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EFFICACY OF FIRE, HERBICIDE AND MOWING ON SMOOTH BROME AND RE-ESTABLISHMENT OF A SAND PRAIRIE

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EFFICACY OF FIRE, HERBICIDE AND MOWING ON SMOOTH BROME AND RE-ESTABLISHMENT OF A SAND PRAIRIE

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ABSTRACT

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Smooth brome (*Bromus inermis*) is an invasive grass native to Eurasia that is now nearly ubiquitous in North America and is frequently encountered in sites targeted for prairie restoration. For this study, I investigated the efficacy of fire, herbicide (2% glyphosate), mowing, and fire plus herbicide for controlling smooth brome and re-establishing a sand prairie community in southwestern Wisconsin. Seven treatments, a seed only control, and full control were replicated 8 times in a randomized block design. Treatments were applied after the presence of five leaves per tiller. Repeat treatments were applied the following year. Smooth brome foliar cover and stem density, seeded species foliar cover and richness, litter depth, light availability, and soil moisture measurements were obtained throughout the study period. Model III two-factor ANOVAs were utilized to determine any differences among treatments. The fire plus herbicide combination treatment was by far the most effective treatment for removing smooth brome and promoting seeded species establishment. However, this may not be the most appropriate method for all land managers. Understanding the effect of the other treatments examined here will increase the confidence in the expected outcome of a restoration and contribute to sound management decisions with fewer wasted resources.

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CHAPTER 1

INTRODUCTION

The prairie ecosystem once covered roughly 162 million ha in North America (Samson and Knopf, 1994), from the Rocky Mountains east across Illinois and Indiana, and from Texas north into the provinces of Alberta, Saskatchewan, Manitoba, and Ontario in Canada. Smaller, isolated areas also extended east as far as Ohio, Kentucky and Tennessee in the "prairie peninsula" (Transeau, 1935). Within this vast expanse, the prairie ranges from xeric shortgrass prairie in the west to lush tallgrass prairie in the east. Variation in soils and topography produce additional pockets of prairie diversity; tallgrass prairie also includes swampy sedge meadows as well as dry sand prairies more akin to Great Plains mixed grass prairies.

Described as a sea of grass and devoid of trees, early American explorers originally believed the area a wasteland (Weaver, 1954; Severson and Hull Sieg, 2006); that perception later changed as the rich soil began drawing settlers from the east to homestead farms (Weaver, 1954; Samson and Knopf, 1994). The rate of conversion from prairie to agricultural use increased as the nation grew (Turner and Rabalais, 2003) and government policies promoted settlement in the west (Weaver, 1954; Samson *et al.*, 2004). Following World War II, and the advent of industrialized agriculture, pastures and marginal lands were also converted into soybean and corn fields (Weaver, 1954; Samson *et al.*, 2004). Today, more than 82-99% of the original prairie ecosystem has disappeared, and exists largely in fragmented pieces (Samson and Knopf, 1994). Remaining grassland areas continue to shrink through additional development pressure, woody encroachment facilitated by fire suppression, and invasion of exotic plant species (Koper *et al.* 2009).

The near-complete conversion of the diverse, perennial prairie ecosystem to the continuously disturbed annual monoculture of row crops has caused a number of significant problems. The populations of species dependent on the prairie ecosystem have declined dramatically (Samson *et al.*, 2004). Grassland bird populations, for example, have steadily decreased since settlement in the Great Plains and continue to decline today (Sample and Mossman, 1997). Arthropod assemblages have been impacted by both habitat loss and fragmentation (Isaacs *et al.*, 2009). Largely ignored, arthropods are an important component of prairie ecosystem function (e.g. pollinators, herbivores, and predators) and provide important ecosystem services to the agricultural industry, especially in the areas of pollination and biological control of insect pests (Peterson, 1997; Allen-Wardell *et al.* 1998; Friesen, 2000; Kremen *et al.*, 2007). Additionally, soil erosion (Weaver, 1954; Weaver and Albertson, 1956) and nutrient runoff have increased dramatically and contribute not only to the eutrophication of local waters, but also to the "dead zone" in the Gulf of Mexico (Turner and Rabalais, 2003). Iowa alone had lost 192,643 metric tons of soil per km^2 by 1935, with losses of 50% to 75% of surface soils over 40% of the state (Turner and Rabalais, 2003).

The practice of prairie restoration has become a means to preserve biodiversity, expand rapidly shrinking grassland habitat, and help reverse the negative impacts described above (Shirley, 1994; Fletcher and Koford, 2003; Samson *et al.*, 2004).

Notable conservation figures attempted the first prairie restorations in the 1930s in and around Madison, WI. The first North American Prairie Conference (at the time called the Symposium on Prairie and Prairie Restoration) was held in 1968 at Knox College in Galesburg, IL, as a means for managers and researchers to discuss issues related to prairie restoration and management.

Today, conservationists and government conservation programs promote restoration as a means to improve ecosystem services such as soil and nutrient retention in watersheds. During the 1980s, the United States Department of Agriculture (USDA), through the Natural Resource Conservation Service (NRCS) implemented the Conservation Reserve Program (CRP) as an incentive for farmers to idle lands susceptible to erosion, thereby creating habitat for grassland-dependent species. New initiatives address declining pollinator populations (USDA, 2008); prairie restoration is proposed to help boost arthropod numbers and diversity in intensely farmed landscapes (Isaacs *et al.*, 2009). Roadside right-of-ways have also been identified as opportunities for prairie restoration to provide habitat and increase connectivity between prairie habitat fragments (Ehley, 1992; McDaniel, 2000).

There are numerous obstacles to be overcome in any successful restoration project, including the removal of resident invasive plant species and the prevention of their subsequent return (D'Antonio and Thomsen, 2004). *Bromus inermis* Leyss, hereafter smooth brome, is a near-ubiquitous cool season grass frequently encountered in North American restoration sites and generally difficult to remove. Imported from Eurasia in the late 1800's, smooth brome is a sod-forming perennial that spreads primarily through rhizomatous growth and has been noted to invade prairie from roadside plantings. Over time, it forms a dense monoculture that excludes native plant species and decreases the suitability of a site for grassland-dependent animal species (Sather, 1997; Grace *et al.*, 2002). Bowles *et al.* (2003) found that brome had increased in abundance on unburned sand prairies while native plant diversity decreased over a 20-year period. Brome did not increase in abundance and native plant diversity remained similar on sites managed by fire during the same time period. Grant *et al.* (2009) reports that smooth brome, along with Kentucky bluegrass, is one of the "most significant invaders" of prairies maintained by the Fish and Wildlife Service (FWS) in the Dakotas. The presence and abundance of brome was attributed by these authors partially to changes in both grazing and fire regimes – largely a move to no-disturbance management on FWS prairies. Its aggressive behavior, invasion of natural areas, and contribution to biodiversity losses is a subject of concern among land managers. Locally, smooth brome control is of special concern in former cropland and pasture areas that are targeted for restoration to sand prairie.

Some published work exists for controlling smooth brome, but most manipulative experiments have focused on other invasive species, and little information is available regarding best practices. The only review of management techniques was compiled more than 20 years ago (Sather, 1987). Land managers often do not have the budgets and time required to conduct detailed studies or to monitor restoration projects (Cook *et al.*, 2009). Many also feel the process does not address the immediate issues they are facing in a timely manner. Instead, decisions frequently rely on experiential evidence – personal experience, observational/anecdotal evidence and/or advice from other professionals (Cook *et al.*, 2009). Since land managers are still struggling with control of this grass in the tallgrass prairie region of North America, it is important to update the state of current knowledge. Understanding the biology of smooth brome, as well as identifying potential tools for control, is an important first step towards developing best management practices to remove this plant from prairie restorations.

In the chapters that follow, I will first review our knowledge about the origins, extent, and efforts to minimize smooth brome invasion of North American grasslands. I will focus especially on previous attempts to identify effective management strategies to simultaneously decrease smooth brome cover and promote the establishment of more desirable prairie species. In Chapter 3, I will report the results of my own three-year manipulative experiment comparing the effects on smooth brome and prairie species of restoration treatments involving mowing, fire, and herbicide.

CHAPTER 2

SMOOTH BROME (*Bromus inermis* Leyss): A REVIEW OF BASIC BIOLOGY AND STRATEGIES FOR CONTROL

Invasive species generally have two modes of introduction to a new area: unintentional or intentional. The latter is common; people have been moving plants around, primarily for agricultural purposes, for thousands of years. It is no surprise then that one can look at any list of invasive plants and identify many that have been introduced for agricultural or horticultural purposes.

Smooth brome is an example of an invasive plant species with a history of intentional introduction. It was imported to the California Agriculture Experiment station around 1880, likely from Hungary, as a potential cold- and drought-tolerant livestock forage grass. Initially, distribution was limited. Small, four ounce packets of seed were made available to farmers and ranchers at 5 cents a packet. N. E. Hansen, a plant explorer for the USDA, imported the first bulk supply of seeds – 12 tons, from the Volga River Valley (Penza province) of Russia in 1897. The shipment was divided and sent out to state research facilities all across the United States (Dunn, 1985). Cultivars were later developed to improve particular qualities or suitability for specific geographical areas. Research continues today to create improved cultivars for forage production (Coulman, 2006). Smooth brome has also been used for other applications, such as erosion control, open pit mine reclamation, phytoremediation and stabilization of areas affected by severe forest fires. It is now found in all Canadian provinces and all but three states in the United States (USDA PLANTS database).

