cognata* (Schult.) Pilger	G	Fall Witchgrass	Warm	Native	Perennial	TXRP
ECCR	*Echinochloa crus-galli* (L.) Beauu.	G	Barnyard-grass	Warm	Intro	Annual	Weeds
ELCA	*Elymus canadensis* L.	G	Canada Wildrye	Cool	Native	Perennial	TXRP
ELVI	*Elymus virginicus* L.	G	Virginia Wildrye	Cool	Native	Perennial	TXRP
ERSP	*Eragrostis spectabilis* (Pursh) Steud.	G	Purple Lovegrass	Warm	Native	Perennial	NRCS hbk
ERTR	*Eragrostis trichodes* (Nutt.) Wood	G	Sand Lovegrass	Warm	Native	Perennial	USDA
ERCO	*Eriochloa contracta* Hitchc.	G	Prairie Cupgrass	Warm	Native	Annual	IFNCT
MUSC	*Muhlenbergia schreberi* J.F. Gmel.	G	Nimblewill	Warm	Native	Perennial	NRCS hbk
PAAN	*Panicum anceps* (Michx.)	G	Beaked Panicum	Warm	Native	Perennial	TXRP
PACA	*Panicum capillare* L.	G	Withchgrass	Warm	Native	Annual	IFNUS
PASC	*Panicum scoparium* Lam.	G	Hairy Panicum	Warm	Native	Annual	IFNUS
PAFL	*Paspalum floridanum* Michx.	G	Florida Paspalum	Warm	Native	Perennial	NRCS hbk
PASE	*Paspalum setaceum* Michx.	G	Hairy Paspalum	Warm	Native	Perennial	IFNUS
SCPA	*Schedonnardus paniculatus* (Nutt.) Trel.	G	Tumblegrass	Warm	Native	Perennial	NARP 3rd
SEGE	*Setaria geniculata* (Lam.) Beauu.	G	Knotroot Bristlegrass	Warm	Native	Perennial	TXRP
SPAS	*Sporobolus asper* (Michx.) Kunth	G	Tall Dropseed	Warm	Native	Perennial	NARP 3rd
SPCR	*Sporobolus cryptandrus* (Torr.) Gray	G	Sand Dropseed	Warm	Native	Perennial	NARP 3rd
TRFL	*Tridens flavus* (L.) Hitchc.	G	Purple Top	Warm	Native	Perennial	TXRP
TRST	*Tridens strictus* (Nutt.) Nash	G	Longspike Tridens	Warm	Native	Perennial	IDOKPL
VUOC	*Vulpia octoflora* (Walt.) Rydb.	G	Sixweeks Fescue	Cool	Native	Annual	USDA
Graminoids							

Code	Scientific Name		Common Name	Season of Growth	Origin	Life	Source
CASP	*Carex sparganioides* Muhl.	G	Bur-reed (Tall) Sedge	Warm	Native	Perennial	IFNUS
CAREX	*Carex* spp.	G	Sedge	Warm	Native	Perennial	IDOKPL
CAFS	*Carex festucacea* Schkuhr ex Willd.	G	Fesue like Sedge	Cool	Native	Perennial	IFNCT
CAMI	*Carex microdonta*	G	Small-tooth caric Sedge	Cool	Native	Perennial	IFNCT
CATE	*Carex texensis* (Torr.) Bailey	G	Texas (Threadlike) Sedge	Cool	Native	Annual	IFNUS
CYES	*Cyperus esculentus* L.	G	Yellow Nutsedge	Warm	Native	Perennial	IFNUS
CYOV	*Cyperus ovularis* (Michx.) Torr.	G	Ball Sedge	Warm	Native	Perennial	IFNUS
CYSP	*Cyperus* spp.	G	Sedge	Warm	Native	Perennial	
ELSP	*Eleocharis* spp.	G	Spike Sedge	Warm	Native	Perennial	
JUNCUS	*Juncus tenuis* Willd.	G	Rush	Cool	Native	Perennial	NRCS hbk
SCIRP	*Scirpus* spp.	G	Bulrush	Warm	Native	Perennial	IDOKPL
Forbs and Legumes							
ACVI	*Acalypha virginica* L.	F	Three-seeded Mercury	Cool	Native	Annual	NRCS hbk
ACLA	*Achillea lanulosa* Nutt.	F	Common Yarrow	Cool	Native	Perennial	Weeds
AGHE	*Agalinus heterophylla* (Nutt.) Small	F	Prairie Agalinus	Warm	Native	Annual	IDOKPL
AGTE	*Agalinus tenuifolia* (Vahl) Raf.	F	Slender Gerardia	Warm	Native	Annual	IFNCT
AMBL	*Amaranthus blitoides* Wats.	F	Prostrate Pigweed	Warm	Intro	Annual	NRCS hbk
AMAR	*Ambrosia artemisifolia* L.	F	Common Ragweed	Warm	Native	Annual	IFNUS
AMBI	*Ambrosia bidentata* Michx.	F	Lanceleaf Ragweed	Warm	Native	Annual	NRCS hbk
AMPS	*Ambrosia psilostachya* DC.	F	Western Ragweed	Warm	Native	Perennial	NARP 3rd
ANPA	*Antennaria neglecta* Greene	F	Cudweed	Warm	Native	Perennial	IFNUS
ANPL	*Antennaria plantaginifolia* (L.) Richards	F	Pussytoes	Cool	Native	Perennial	NRCS hbk
APCA	*Apocyrum cannabinum* L.	F	Hemp Dogbane	Warm	Native	Perennial	Weeds
ARLU	*Artemisia ludoviciana* Nutt.	F	Silver Sage (sagewort)	Warm	Native	Perennial	NARP 3rd

Code	Scientific Name		Common Name	Season of Growth	Origin	Life	Source
ASSY	*Asclepias syriaca* L.	F	Common Milkweed	Warm	Native	Perennial	Weeds
ASST	*Asclepias stenophylla* Gray	F	Narrow-leaved Milkweed	Warm	Native	Perennial	IFNUS
ASVI	*Asclepias viridis* Walt.	F	Antelopehorn Milkweed	Warm	Native	Perennial	NRCS hbk
ASER	*Aster ericoides* L.	F	Heath Aster	Warm	Native	Perennial	Weeds
ASEX	*Aster exilis* Ell.	F	Slender Aster	Warm	Native	Annual	IFNUS
ASSB	*Aster subulatus* Michx.	F	Purple Aster	Warm	Native	Annual	IFNUS
BREU	*Brickellia eupatorioides*(L.) Shinners	F	False Bonneset	Warm	Native	Perennial	IFNCT
CAIN	*Callirhoe involucrata* (Nutt.) A. Gray	F	Purple Poppy Mallow	Cool	Native	Annual	IFNCT
CHAL	*Chenopodium album* L.	F	Lambsquarters	Warm	Intro	Annual	IFNCT
CHCA	*Chrysopsis villosa* (Pursh) Nutt. var. *canescens*	F	Hairy Golden Aster	Warm	Native	Perennial	Noble
CIRAL	*Cirsium altissimum* (L.) Speng.	F	Tall Thistle	Warm	Native	Annual	THISTLES
CIRUN	*Cirsium undulatum*	F	Wavy Leaf Thistle	Warm	Native	Perennial	Roads
COCA	*Conyza canadensis* (L.) Cronq.	F	Mare's Tail (horseweed)	Warm	Native	Annual	Weeds
CRCA	*Croton capitatus* Michx.	F	Woolly Croton	Warm	Native	Annual	Noble
CRGL	*Croton glandulosus* L.	F	Glandular (toothed) Croton	Warm	Native	Annual	IFNUS
TX Croton	*Croton texensis* (Kl.) Muell.Arg.	F	Texas Croton	Warm	Native	Annual	Weeds
CRMO	*Croton monanthogynus* Michx.	F	One-seeded Croton	Warm	Native	Annual	IDOKPL
DITE	*Diodia teres*Walt.	F	Poor Joe	Warm	Native	Annual	NRCS hbk
ECAN	*Echinacea angustifolia* DC.	F	Black Sampson	Cool	Native	Perennial	Noble
ECPA	*Echinacea pallida* Nuttall	F	Pale Purple Coneflower	Warm	Native	Perennial	IFNUS
ERRE	*Erysimum repandum* L.	F	Bushy Wallflower	Warm	Native	Annual	IDOKPL
ERST	*Erigeron strigosus* Muhl. ex Willd.	F	Daisy Fleabane	Cool	Native	Annual	NRCS hbk
ERLO	*Eriogonum longifolim* Nutt.	F	Wild Buckwheat	Warm	Native	Perennial	Noble
EUSE	*Eupatorium serotinum* Michx.	F	Late Eupatorium	Warm	Native	Perennial	IFNUS
EUMC	*Euphorbia maculata* Raf.	F	Spotted Spurge	Warm	Native	Annual	Wds NE
EUMA	*Euphorbia marginata* Pursh.	F	Snow-on-the-mountain	Warm	Native	Annual	Weeds