Drought tolerance, palatability, digestibility, higher crude protein content and relatively rapid establishment are among the characteristics that make smooth brome an attractive forage grass (references in Otfinowski *et al.*, 2007). However, these and other characteristics are less than desirable from a management viewpoint as they have facilitated the spread of smooth brome into natural areas from roadsides, pastures and other established areas (Larson *et al.* 2001).

Smooth brome's contribution to biodiversity losses is a subject of concern among land managers. Much of this concern stems from the negative effect its presence has on plant community diversity. For example, Bowles *et al.* (2003) found that over a 20-year period, the abundance of smooth brome increased in unburned sand prairies while native plant diversity decreased. Over time, smooth brome forms a dense monoculture that excludes native plant species, leading to decreased plant diversity and a decline in the suitability of a site for grassland-dependent animal species (Sather, 1997; Grace *et al.*, 2002). It can also affect predator-prey interactions among insects (Cronin and Haynes, 2004).

Smooth brome's invasiveness and persistence in the face of control efforts have raised a red flag with national land management organizations, including the US Fish and Wildlife Service (Grant *et al.*, 2009) and The Nature Conservancy (Sather, 1987). Grant *et al.* (2009) reports that smooth brome is one of the "most significant invaders" of prairies maintained by the Fish and Wildlife Service (FWS) in the Dakotas.

Understanding the plant's biology is the first step towards identifying effective control measures that will allow land managers to reduce the impacts of an important and problematic species.

Life History and Ecology

Smooth brome is a fast-growing, perennial, cool-season (C_3) rhizomatous grass. These characteristics alone can confer an advantage in the tallgrass prairie region, where the dominant native grasses are warm-season (C_4) bunchgrasses. Smooth brome biomass production begins much earlier in the year than the dominant C_4 grasses, allowing for a window of opportunity during which it can obtain resources (e.g. light, water, nutrients) with little to no competition, thereby reducing resource availability for warm season grasses later in the growing season (Willson and Stubbendieck, 1995). Peak biomass production occurs during the late spring, with flower and seed set occurring in mid- to late-July, before warm season grasses begin their greatest period of growth (Sather, 1987).

Spring tiller emergence depletes smooth brome's root carbohydrate reserves, which rebound by the mid-summer months. Meristematic tissues within each tiller are raised above the soil surface during elongation, leaving the plant susceptible to considerable damage by defoliation if the growth point is removed (references within Sather, 1987; Willson, 1992). Like other cool-season grasses, smooth brome experiences little to no growth during the hot and dry conditions of the mid- to late-summer months, but resumes growth in the fall. The timing of smooth brome's second growth phase presumably corresponds with declining uptake by senescing warm-season plants. New tillers emerge, but do not elongate like tillers produced in the spring (Otfinowski *et al.*, 2007); meristematic tissues remain belowground and the plants may not be as susceptible to mechanical removal. Root carbohydrate reserves are greatest going into the winter months (Sather, 1987)

Early-season prescribed fire, a common practice for maintaining prairie, can exacerbate the "early start advantage", especially during dry years (Willson, 1992), and presumably in drier sites. Early-spring burns occur prior to tiller elongation and do not negatively affect smooth brome's performance. The bare ground warms more quickly than if left unburned and smooth brome responds with vigorous growth, removing water and shading the soil before C_4 species emerge from dormancy. Later in the growing season, performance of native warm season grasses is reduced by the decreased soil temperature and moisture availability (Willson and Stubbendieck, 1992).

Although native C_3 grasses experience the same early season biomass production as smooth brome, they do not exhibit the same degree of competitive dominance. Growth habit may play a role, as native C_3 grasses are primarily bunch-forming (Grilz and Romo, 1995). As a sod-forming grass, smooth brome rhizomes can infiltrate the spaces between bunch-forming individuals, not only taking advantage of unoccupied gaps, but also placing tillers in position to take advantage of any additional gaps that may be created by mortality or disturbance. The rhizomatous connections between mother clone and daughter ramets allows for physiological integration of patchy resources. New rhizomes can invade nutrient-limited areas because of the supporting connections supplying nutrients, and conversely, can support the mother clone when invading nutrient-rich areas

(Otfinowski and Kenkel, 2008). This growth habit allows the plant to maintain its dominance of that space for many years (Otfinowski and Kenkel, 2008).

Another aspect of smooth brome's competitive dominance is its relatively high production of litter (Williams and Crone, 2006). Presence of litter alone can affect the availability of mineral resources, light, and water in any prairie site (Knapp and Seastedt, 1986), but the accumulation of brome litter can also facilitate its invasion through positive feedback (Vinton and Goergon, 2006). The characteristics that make smooth brome a desirable forage grass – lower quantity of lignin and higher levels of leaf nitrogen (increased digestibility and protein content), translate into litter that degrades faster relative to the native grass species. This in turn allows for efficient nitrogen cycling under the clone, aiding smooth brome's expansion and persistence (Vinton and Goergen, 2006). In unmanaged grasslands, brome litter buildup can suppress growth of some established native plants, creating a physical barrier to plant emergence (Williams and Crone, 2006) or slowing soil warming in the spring (Willson and Stubbendieck, 1995). This may be especially important in sand prairie sites, where the natural level of litter accumulation is relatively low (Bowles *et al.*, 2003; pers. obs.).

Although some information exists outlining the suppressive nature of smooth brome litter on established native plants in the tallgrass prairie (Williams and Crone, 2006) no information is available concerning its effect on germination of tallgrass prairie species. Presence and abundance of litter can influence microsite conditions (i.e. moisture, temperature, etc.) that promote or inhibit germination and emergence of seedlings, playing an important role in determining the abundance and distribution of prairie species (Myster, 2006). It is unknown at this time whether smooth brome, or the decomposition of its litter, produces allelopathic chemicals, as suggested by Grant and Sallans (1964, cited in Sather 1987). It is known to have a self-suppressive effect and can become “sod bound” if left unmanaged for a period of years (Sather, 1987).

Asexual reproduction through rhizome and new tiller production is the primary means for the spread of smooth brome; however, prolific seed production provides another avenue for establishment. Most seeds fall relatively close to parent plants (Blankespoor and May, 1996), but movement of seed by animals (i.e. rodents, ants) (reference in Sather, 1987) and wind (Otfinowski *et al.*, 2007), can aid in the establishment of new satellite populations away from the parent clone. Germination of smooth brome seeds is rare in intact tallgrass prairies (Blankespoor and May, 1996); it is likely that a soil disturbance is needed to create a gap, making light and nutrients available (Blankespoor and May, 1996; Jutila and Grace, 2002, Otfinowski *et al.*, 2007). Smooth brome may benefit from sparsely canopied areas, such as sand prairies, where light is more available at the soil surface and patch disturbances are more frequent (Bowles *et al.*, 2003).

Humans may be the animal most responsible for creating new populations of smooth brome (Larson *et al.*, 2001; Otfinowski *et al.*, 2007). Smooth brome has been widely planted for forage, roadside cover, and conservation (e.g. CRP plantings). Introduction of smooth brome seed to a wide geographic area, its aggressive nature, and the “hands off” land management strategies that prevailed until relatively recently have led to the degradation of many prairie remnants (Larson *et al.*, 2001; Bowles *et al.*, 2003; Grant *et al.*, 2009). There is a clear need to identify successful management techniques for smooth brome in tallgrass prairie restorations.

Management Strategies

Some published work exists for controlling smooth brome, but most manipulative experiments have focused on other invasive species, and little information is available regarding best practices. The only review of management techniques was compiled more than 20 years ago (Sather, 1987). Some of the techniques currently employed by land managers and discussed in this review are documented only in the minds and listserve discussions of the restoration community. Land managers often do not have the budgets and time required to conduct detailed studies or to monitor restoration projects (Cook *et al.*, 2009). Many also feel the formal research process does not address the immediate issues they are facing in a timely manner. Instead, decisions frequently rely on experiential evidence – personal experience, observational/anecdotal evidence and/or advice from other professionals (McPherson, 2004; Cook *et al.*, 2009). Since land managers are still struggling to control smooth brome, it is important to update the state of current knowledge.

Differences in geography pose a significant problem in translating management strategies from one geographic region to the next. Smooth brome is adapted to conditions across a large geographic area and tolerates a wide range of soil conditions within each geographic region. Northern and southern cultivars were developed for pasture plantings, so it is likely that the invasive populations in different regions of the country differ genetically as well. Here, the focus is the management of smooth brome in the context of tallgrass prairie restoration, where the native flora is dominated by warm-season grasses. Effective control strategies will necessarily differ for the restoration of ecosystems where C_3 species dominate, such as the fescue prairies of Canada (Grilz and Romo, 1995).

The phenological difference between smooth brome and the warm-season grasses of the tallgrass prairie provides a window of opportunity for land managers. Treatments targeting smooth brome early in the season can be applied with little or no effect on native warm season grasses. Clearly, with early-season treatments there is a potential for negative impacts on cool season natives. Where sites are dominated by smooth brome, with little to no remnant native plant community present, the first round of treatments can be applied with no harm to natives. Where natives co-exist with smooth brome, however, estimating the magnitude of potential collateral damage for a particular treatment will be an important step in determining the best course of action.

Fire

Fire has generally been indicated as the preferred method for establishment and maintenance of prairie restorations, as it was a naturally occurring disturbance process prior to European settlement (Weaver, 1954; Brockway *et al.*, 2002; Severson and Hull Sieg, 2006). Fire removes accumulated litter and thereby releases nutrients, increases soil warming, and allows more rainfall to reach the soil surface (Knapp and Seastedt, 1986). Ultimately, these changes contribute to increased net primary production. As the preferred method for the management of prairie, fire may also be the preferred method for the control of invasive species in prairies, including smooth brome. Unburned sand prairies in Illinois were more extensively invaded with smooth brome than burned sites (Bowles *et al.*, 2003). Fire also decreased presence of smooth brome when compared to grazing treatments at the Broken Kettle Grassland in Iowa (Brudvig *et al.*, 2007).

Fire affects plant species differently, depending on a plant's life history and the season of application. Although early spring prescribed burns promote growth of warm season grasses (e.g. little bluestem), fires that occur during mid- to late-summer can inhibit them (Howe, 1994). Growth of cool season grasses, including smooth brome, is also promoted by early spring burns, but can be inhibited by late spring burns. Willson (1992) found that prescribed fires simply timed to occur after smooth brome tillers emerged in the spring were not entirely successful in suppressing smooth brome growth. Even though tillers had emerged and leaves were present, they had not yet elongated and the plants were not as susceptible as they could have been. In contrast, slightly later burns, timed to coincide with tiller elongation and low root carbohydrate levels, produced a significant reduction in smooth brome (Willson, 1992).

Sather (1987) discusses burning at the boot stage (where the flowering head is still enclosed within the sheath), or when plants are 18 to 24 inches in height. Willson (1992) takes that one step further and correlates tiller elongation and low root carbohydrate levels to the number of leaves a tiller has produced, instead of relying on height. Plant height can vary significantly from site to site, especially between dry and mesic sites. Instead, Willson recommends treating smooth brome after five leaves have been produced on a majority of tillers at a site. Even though fire significantly reduced smooth brome tiller density at this stage (Willson, 1992), Willson and Stubbendieck (1996, 2000) discourage the use of fire if smooth brome stands are relatively pure, citing highly variable and generally poor establishment of warm season grasses following treatment.

In contrast to Willson and Stubbendieck's (1996, 2000) experience, prescribed fires conducted during the growing season (one in May, one in July) were successful in aiding establishment of tallgrass prairie plants in smooth brome-dominated old-fields on mesic ridgetop soils at Effigy Mounds National Monument, near Marquette, IA (Rodney Rovang, pers. comm.). Although the fires did not kill the smooth brome, they did appear to suppress it. A window of opportunity may have been created, which allowed the seeded species to successfully establish. Additionally, the stressed smooth brome plants may have served as a cover crop (Rodney Rovang, pers. comm.), preventing rapid soil drying and creating a more favorable condition for establishing plants (Jutila and Grace, 2002). Long-term environmental monitoring data show smooth brome presence was reduced to less than 1% within 10 years (Rodney Rovang, pers. comm.).

Herbicide

Herbicides are another tool used for controlling smooth brome, not only in remnants or established prairie, but also during the site preparation and establishment phases of a restoration. Herbicides can eliminate or significantly reduce competition from undesirable grasses and forbs during the early stages of planting a prairie. The effectiveness of any given herbicide is influenced by a number of different factors: drought, time of year, temperature or even light conditions at the time of application. For example, the effectiveness of Sethoxydim (Vantage ®, Poast®) a grass-specific herbicide currently used for controlling Reed canarygrass (*Phalaris arundinacea*), can be reduced when applied on warm sunny days when UV radiation is high.

Glyphosate (Roundup®), a broad spectrum herbicide, is commonly used to "burn down old fields" to prepare them for planting. A fall application of glyphosate, following haying, at the New Amsterdam Grasslands near Holmen, WI, successfully removed smooth brome prior to seeding that same fall (Armund Bartz, pers. comm.). Glyphosate can be applied when smooth brome is green and actively growing. Spring and fall applications are favored because warm-season grasses and most forbs are dormant and therefore are not susceptible to glyphosate. Some restoration practitioners believe that fall applications are as effective, if not more effective, as spring applications because C_3 grasses are actively translocating photosynthetic materials to roots for winter storage (Otfinowski *et al.*, 2007).

There is an additional perception that fall glyphosate application is more sensitive than spring application in areas that are a mixture of smooth brome and native plants. Spring applications can negatively impact native cool-season grasses as well as early season forbs; it is believed that the collateral damage is further minimized in the fall because there may be fewer forb species actively growing at this time. However, no published information could be found examining non-target damage in fall applications of glyphosate to smooth brome in mixed native tallgrass stands.

Other herbicides also appear in the literature. Atrazine was commonly used in smooth brome removal experiments (Waller and Schmidt, 1983; Sather, 1987; Willson and Stubbendieck, 1996), but is not discussed here because it now listed as a restricted-use herbicide, due to its ability to be transported through soil to the water table and contaminate groundwater supplies. Other herbicides, such as 2-4-D, Picloram (Shinn and Thill, 2002) and Imazapic (Shinn and Thill, 2002; 2004), were tested for non-target effect on smooth brome. Imazapic was found to damage smooth brome (Shinn and Thill, 2002, 2004), but no conclusions were drawn concerning suppression for the purpose of control.

Mowing

Mowing is frequently used as a means to manage undesirable vegetation, especially where controlled burns are impractical (Diboll, 1987). The effects of mowing are different, however, from those of fire (Schramm, 1992; Jutila and Grace, 2002). Fire removes all aboveground biomass, where mowing leaves some live aboveground biomass intact. Additionally, cut biomass is not immediately consumed by mowing and remains present as litter. The litter then insulates the ground and keeps soil temperatures lower, in contrast to the uninsulated soil of burned areas (Willson and Stubbendieck, 1995; Jutila and Grace, 2002). Another way that burning and mowing differ is that mowed litter slowly releases nutrients as it decomposes, in contrast to the immediate volatilization of burned material. Haying (i.e. mowing followed by the removal of cut biomass) has been suggested as a better mimic of fire as it removes biomass in addition to cutting it. Christiansen (1972) found that litter accumulation at Hayden Prairie, near Cresco, Iowa, was less than half under haying than no management; consequently, nutrients from the biomass removed from the site do not go back into the prairie.

Although mowing does not affect a grassland in an identical manner as fire, it does have some similar effects. Mowing increases light availability to plants, both established individuals and newly-establishing seedlings (Jutila and Grace, 2002). It also removes living tissue that could affect the competitive ability and/or survivorship of individuals, depending on the timing, frequency, and intensity of application. Because grasses will continue to grow following mowing, it is often believed that repeated defoliation during a growing season is necessary to suppress them. Sather (1987) noted that Martin and Hovin (1980) suggested that four mowings during a growing season were more effective in reducing smooth brome than two or three. However, those findings may have been confounded by the different timing of the initial treatment of the four-mowings method, which coincided with boot stage and lower root carbohydrate levels (Sather, 1987; Willson, 1992).

Grazing

Grazing, along with fire and drought (Brockway *et al.*, 2002; Severson and Hull Sieg, 2006; Brudvig *et al.*, 2007), were major disturbance processes maintaining prairie diversity. The use of grazing in prairie restoration and management is becoming more popular (Brudvig *et al.*, 2007). Grazing animals have multiple effects on grasslands in addition to their consumption of biomass (Knapp *et al.*, 1999), many of which affect establishing prairie plants. For example, animal hooves break up the existing litter layer and disturb the soil, creating gaps and microsites that could facilitate seedling establishment (Jutila and Grace, 2002). Redistribution of nitrogen and organic matter as urine and feces creates patches that could also favor some species (Steinauer and Collins, 2001), which may result in a less homogenized species distribution in seeded restorations.

Like fire and mowing, grazing defoliates smooth brome plants. Hypothetically, high-intensity short-duration grazing timed to coincide with tiller elongation could cause considerable damage to a smooth brome stand. However, no published information specifically investigating grazing as a means for controlling smooth brome could be found. Research into grazing as a control method is needed, as previous research has largely focused on maximizing stocking densities while also maximizing smooth brome herbage yields (Donkor *et al.*, 2002).

Other studies have included cattle grazing as a prairie management technique (Brudvig *et al.* 2007). It is unlikely that conventional cattle grazing would reduce smooth brome presence. Brudvig *et al.* (2007) noted that smooth brome was encountered in less than 3% of quadrats in areas where fire was used for management, compared to roughly 30% of quadrats in areas of light grazing alone (15 cm post-graze vegetation height) and 22% of quadrats where both grazing and burning were used for managing prairie. Even at a moderate defoliation rate (7.5 cm vegetation height, 4 weeks between clippings), maximum aboveground biomass production in a *Bromus-Poa* sod was achieved (Donkor *et al.*, 2002). Given smooth brome's history of introduction as a forage species, it is not surprising that it does well under moderate grazing pressure.