Code	Scientific Name		Common Name	Season of Growth	Origin	Life	Source
EUSU	*Euphorbia supina* Raf.	F	Prostrate Spurge	Warm	Intro	Annual	IDOKPL
GAPU	*Gaillardia pulchella* Foug.	F	Indian Blanket	Warm	Native	Annual	NRCS hbk
GASE	*Gaillardia serotinum* (Walt.) H. Rock	F	Yellow Gaillardia	Warm	Native	Annual	IDOKPL
GASU	*Gaillardia sauvis* (Gray & Engelm.) Brit. & Rus.	F	Rayless Gaillardia	Warm	Native	Annual	IDOKPL
GECA	*Geranium carolinianum* L.	F	Carolina Crane's Bill	Warm	Native	Annual	IDOKPL
GRSQ	*Grindelia squarrosa* (Pursh) Dun.	F	Curly-cup Gumweed	Warm	Native	Perennial	NARP 3rd
GUARA	*Guara villosa* Torr.	F	Woolly Guara	Warm	Native	Perennial	IFNUS
GUDR	*Gutierrezia dracunculoides* (DC.) Blake	F	Annual Broomweed	Warm	Native	Annual	NARP 3rd
GUSA	*Gutierrezia sarothrae* (Pursh) Britt. & Rusby	F	Broom Snakeweed	Warm	Native	Perennial	NARP 3rd
HAPCI	*Haplapappus ciliatus* (Nutt.) DC.	F	Wax Goldenweed	Warm	Native	Annual	Noble
HENI	*Hedyotis nigricans* (Lam.) Fosb.	F	Prairie Bluets	Warm	Native	Perennial	IFNUS
HEAN	*Helianthus annuus* L.	F	Annual Sunflower	Warm	Intro	Annual	IDOKPL
HEMA	*Helianthus maximiliani* Schrad.	F	Maximilian Sunflower	Warm	Native	Perennial	NRCS hbk
HEMO	*Helianthus mollis* Lam.	F	Ashy Sunflower	Warm	Native	Perennial	NRCS hbk
HILO	*Hieracium longipilum* Torr.	F	Long-bearded Hawkweed	Warm	Native	Perennial	Noble
KRLA	*Krameria lanceolata* Torr.	F	Range Ratney	Warm	Native	Perennial	TXRP
LACSE	*Lactuca serriola* L.	F	Prickly Lettuce	Warm	Intro	Biennial	Weeds
LEDE	*Lepidium densiflorum* Schrad.	F	Greenflower Pepperweed	Cool	Native	Annual	IDOKPL
LIPU	*Liatris punctata* Hook.	F	Dotted Gayfeather	Warm	Native	Perennial	NARP 3rd
LINSU	*Linum sulcatum* Riddell	F	Yellow Prairie Flax	Cool	Native	Annual	Noble
MOPE	*Monarda pectinata* Nutt.	F	Spotted Beebalm	Warm	Native	Perennial	Weeds
NOBI	*Northoscordum bivalve* (L.) Britton	F	False garlic	Cool	Native	Perennial	IFNCT
OELA	*Oenothera laciniata* Hill	F	Cutleaf Eveningprimrose	Warm	Native	Annual	IFNCT
OESE	*Oenothera serrulata* Nutt.	F	Slim-leaf Eveningprimrose	Warm	Native	Perennial	IFNUS
OPMA	*Opuntia macrorhiza* Engelm.	F	Prckly Pear Cactus	Warm	Native	Perennial	IDOKPL
OXST	*Oxalis stricta* L.	F	Yellow Wood Sorrel	Warm	Native	Perennial	Wds NE