Combination Treatments

The aforementioned treatments are frequently combined within a single restoration. For example, fire can be used as a means to remove litter prior to herbicide application, rather than as a control method, to improve application coverage on target vegetation (Grilz and Romo, 1995; Rice, 2005). Mowing once or more during a growing season is often recommended for weed control (Kurtz, 1995) following fire or herbicide treatments and for suppression of resident species prior to sod-seeding (Schramm, 1978; Willson and Stubbendieck, 1996). Using fire in conjunction with grazing is currently believed to promote patchiness and therefore greater species diversity in prairies (Brudvig *et al.*, 2007). Combinations treatments can also be the unplanned result of trying to meet multiple management goals on the same property, such as removing more than one invasive plant species with differing life histories.

Regardless of the specific combination, by combining these treatments there is the potential for a synergistic effect – one that could be more beneficial than any of the treatments alone. For example, fire removes litter, creating bare soil, but does not necessarily remove competitive neighbors. Herbicide on the other hand removes competitive neighbors, but does not remove litter. By combining fire and herbicide, a litter- and neighbor-free environment is created, both of which are conducive to germination and establishment of native species (Wilson and Gerry, 1995; Jutila and Grace, 2002). Again, study in this area is currently lacking and may be more difficult than comparing single treatment effects because of the increase in numbers of possible combinations.

Discussion and Future Directions

Although smooth brome was intentionally introduced and frequently planted for purposes related to conservation, it has clear detrimental effects on native grassland community diversity. As reviewed above, our current knowledge of smooth brome allows at least conditional answers to several of the "questions for future research" Sather (1987) posed in her review:

1) *Is a single cut in boot as effective in reducing Bromus persistence as the documented first cut in boot?* No published studies have explicitly examined the response of *Bromus* to single vs. repeated mowing during the same growing season when the first cut occurs after sufficient tiller elongation.

2) *Is burning in boot as effective as cutting in boot for lowering the persistence of Bromus over a period of years?* A number of publications by Willson (1990) and Willson

& Stubbendiek (1996, 1997, 2000) have addressed the issue of brome responses to spring burns. This research has supported the idea that defoliation following sufficient tiller elongation can be an effective strategy for smooth brome control, primarily in sites with sufficient warm-season competition (Willson and Stubbendieck, 2000). Burning was more effective in reducing fall tiller density than mowing in 1991 (37% reduction vs. 10% increase, respectively), but was no more effective when the same experiment was conducted in 1990 (both decreased tiller density 16%) at the same site. Although numerically different, values for either treatment were not significantly different from controls. No experiments compared multi-year applications of both treatments, however.

3) *What is the response of Bromus to fall fires and/or grazing, which might enhance survival of its native cool season competitors, particularly in the northern part of its range?* Grilz and Romo (1995) found that burns conducted in April and October did not reduce smooth brome and injured native cool-season grasses. However, no other studies have been published which address *Bromus* responses to fall defoliation in the tallgrass prairie region where dominant warm-season species should remain uninjured.

Clearly none of the questions posed in 1987 have been completely answered, and our investigations have opened the door to additional questions. A critical next step will be to explore the mechanisms that underlie the results we observe. We need to move beyond simply asking "did we kill it?" and to try and understand the differences among single-treatment types (fire alone, mowing alone, etc.) vs. their effect in combination, a step that has not been covered in previous research on smooth brome. Furthermore, the timing of treatments and the possibility of interaction effects when treatments are combined, or when treatments are repeated within the same growing season, have been largely ignored. Side-by-side comparisons of multiple treatments are still rare in restoration ecology, making it difficult to know if contrasting results are driven by treatment or site differences (Weiher, 2007). Such information is key in understanding the observed effects in restorations, as well as in choosing the most appropriate method(s) for a given site.

I propose an expanded set of questions to guide continuing research into the control of smooth brome in prairie restorations, to follow up on those posed by Sather (1987) more than twenty years ago:

1) How do spring (post tiller elongation) fire, mowing, grazing, and herbicide treatments compare in efficacy?
2) Is a single spring cut (post tiller elongation) as effective in reducing smooth brome persistence as multiple cuts initiated during this same time?
3) What is the response of smooth brome to fall application of fire, herbicide, mowing and/or grazing?
4) How do combination treatments compare to each other as well as to single treatments?
5) How do the treatments affect native species establishment, the survival of resident natives, and the resulting species composition in a prairie restoration?
6) What drives differences in treatment efficacy from site to site and from year to year?

Ultimately, how and what treatments are used will depend not only on the efficacy of the treatment, but also on the preserve size and accessibility, management goals, species present, robustness of populations if any are species of concern, human and financial resources, as well as social perception and degree of acceptance. Providing land managers with adequate information and confidence in expected outcome will contribute to more sound management decisions and fewer wasted resources. In the next chapter I focus on my own manipulative experiment, which sets out to answer some of these questions.

CHAPTER 3

COMPARING THE EFFICACY OF FIRE, MOWING, AND HERBICIDE FOR CONTROLLING SMOOTH BROME AND RE-ESTABLISHING SAND PRAIRIE

Control of invasive plants is necessary if a prairie restoration is to be successful. Smooth brome is a cool season grass native to Eurasia that has been imported and used widely in the United States for forage, erosion control and reclamation for nearly 130 years. A sod-forming perennial, smooth brome spreads primarily through rhizomatous growth, and has been noted to invade prairie from roadside plantings. It is frequently encountered in both prairie remnants and in sites slated for restoration. Its aggressive behavior, invasion of natural areas, and contribution to declining diversity is a subject of concern to land managers (Bowles *et al.*, 2003; Grant *et al.*, 2009).

Methods for controlling smooth brome vary greatly depending on geographic location, season, and local conditions (e.g. topography) present at a site. Three common management tools, prescribed fire, mowing, and herbicide, are used alone and at varying frequencies in different restorations (Sather, 1987; Howard, 1996; Grace *et al.*, 2002). In addition, these treatments are frequently combined within a single restoration, although sometimes for purposes other than smooth brome control. Fire can be used as a means for litter removal prior to herbicide application rather than as a control method. Mowingonce or more during a growing season is often recommended for weed control following fire or herbicide treatments in the establishment phase and for suppression prior to sod-seeding. Combination treatments may also be used because more than one invasive species is present in a restoration. Regardless of the reason, there is the potential for a synergistic effect when treatments are combined.

Understanding the basic differences among single – treatment types (fire alone, mowing alone, etc.) vs. their effect in combination, is a step that has not been covered in previous research on smooth brome. Furthermore, the timing of treatments and the possibility of compounding effects when treatments are repeated or combined has been largely ignored. Such information is key to understanding the observed effects in restorations, as well as in choosing the most appropriate method(s) for a given site.

Research Objectives

I investigated the effects of fire, mowing and herbicide on the survival of smooth brome and the establishment of seeded prairie species. Specifically, I studied the effect of two frequencies (a single application and two annual applications) of late spring prescribed fire, mowing, and foliar application of a two percent glyphosate solution, as well as a single application of prescribed fire plus two percent glyphosate. The treatments were chosen to mimic restoration practices currently employed by land managers and provide a realistic setting for the study. Each treatment potentially alters the physical factors (litter depth, soil temperature) and resources (light, moisture, nutrients) available to both smooth brome and establishing plants. Therefore, the objectives of the study were to compare 1) the efficacy of each treatment for eliminating smooth brome and 2) how well the seeded native species established under the conditions produced by each treatment. Additionally, abiotic factors (light, moisture, and litter depth) were tracked for the purpose of understanding the mechanisms of the observed effects.

The experiment described here addresses the need for statistically significant research demonstrating the effectiveness of common tools for controlling smooth brome in a prairie restoration. My study will also aid in understanding treatment effects on prairie establishment. Some of the treatments examined here may not be options for all land managers. Knowing what options are available and the efficacy of each will aid land managers in choosing the most effective and appropriate method for the site under consideration, minimize wasted resources (e.g. staff time, money) and add a level of confidence in the expected results of a planned prairie restoration project.

Study System

A xeric component of the tallgrass prairie biome, sand prairie is generally dominated by little bluestem (*Schizachyrium scoparium*). The quintessential tallgrass species, big bluestem (*Andropogon gerardii*), indiangrass (*Sorghastrum nutans*), and switchgrass (*Panicum virgatum*), are only minor components; as a result, there is a greater presence of smaller-stature and drought-tolerant grasses, such as side-oats grama (*Bouteloua hirsuta*), junegrass (*Koeleria macrantha*), porcupine grass (*Stipa spartea*), sand dropseed (*Sporobolus cryptandrus*), and panic grasses (*Dichanthelium* sp.). Vegetation is sparse compared to more mesic sites, with frequent gaps between plants where the soil is relatively bare (Bowles *et al.*, 2003). Smooth brome may take dvantage of these canopy gaps to invade and dominate a site (Otfinowski and Kenkel, 2008).

Sand prairie is categorized as a threatened plant community type in Wisconsin (State of Wisconsin, 2005), in part due to its relatively restricted locations on sandy outwash plains along major river corridors. Conversion of sand prairie to row crops and pine plantations has occurred in many areas and continues to occur today (State of Wisconsin, 2005). Remnant and restored sand prairie sites are valued for their high levels of plant and animal biodiversity. More than 100 native species can be found on the Holland Sand Prairie, a 60-acre degraded sand prairie remnant near Holmen, WI (Mississippi Valley Conservancy, 2007). In Wisconsin, approximately 35 plant species associated with sand prairie are designated as "special concern" or rarer by the WI DNR. Twelve species of birds listed as Species of Greatest Conservation Need" (SGCN) or rarer are moderately or strongly associated with the sand prairie community, including two state Threatened species – Bell's vireo, and Henslow's sparrow (State of Wisconsin, 2005; Sample and Mossman, 1997). Sand prairies located along river corridors have also been utilized by nesting herptiles, such as the Blandings turtle (WI state Threatened status); nine other herptile species listed as SGCN or rarer are also strongly associated with sand prairie (State of Wisconsin, 2005).

Methods

Study Site

The New Amsterdam Grasslands site (portions of Sections 35 and 36, T18N R8W), owned and managed by the Mississippi Valley Conservancy (La Crosse, WI), is located about two miles northwest of Holmen, WI, and was chosen because of its large size (320 acres), protected status, and relatively uniform cover of smooth brome. The property is located on an ancient glacial outwash terrace near the confluence of the Mississippi and Black Rivers, with stabilized eolian features (sand dunes) providing gentle topography. USDA soil maps identify Chelsea Fine Sand as the predominating soil type. The area receives an average of approximately 82 cm of precipitation per year. Normal high temperatures range between 26 and 32 °C (80 – 90 °F) during the summer months and -7 to -1 °C (20 – 30 °F) during the winter months. Normal low temperatures range between -15 and -10 °C (5 – 15 °F) in the winter and 7 to 18 °C (45 – 65 °F) in the summer. The land was cultivated for decades before being taken out of production in the mid-1980s and seeded in smooth brome and bluegrass (*Poa* sp.) according to USDA NRCS recommended practices (Greg Yakle, pers. comm.). Individuals of native prairie species, such as puccoon (*Lithospermum* sp.), round headed bushclover (*Lespedeza capitata*), big bluestem (*Andropogon gerardii*), and prairie ragwort (*Senicio* sp.) have recolonized to a limited degree. Sand prairie restoration to benefit the grassland bird community is already occurring in portions of the site; however the experimental plots discussed here were located in an area unaffected by prior restoration efforts and dominated by smooth brome.

Treatments

Eight treatments (two burn, two mowing, two herbicide, one combination, and seed addition only) and one control were replicated eight times in a randomized block design (Table 1) resulting in 72 plots, each 2m x 2m. Plots were laid out with six per row for a total of 12 rows, each block then encompassing a contiguous row and a half (Fig. 1). Plots were separated by 3m lanes, which were mowed in late May/early June and again in early September of each year. The northwest corner of each plot, as well as the northeast and southwest corners of the study area, was identified with a Total Station (Topcon, Tokyo, Japan) and initially marked with a pin flag. The station was located at the southwest corner of the study area. Relative elevation for each plot was also recorded at the same points. The remaining three corners for each plot were identified with reel tapes and marked with pin flags. Six-inch long ¾" diameter rebar stakes were later positioned at the corners and driven flush with the soil surface. Plots were assigned treatments using a random number generator.

A seeding-only control was included in the study design. The seeding treatment tests the hypothesis that propagule limitation is a primary factor preventing natural regeneration of the sand prairie community. Christiansen (1995) also utilized sowing alone as a means to establish prairie species along a roadside with minimal disturbance for preparation. Repeat treatments were included because managers often apply control measures on a multi-year basis until a prairie is deemed "established" (Becic and Bragg, 1978), or the invasive species is believed to be extirpated from the site (Grilz and Romo, 1995; Blankespoor and May, 1996). There has been little study conducted on combination treatments, so a single combination treatment (burn + herbicide) was also included. Combination treatments have been used intentionally, for example, to remove litter prior to herbicide application, presumably to increase herbicide coverage on actively growing leaves. However, combination treatments are often applied unintentionally, as an artefact of applying management treatments to accomplish different goals in a restoration. Grazing and haying were not included as treatments; this was due to the small size of the plots, logistics, and restrictions stemming from the enrollment of the property in the CRP program.

Initial treatments were applied after smooth brome tillers had produced at least five leaves, but before plants were fully headed out. Willson (1992) identified the "five leaves" stage as a field indicator of smooth brome's susceptibility to fire. At this point, tiller meristematic tissue is above ground, root carbohydrate reserves are low, and new shoots must be initiated by basal buds (Willson, 1992). All treatments were conducted as simultaneously as possible; the burn portion of the combination treatment occurred two weeks prior to all others. Conducting treatments at the same time allows for a more direct comparison of the observed effects. Follow-up mowing, often recommended for prairie establishment, was not conducted to avoid any potential synergistic effects that could confound comparisons among the primary treatments.

Due to the very small size of areas to be burned, burn and combination plots were treated with a backing fire (i.e. a fire ignited on the downwind side of a particular unit). The mowed lanes served as the firebreaks and were wet-lined (sprayed with water beyond the point of runoff) to decrease fuel flammability within the break, reducing the chances of ignition outside the plots. Combination plot burn treatments occurred on May 11th. Ignition occurred between 8 am and 11am to take advantage of higher relative humidity and calmer winds. Burn and burn repeat plots were treated the 8th of June. On-site weather conditions were not recorded, but were later determined using the National Weather Service records from the La Crosse Municipal Airport, located 11 miles south of the site and also within the Mississippi River valley. Fuel moisture measurements were not obtained; grass litter was dry to the touch and produced a distinct crunching sound when crushed.

Initial mowing treatments commenced on the 10th of June. Mowed plots and lanes were treated with a standard walk behind lawn mower, without bagging or mulching attachments, with the cutting deck set to a height of approximately 7.5 cm (3 in). Although Willson and Stubbendeick (1996, 2000) recommend cutting smooth brome to a height of 4 cm (approx. 1.5 in), it was deemed not practical for this type of equipment (i.e. mower bogs down) and is likely not practical on a large scale with a tractor-pulled mower due to uneven ground and the potential for stumps or other obstructions to damage equipment.

Herbicide plots and the regrowth in combination plots were treated on the 11th of June. A two percent solution of Glyphosate (Roundup® Concentate, 18% glyphosate formulation, Monsanto Company, St. Louis, MO) was applied by a hand sprayer. The solution was not applied to the plants to the point of runoff, as directed by most instructions for proper spot herbicide applications. The intent was to simulate herbicide application by commercial application equipment, so broad sweeping motions were used to apply the solution with as little overlap as possible.

All plots, except for the full control, were seeded with a low diversity (21 species) native seed mix appropriate for the site and of local ecotype (Table 2) (sourced from Prairie Moon Nursery, near Winona, MN, and Ion Exchange Nursery, near Marquette, IA). Species were chosen based on presence and abundance in local sand prairie remnants (Henderson, 1995; pers. obs.), life history (annual vs. perennial), photosynthetic pathway (C3 vs. C4) and taxonomic family group.

No-till seed drills are frequently used for seeding into sod. However, it was not practical in this case due to the small size of the plots. Broadcast seeding has been employed successfully for many plantings and was the seeding technique utilized for this experiment. Seeds were hand scattered evenly across each plot and then the soil and/or vegetation was raked with a metal-tined leaf rake to knock seeds off any remaining vegetation and help ensure good seed-soil contact. Plots were seeded at a rate of 450 – 540 seeds per square meter (50 – 60 seeds/ft^2).

Repeat treatments were conducted in June of 2008; mowing and herbicide on June 15th and burning on June 16th. Temperatures remained cool in the spring, with snow accumulating as late as the 26th of April. The late spring delayed smooth brome development and pushed back treatment dates.

Vegetation Sampling

Post-treatment sampling occurred six times during the study period: September of 2007, April, July and September of 2008, and July and September of 2009. Sampling in both summer and fall allowed for the identification of the greatest number of species present within the study plots. The summer sampling also occurred following the time of greatest biomass accumulation by smooth brome.

Foliar cover. Identical sampling methods were used for smooth brome, seeded species, and volunteer species. The center $1m^2$ of each plot was sampled for both stem and foliar cover of each species present using a modified Daubenmire scale, as outlined in the long term environmental monitoring protocol for prairie areas at Effigy Mounds National Monument (Heartland Network, 2004). Categories include: less than 1% (1), 1-5% (2), 5-25% (3), 25-50% (4), 50-75% (5), 75-95% (6) and 95-100% (7)). Foliar cover reported was absolute cover, not relative cover. Foliar cover estimates reported here are for green tissues only; senesced material was not included.