Code	Scientific Name		Common Name	Season of Growth	Origin	Life	Source
PAJA	*Paronychia jamesii* T. & G.	F	James Nailwort	Warm	Native	Perennial	Noble
PASSA	*Pastinaca sativa* L.	F	Wild Parsnip	Warm	Intro	Biennial	IFNUS
PENCO	*Penstemon Cobea* Nuttall	F	Cobea Penstemon	Cool	Native	Perennial	IFNUS
PHPI	*Phlox pilosa* L.	F	Prairie Phlox	Cool	Native	Perennial	NRCS hbk
PHHE	*Physalis heterophylla* Nees	F	Groundcherry	Warm	Native	Perennial	Noble
PHVI	*Physalis virginiana* P. Mill.	F	Virginia Groundcherry	Warm	Native	Perennial	Weeds
PHAM	*Phytolacca americana* L.	F	Common Pokeweed	Warm	Native	Perennial	IDOKPL
PLAAR	*Plantago aristata* Michx.	F	Bracted Plantain	Warm	Native	Annual	IFNUS
PLAMA	*Plantago major* L.	F	Blackseed Plantain	Warm	Intro	Perennial	Weeds
PLAPA	*Plantago patagonica* Jacq.	F	Woolly Plantain	Warm	Native	Perennial	Weeds
POLAL	*Polygala alba* Nuttall	F	White Polygala	Warm	Native	Perennial	IDOKPL
POLIN	*Polygala incarnata* L.	F	Slender Milkwort	Warm	Native	Annual	IFNCT
POVE	*Polygala verticillata* var. *ambigua* (Nutt) Wd.	F	Purple Polygala	Warm	Native	Annual	IDOKPL
POAV	*Polygonum aviculare* L.	F	Prostrate Knotweed	Warm	Intro	Annual	IFNCT
PSOB	*Pseudognaphalium obtusifolium*(L.) Hilliard & Burtt.	F	Fragrant Cudweed	Warm	Native	Annual	IFNCT
RACO	*Ratibida columnifera* (Nutt.) E.S.	F	Prairie Coneflower	Warm	Native	Perennial	NARP 3rd
ROMU	*Rosa multiflora* Thunb.	F	Multiflora rose	Warm	Native	Perennial	IDOKPL
ROPR	*Rosa pratincola* Greene.	F	Arkansas Rose	Warm	Native	Perennial	IFNUS
RUHI	*Rudbeckia hirta* L.	F	Black-eyed Susan	Warm	Native	Perennial	TXRP
RUHU	*Ruellia humilis* Nuttall	F	Wild Petunia	Warm	Native	Perennial	NRCS hbk
RUMAL	*Rumex altissimus* Wood	F	Smooth Dock	Warm	Native	Perennial	IFNUS
RUMCR	*Rumex crispus* L.	F	Curly Dock	Warm	Native	Perennial	IFNUS
SBCA	*Sabatia campestris* Nuttall	F	Prairie Sabatia (Gentain)	Warm	Native	Annual	IFNUS
SAAZ	*Salvia azurea* Lam.	F	Pitcher Sage	Warm	Native	Perennial	NRCS hbk
SOCAR	*Solanum carolinense* L.	F	Horsenettle	Warm	Native	Perennial	Weeds
SOLE	*Solanum elaeagnifolium* Cav.	F	Silver-leaf Nightshade	Warm	Native	Perennial	TXRP