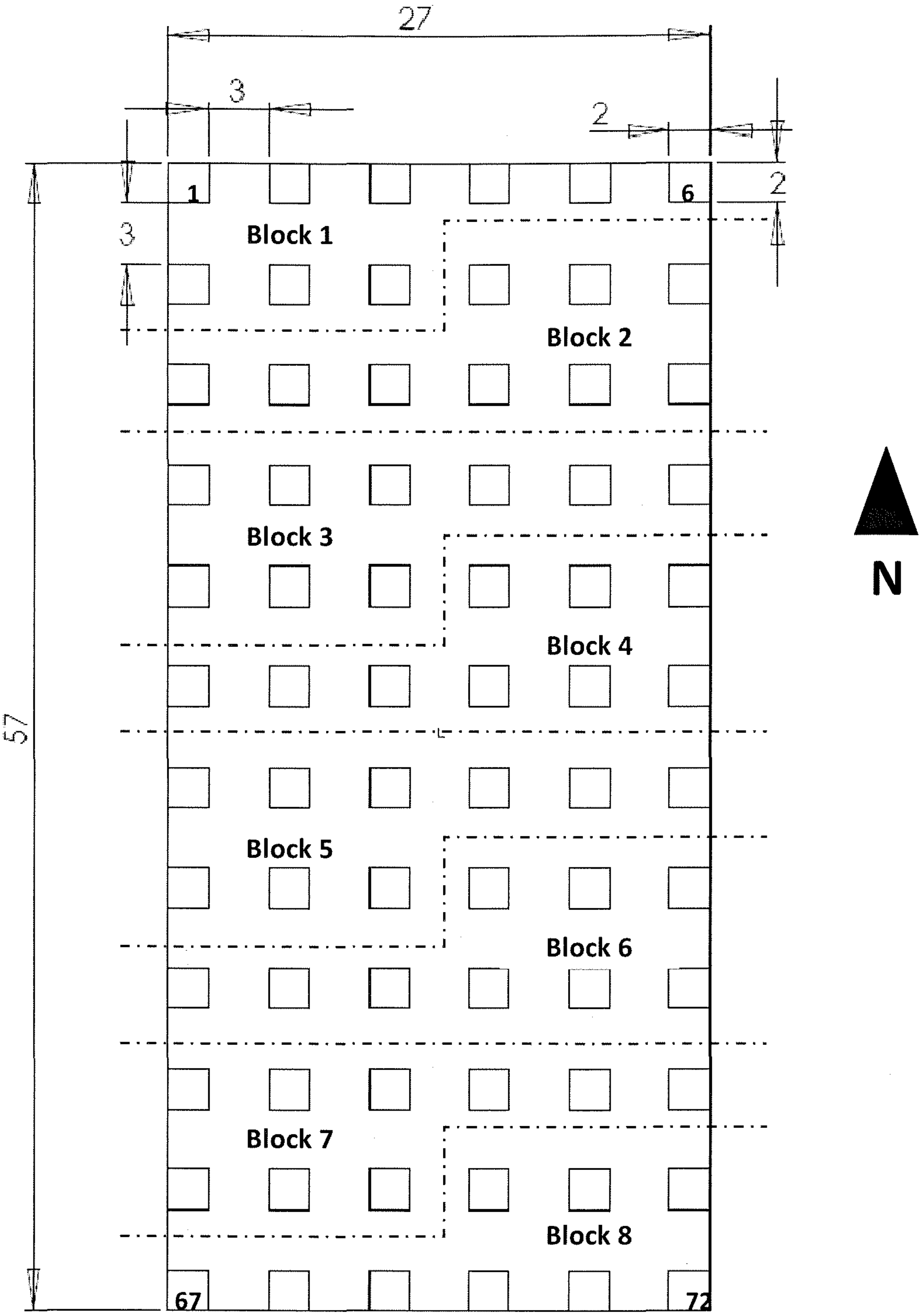

Figure 1. Randomized block design of the experimental plots. All measurements are in meters; plot numbers are given in the four corner plots. Blocks run horizontally across the slope where plots were located; the exact elevation of each plot was also determined using a Total Station.

Table 1. Treatments and timeline of activities. Treatments indicated with a 1 are conducted only once during the study period. Treatments indicated with a 2 are conducted twice during the study period on an annual basis.

	Activity Timeline		
Plot Treatment	Year 1	Year 2	Year 3
Control	No treatment No seeding Sample fall	No treatment Sample Summer & Fall	No Treatment Sample Summer & Fall
Seed Only Control	No treatment Seed Sample Fall	No treatment Sample Summer & Fall	No Treatment Sample Summer & Fall
Burn 1	Treat Seed Sample Fall	No treatment Sample Summer & Fall	No Treatment Sample Summer & Fall
Burn 2	Treat Seed Sample Fall	Treat Sample Summer & Fall	No Treatment Sample Summer & Fall
Mow 1	Treat Seed Sample Fall	No Treatment Sample Summer & Fall	No Treatment Sample Summer & Fall
Mow 2	Treat Seed Sample Fall	Treat Sample Summer & Fall	No Treatment Sample Summer & Fall
Herbicide 1	Treat Seed Sample Fall	No Treatment Sample Summer & Fall	No Treatment Sample Summer & Fall
Herbicide 2	Treat Seed Sample Fall	Treat Sample Summer & Fall	No Treatment Sample Summer & Fall
Combination (burn + herbicide)	Treat Seed Sample Fall	No Treatment Sample Summer & Fall	No Treatment Sample Summer & Fall

Table 2. Native sand prairie species included in seed mix. All plots, except the 8 full control plots, were seeded following treatments. Nomenclature follows Gleason and Cronquist, 1989.

Scientific Name	Common Name	Family	Life History
Graminoids			
Andropogon gerardii	Big bluestem	Poaceae	Perennial
Bouteloua curtipendula	Side oats grama	Poaceae	Perennial
Carex brevior	Plains oval sedge	Cyperaceae	Perennial
Dichanthelium leibergii	Scribner's panic grass	Poaceae	Perennial
Elymus canadensis	Canada wild rye	Poaceae	Perennial
Koeleria macrantha	June grass	Poaceae	Perennial
Paspalum setaceum	Hairy lens grass	Poaceae	Perennial
Schizachyrium scoparium	Little blue stem	Poaceae	Perennial
Sorghastrum nutans	Indian grass	Poaceae	Perennial
Forbs			
Chamaecrista fasciculata	Partridge pea	Caesalpiniaceae	Annual
Froelichia floridana	Cottonweed	Amaranthaceae	Annual
Monarda punctata	Spotted bee balm	Lamiaceae	Biennial
Allium cernuum	Nodding prairie onion	Liliaceae	Perennial
Asclepias amplexicaulis	Sand milkweed	Asclepiadaceae	Perennial
Aster ericoides	Heath aster	Asteraceae	Perennial
Dalea purpurea	Purple prairie clover	Fabaceae	Perennial
Geum triflorum	Prairie smoke	Rosaceae	Perennial
Helianthus occidentalis	Western sunflower	Asteraceae	Perennial
Liatris aspera	Rough blazing star	Asteraceae	Perennial
Sisyrinchium campestre	Blue eyed grass	Iridaceae	Perennial
Viola pedatifida	Prairie violet	Violaceae	Perennial

Species frequency. Species frequency was sampled using a point frame method (Fig. 2; Mueller-Dombois and Ellenberg, 1974). Sampling began in July of 2008, during the first summer sampling time point and a full year after the application of the initial treatments. Again, the center $1m^2$ of each plot was sampled. Forty-nine equally spaced points (7 x 7 grid, Fig. 2) were located within the quadrat. Canopy species were noted by recording the identity of the first plant encountered as the point rod was lowered into the plot. The identity of the plant stem rooted closest to the point, within a radius of 2.5 cm was recorded. If no stem fit these criteria, no species was recorded for that location.

Physical Conditions and Resource Availability

Unless otherwise noted, condition and resource availability sampling occurred during vegetation sampling.

Ground cover and litter depth. The general ground cover condition, bare soil or litter present, was estimated with the same Daubenmire method used for measuring vegetative cover. Ground cover was also noted at each point frame sampling point, but litter depth was measured at 8 evenly distributed subsample points (see Fig. 2) to the nearest 1/10 of an inch (Heartland Network, 2004) and averaged for each plot.

Light availability. Available photosynthetically active radiation (PAR) near the soil surface was measured in the center of each plot with a hand-held quantum sensor (LI-COR Environmental, Lincoln, Nebraska). The height of the collection sensor was 2.5cm. Plant litter was carefully moved to allow the sensor to rest directly on the soil surface. When a canopy was present, care was taken to place the sensor without disrupting the arrangement of leaves. PAR measurements were generally collected under uniformly clear or overcast skies and standardized as a percent of available light by dividing each measurement by the highest value recorded on that sample date.

Soil Moisture. Watermark soil moisture sensors (Irrometer Company, Inc.; Riverside CA) were installed at 10cm and 30cm depths in two plots per treatment, for a total of 18 sensors. Plots with moisture meters were stratified across the elevation gradient of the study area. Soil cores were obtained from the 0.5m buffer area of each plot at the same time the first meter readings took place. Soil samples were placed in plastic bags, transported to the lab and analyzed for gravimetric water content to calibrate the meter readings. Calibration samples were taken several additional times during this study. Samples were sieved through 2mm mesh to homogenize the soil and remove any pebbles or root fragments. A subsample was weighed, dried at 100°C, and then re-weighed to determine gravimetric water content. Meter readings were obtained throughout the study period as time permitted.