Code	Scientific Name		Common Name	Season of Growth	Origin	Life	Source
SORA	*Solanum rostratum* Dunal.	F	Buffalobur	Warm	Intro	Annual	IDOKPL
SOLT	*Solanum torreyi* A. Gray	F	Robust Horsenettle	Warm	Native	Perennial	IFNUS
SOCA	*Solidago canadensis* L.	F	Canada Goldenrod	Warm	Native	Perennial	IFNUS
SOMI	*Solidago missouriensis* Nutt.	F	Missouri Goldenrod	Warm	Native	Perennial	NARP 3rd
SONI	*Solidago nitida* L.	F	Smooth Goldenrod	Warm	Native	Perennial	IFNUS
SORI	*Solidago rigida* L.	F	Stiff Goldenrod	Warm	Native	Perennial	Noble
SOSP	*Solidago speciosa* Nutt.	F	Tall Goldenrod	Warm	Native	Perennial	IFNUS
SONAS	*Sonchus asper* (L.) Hill	F	Prickly Sowthistle	Warm	Intro	Annual	IFNCT
SPVE	*Spiranthes vernalis* Engelm. & A. Gray	F	Spring Ladies Tresses	Cool	Native	Perennial	IFNCT
STVI	*Stenosiphon virgatus* Spach.	F	Flax-leaved Stenosiphon	Warm	Native	Perennial	IDOKPL
STSY	*Stillingia sylvatica* L.	F	Queen's Delight	Warm	Native	Perennial	IFNUS
TECA	*Teucrium canadense* L.	F	American Germander	Warm	Native	Perennial	Wds NE
TORAR	*Torillis arvensis* (Huds.) Link	F	Hedge Parsley	Cool	Native	Annual	IFNUS
TRRA	*Tragia ramosa* Torrey	F	Nose Burn	Warm	Native	Annual	IDOKPL
TRPR	*Tragopogon pratensis* L.	F	Western Salsify	Warm	Intro	Perennial	IFNUS
TRIPE	*Tridanis perfoliata* (L.) Nieuw.	F	Venus Lookingglass	Cool	Native	Annual	Weeds
VEBA	*Vernonia baldwinii* Torr.	F	Ironweed	Warm	Native	Perennial	Weeds
ACAN	*Acacia angustissima* (Mill.) Kuntze	L	Prairie Acacia	Warm	Native	Perennial	NRCS hbk
AMCA	*Amorpha canescens* (Nutt.) Pursh	L	Leadplant	Cool	Native	Perennial	NARP 3rd
BAAU	*Baptisia australis* (L.) R. Br.	L	Blue Wild Indigo	Cool	Native	Perennial	NRCS hbk
BABR	*Baptisia leucophaea* Nutt.	L	Large-bracted Wild Indigo	Warm	Native	Perennial	IFNUS
CHFA	*Cassia fasciculata*Michx.	L	Showy Partridge Pea	Warm	Native	Annual	Noble
CHMA	*Cassia marilindica* L.	L	Sensitive Partridge pea	Warm	Native	Perennial	IFNUS
DALAU	*Dalea aurea* Nuttall ex. Pursh	L	Golden Dalea	Warm	Native	Annual	Noble
DALEN	*Dalea enneandra* Nutt.	L	Feather Dalea	Warm	Native	Perennial	USDA
DEIL	*Desmanthus illoensis* (Michx.) Macm.	L	Illinois Bundle-Flower	Warm	Native	Perennial	TXRP