Data Analysis

All analyses were conducted using JMP® 7 (SAS Institute Inc., Cary, NC). Data were transformed as necessary to improve normality and equality of variances, and analyzed separately for each sample time point. Model III two-factor ANOVAs were used to evaluate treatment and block effects on smooth brome cover, prairie plant establishment, physical conditions and resource availability (Zar, 1999). When treatment was significant, means were compared using Tukey-Kramer post-hoc tests. When block was significant, linear regression was used to evaluate the effect of plot elevation on the dependent variable in question.

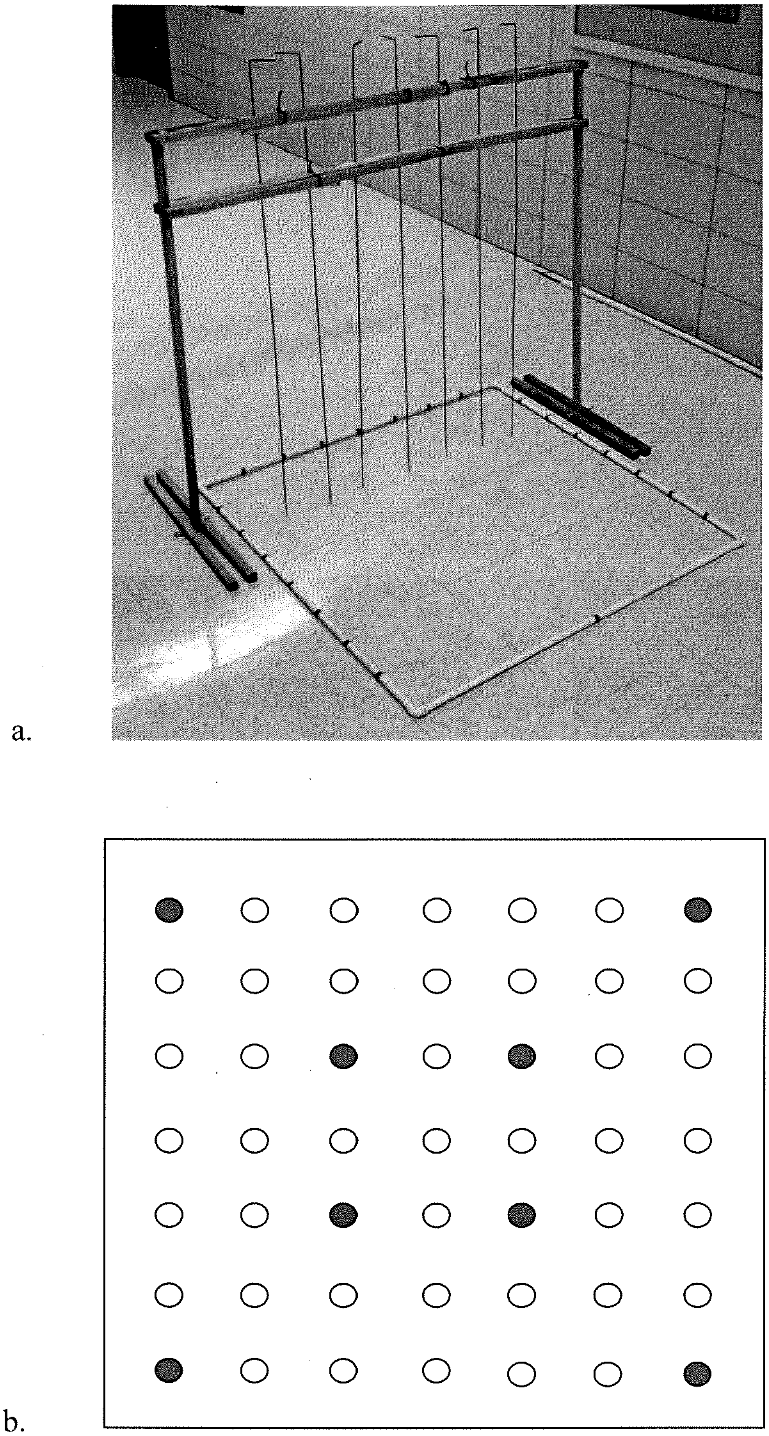

Figure 2. Point frame construction (a) and sampling layout (b). At each sample point the identity of the canopy individual (first species touched by bottom of pin) and the plant rooted closest to where the pin hit the ground (within 2.5 cm) was recorded. Filled circles indicate locations where canopy height and litter depth measurements were taken.

Figure 3. View of the experimental plots at the Mississippi Valley Conservancy's New Amsterdam Grasslands site, near Holmen, WI. Prior to plot establishment, the site was dominated by a uniform cover of smooth brome. Plots were 2m on a side and separated by a 3m mowed buffer. Photo was taken from the southwest corner of the experimental array, facing northeast; plot 67 is in the foreground. Facing upslope, Block 1 is at the top and Block 8 is at the bottom.

Results

Response of Smooth Brome

Prior to initial treatment, foliar cover was similar across experimental plots (Table 3). Significant differences in living smooth brome cover were observed the first fall following initial treatment (Table 3, Fig. 4). Full control and seed control plots had approximately 40% average foliar cover of smooth brome, while smooth brome cover was half as dense in burned and mowed plots. No brome cover existed in the herbicide and combination plots at the fall sample date following initial treatments.

The following year (2008), a more complex pattern arose following the application of repeat treatments (Table 3, Fig. 4). Average smooth brome foliar cover in the controls was again approximately 40%. Plots that had been mowed once the previous year had significantly lower smooth brome foliar cover (26%) than controls, and significantly higher brome cover than the repeatedly burned and mowed plots. The foliar cover in plots burned once the previous year (16%) was intermediate between that in the once-mowed and the repeatedly burned or mowed treatment plots. Smooth brome remained absent from the herbicide and combination plots, significantly lower than the cover found in all other treatments.

During the third year of the experiment (summer 2009) no additional treatments were applied. Two years after initial treatment and one year after the application of repeat treatments, smooth brome foliar cover had recovered to control levels in the once-mowed plots (Table 3, Fig. 4). Smooth brome foliar cover in repeat mow and burn plots remained significantly less than controls (20.6% and 23.4%, respectively). The average smooth

Table 3. One-way ANOVA results for treatment effects on smooth brome cover and stem density, seeded species cover, species richness, and seeded species richness. * Indicates significance at the $\alpha = 0.05$ level.

		Block			Treatment		
Variable	Time	df	F	p	df	F	p
Brome Cover							
	Spring Year 1	7, 56	5.00	< 0.0002*	8, 56	1.69	> 0.12
	Fall Year 1	7, 56	1.05	> 0.40	8, 56	37.20	< 0.0001*
	Summer Year 2	7, 56	1.99	> 0.07	8, 56	41.89	< 0.0001*
	Summer Year 3	7, 56	1.66	> 0.14	8, 56	29.47	< 0.0001*
Brome Stem Density							
	Summer Year 2	7, 56	1.79	> 0.11	8, 56	97.65	< 0.0001*
	Summer Year 3	7, 56	0.76	> 0.63	8, 56	62.72	< 0.0001*
Average Foliar Cover, Seeded Species							
	Year 3	7, 56	0.93	> 0.49	8, 56	13.74	< 0.0001*
Mean Species Richness							
	Year 3	7, 56	1.31	> 0.26	8, 56	32.95	< 0.0001*
Mean Seeded Species Richness							
	Year 3	7, 56	0.64	> 0.72	8, 56	21.16	< 0.0001*

Table 4. One-way ANOVA results for treatment effects on litter depth, gravimetric water content, and available PAR. Block effect was not tested for with the gravimetric water data due to uneven numbers among blocks. * Indicates significance at the $\alpha = 0.05$ level.

		Block			Treatment		
Variable	Time	df	F	p	df	F	p
Mean Litter Depth							
	Summer Year 2	7, 56	2.95	< 0.011*	8, 56	54.01	< 0.0001*
	Summer Year 3	7, 56	3.57	< 0.003*	8, 56	61.15	< 0.0001*
Gravimetric Water Content							
	10 cm Fall Year 1		n/a		8, 17	1.36	> 0.33
	30 cm Fall Year 1		n/a		8, 17	1.57	> 0.26
	10 cm Summer Year 3		n/a		8, 17	1.14	> 0.42
	30 cm Summer Year 3		n/a		8, 17	0.98	> 0.51
% Available PAR							
	Summer Year 1	7, 56	3.10	< 0.01*	8, 56	13.31	< 0.0001*
	Fall Year 1	7, 56	1.29	> 0.27	8, 56	9.23	< 0.0001*
	Spring Year 2	7, 56	1.92	> 0.08	8, 56	16.49	< 0.0001*
	Summer Year 2	7, 56	2.07	> 0.06	8, 56	14.60	< 0.0001*
	Summer Year 3	7, 56	2.79	< 0.02*	8, 56	3.47	< 0.0026*
	Fall Year 3	7, 56	2.62	< 0.02*	8, 56	9.45	< 0.0001*