Code	Scientific Name		Common Name	Season of Growth	Origin	Life	Source
DELE	*Desmanthus leptoloba* (T. &G.) Kuntze	L	Prairie Mimosa	Warm	Native	Perennial	IFNUS
DECA	*Desmodium canescens* (L.) DC	L	Hoary Tick Clover	Warm	Native	Perennial	IFNCT
DEPA	*Desmodium paniculatum* (L.) DC	L	Panicled Tick Clover	Warm	Native	Perennial	IFNCT
DMSE	*Desmodium sessilifolium* (Torr.) T. & G.	L	Sessile Tick Clover	Warm	Native	Perennial	Noble
LECA	*Lespedeza capitata*Michx.	L	Roundhead Lespedeza	Warm	Native	Perennial	Noble
LECU	*Lespedeza cuneata* (Dumont) G. Don	L	Sericea Lespedeza	Warm	Intro	Perennial	Noble
LEPR	*Lespedeza procumbens* Michx.	L	Trailing Lespedeza	Warm	Native	Perennial	IDOKPL
LEST	*Lespedeza striata* (Thunb.) H. & A.	L	Japanese Lespedeza	Warm	Intro	Perennial	IFNUS
LESU	*Lespedeza stueveii* Nutt.	L	Tall Lespedeza	Warm	Native	Perennial	IFNCT
LEVI	*Lespedeza virginica* (L.) Britt.	L	Slender Lespedeza	Warm	Native	Perennial	Noble
LUPU	*Lupinus pusillus* Pursh	L	Blue Lupine	Cool	Native	Annual	IDOKPL
MELU	*Medicago lupulina* L.	L	Black Medic	Warm	Intro	Annual	Weeds
MELOF	*Melilotus officinalis* (L.) Lam	L	Sweetclover	Warm	Intro	Annual	IFNCT
NELU	*Neptunea lutea* (Leavenw.) Benth.	L	Yellow Neptunea	Warm	Native	Perennial	TXRP
PECA	*Petalostemon cadidum* (Willd.) Michx.	L	White Prairie Clover	Warm	Native	Perennial	IFNUS
PEPU	*Petalostemon purpureum* (Vent.) Rydb.	L	Purple Prairie Clover	Warm	Native	Perennial	NARP 3rd
PSTE	*Psoralea tenuiflora* Pursh	L	Slimflower Scurfpea	Warm	Native	Perennial	NARP 3rd
SCUN	*Schrankia uncinata* Willd.	L	Catclaw Sensitivebriar	Warm	Native	Perennial	TXRP
SENMA	*Senna marilandica* (L.) Link	L	Maryland Senna	Warm	Native	Perennial	USDA
STRLE (RYTE)	*Strophostyles leiosperma* (T. & G.) Piper	L	Trailing Bean (pea vine)	Warm	Native	Annual	Noble
TRVE	*Trifolium vesiculosum* Savi.	L	Arrowleaf Clover	Warm	Intro	Annual	IDOKPL
Trees, Shrubs, etc.							
BULA	*Bumelia lanuginosa* (Michx.) Pers.	S	Chittamwood	Warm	Native	Perennial	IFNUS
CATX	*Carya texana* Buckl.	S	Texas Hickory	Warm	Native	Perennial	IDOKPL

Code	Scientific Name		Common Name	Season of Growth	Origin	Life	Source
CERE	*Celtis reticulata* Torr.	S	Hackberry	Warm	Native	Perennial	Noble
CODR	*Cornus drummondii* Meyer	S	Rough-leaf Dogwoood	Warm	Native	Perennial	NRCS hbk
CREN	*Crataegus Engelmannii*	S	Hawthorn	Warm	Native	Perennial	IFNCT
CUPE	*Cuscata pentagona* Engelm.	S	Field Dodder	Warm	Native	Annual	Weeds
DIVI	*Diospyros virginiana* L.	S	Persimmon	Warm	Native	Perennial	NRCS hbk
JUNVI	*Juniperus virginiana* L.	S	E. Red Cedar	Cool	Native	Perennial	IFNUS
MOSP	*Morus* spp.	S	Mulberry	Cool	Native	Perennial	IFNUS
PAQU	*Parthenocissus quinquefolia* (L.) Planch.	S	Virginia Creeper	Warm	Native	Perennial	IFNUS
PRAN	*Prunus angustifolium* Marsh.	S	Sand Plum	Cool	Native	Perennial	NRCS hbk
PRMX	*Prunus mexicana* Wats.	S	Mexican Plum	Cool	Native	Perennial	TXRP
QUMA	*Quercus marilindica* Muench.	S	Blackjack Oak	Cool	Native	Perennial	IFNUS
QUST	*Quercus stellata* Wang.	S	Post Oak	Cool	Native	Perennial	IFNUS
RUCO	*Rhus copallina* L.	S	Winged Sumac	Warm	Native	Perennial	Noble
RHGL	*Rhus glabra* L.	S	Smooth Sumac	Warm	Native	Perennial	Weeds
RUOK	*Rubus oklahomus* Bailey	S	Blackberry	Cool	Native	Perennial	Noble
SMBO	*Smilax rotundifolia* L.	S	Greenbriar	Warm	Native	Perennial	IDOKPL
SYOR	*Symphoricarpos orbiculatus* Moench	S	Buckbrush	Warm	Native	Perennial	Weeds
TORA	*Toxicodendron radicans* (L.) Kuntze	S	Poison Ivy	Warm	Native	Perennial	IDOKPL
ULMA	*Ulmus americana* L.	S	American Elm	Warm	Native	Perennial	NRCS hbk
VISP	*Vitis* spp.	S	Grape Vine	Warm	Native	Perennial	IDOKPL

Sources Legend

NARP 3rd:	North American Range Plants 3rd Edition
NRCS hbk	Rangeland and Pasture Handbook for Western Oklahoma by NRCS and OSU EXT.
Wds NE	Weeds of Nebraska
Weeds	Weeds of the West

Sources Legend

TXRP	Texas Range Plants by S.L. Hatch & J. Pluhar
Noble	S. R. Noble Web Page
IFNUS	An Illustrated Flora of the Northern United States and Canada
IDOKPL	Identification of Oklahoma Plants R.J. Tyrl & U.T. Waterfall
IFNCT	Illustrated Flora of North Central TX
USDA	USDA Plants Database

VITA

Daniel Chad Cummings

Candidate for the Degree of

Doctor of Philosophy

Thesis: VEGETATION DYNAMICS AND LIVESTOCK PRODUCTION ON

RANGELANDS IN THE SOUTHERN GREAT PLAINS

Major Field: Conservation Science

Biographical:

Personal Data: Born in Oklahoma City, OK; raised in Stillwater, OK

Education:
Bachelors of Science Agronomy, Minor in Animal Science, Oklahoma State
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Masters of Science Plant and Soil Science, Oklahoma State University,
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Name: Daniel Chad Cummings   Date of Degree: July, 2007

Institution: Oklahoma State University   Location: Stillwater, Oklahoma

Title of Study: VEGETATION DYNAMICS AND LIVESTOCK PRODUCTION ON
RANGELANDS IN THE SOUTHERN GREAT PLAINS

Pages in Study: 138   Candidate for the Degree of Doctor of Philosophy

Major Field: Conservation Science

Scope and Method of Study: We examined vegetation dynamics and livestock production
        in response to land management practices on rangelands in two different studies,
        one in north central and one in western Oklahoma. The study in north central
        Oklahoma tested the effects of altered grazing selectivity of herbivores with patch
        burning on sericea lespedeza (*Lespedeza cuneata*) invasion and native plant
        dynamics compared to traditional rangeland management in the area. The patch-
        burn study was initiated in 1999 and concluded in 2006. The study in western
        Oklahoma tested the effects of broad spectrum herbicide application on vegetation
        dynamics and livestock production in eroded rangelands. This study was initiated
        in 2000 and concluded in 2006. Both studies were moderately grazed by mixed
        breed cattle throughout their duration.

Findings and Conclusions: In the north central Oklahoma study, sericea lespedeza
        invasion rate was four times greater in the traditional management than in the
        patch-burn study over the seven year study. In addition, vegetative cover of most
        plant functional groups were negatively correlated with sericea lespedeza cover,
        though the correlation coefficients were not as high as we had predicted.
        Herbicide applications to control sericea lespedeza invasions rarely resulted in
        increased desirable forage production, which commonly serves as the impetus for
        herbicide application. These results indicate that altering grazing selectivity of
        large herbivores with patch burning does provide a viable alternative to herbicide
        applications for the control of sericea lespedeza invasion. Further information
        about the biology and ecology of this invasive species is also included.
        In the western Oklahoma study, herbicide applications only resulted in significant
        reduction of target forbs in one year, and only resulted in increased grass
        production in one of the six years of the study. There were no significant
        differences in livestock average daily gain or gain per area between herbicide
        treatments and the control in any year or over the course of the study. These
        results indicate that while herbicide applications might be necessary for specific
        management objectives, they do not result in increased animal production when
        applied for herbaceous weed control.

ADVISER'S APPROVAL: Samuel D. Fuhlendorf