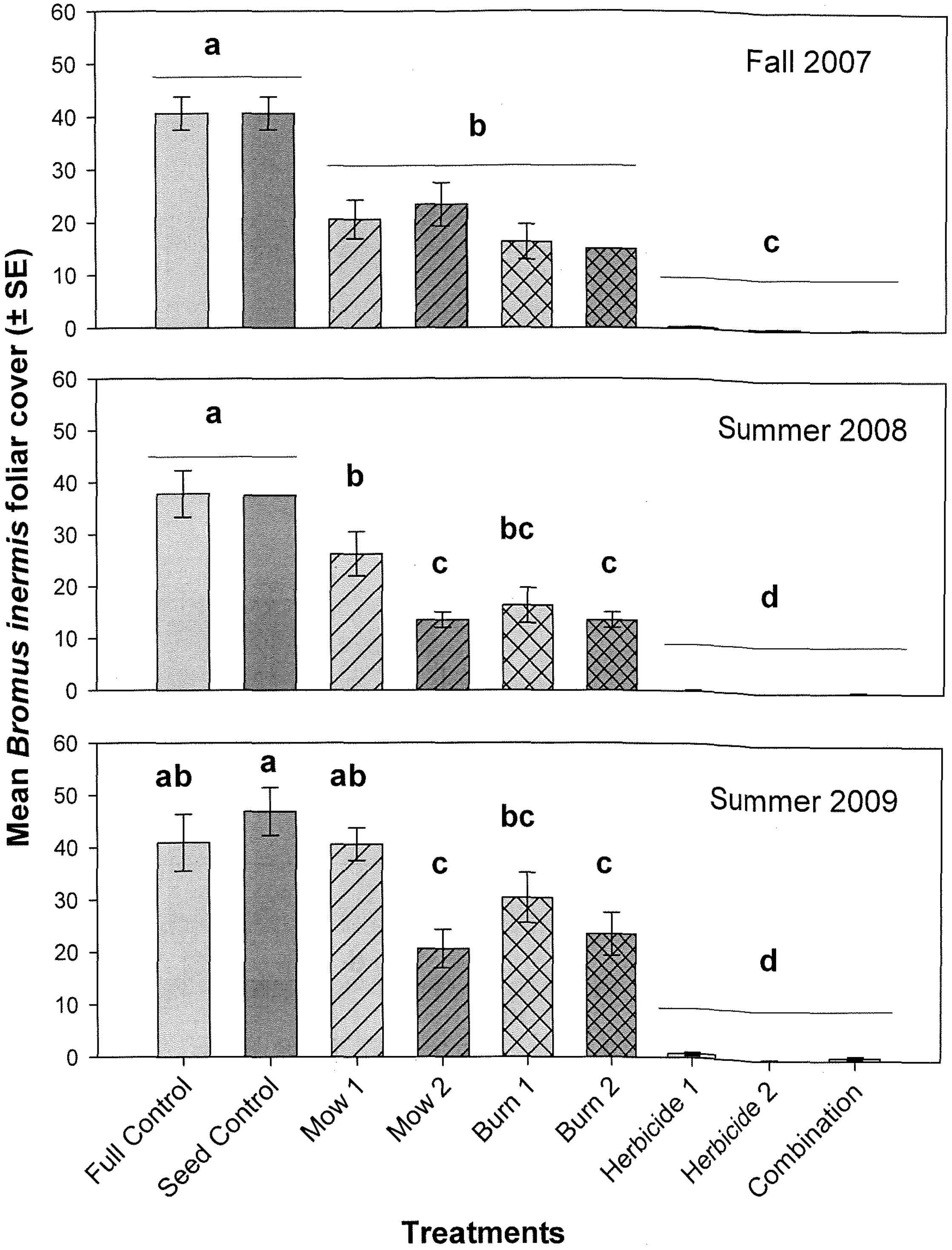

Figure 4. Smooth brome foliar cover following treatment application. Median category values were used for calculating means. Treatments not sharing letters are significantly different from one another in post-hoc tests. Error bars indicate standard error.

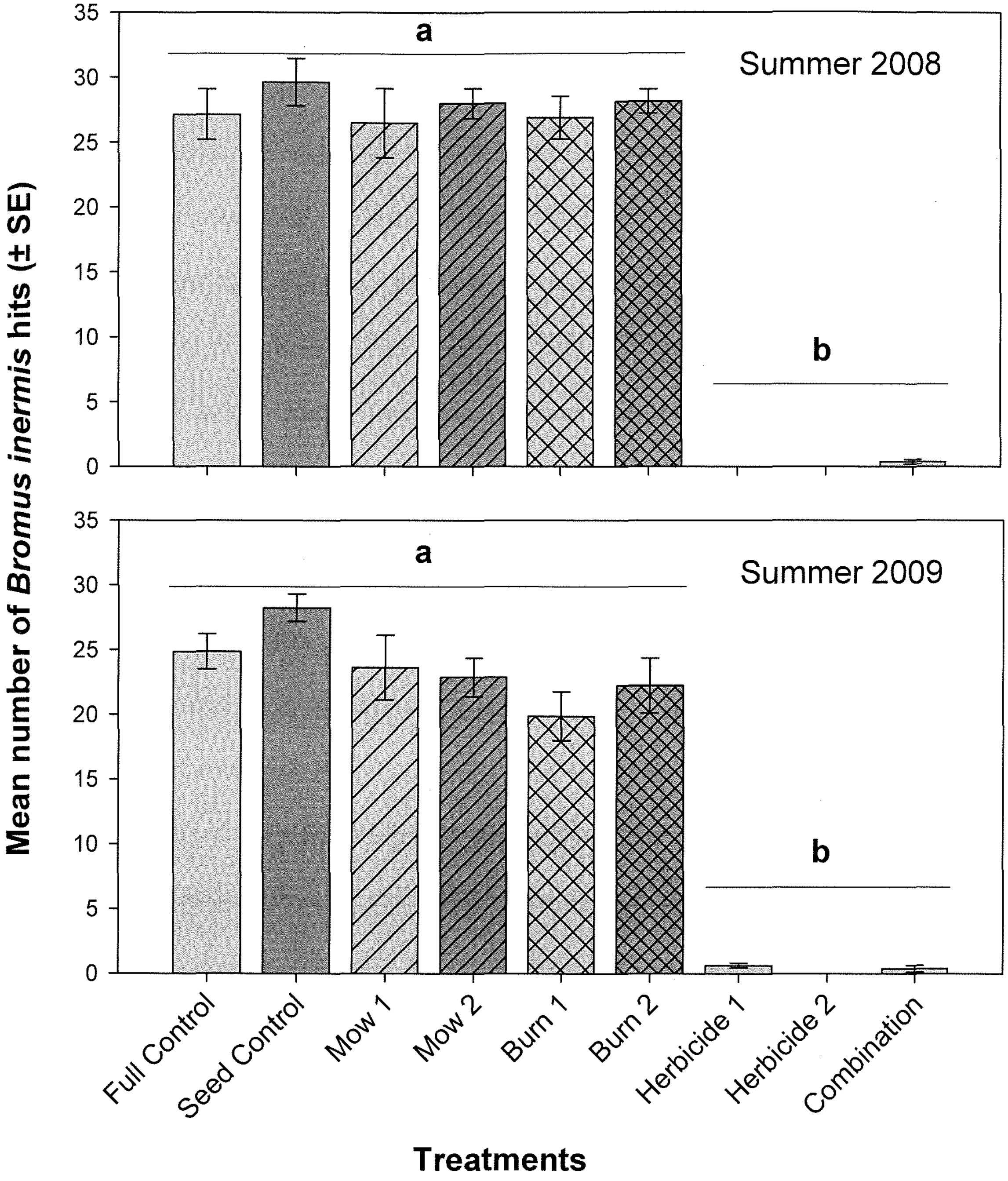

Figure 5. Smooth brome stem density following treatment application. Values reported here are the mean number of times smooth brome was encountered at a sampling point. Forty-nine sampling points were located within a $1m^2$ area. Treatments not sharing letters are significantly different from one another in post-hoc tests. Error bars indicate standard error.

brome cover in plots burned only during the first year of the experiment was again intermediate (30.4%) and not significantly different from either group. Smooth brome foliar cover in combination and herbicide treatments plots remained near zero, significantly lower than that found in all other treatments.

Point frame data revealed a different pattern of brome responses to restoration treatments. In both the summer 2008 and 2009 data, only the herbicide and combination treatments significantly reduced brome stem density when compared to controls (Table 3, Fig. 5).

Response of Seeded Species

At the end of the third year of the experiment (2009) both seeded species cover and richness remained very low across all treatments; seeded species comprised less than 10% foliar cover in any one plot (Fig. 6). Only about half the species included in the seed mix were detected in the plots at any time during the course of the experiment (Table 5). Single herbicide and combination treatments were the only treatments significantly different from controls in either seeded species foliar cover or richness (Table 3, Fig. 6, Fig. 7). However, seeded species foliar cover was significantly greater in combination plots than in single herbicide plots (7% and 4%, respectively).

All treatments, with the exception of the single mowing treatment, significantly increased total species diversity when compared to controls (Table 3, Fig.7). In addition to the expected presence of seeded species, native and exotic volunteer species were also recorded in treatments plots. Total species richness patterns are similar to seeded species richness patterns; combination and single herbicide treatments had the greatest total species diversity (Fig. 7).

Physical Conditions and Resource Availability

Litter. Significant differences in litter depth were observed as a result of treatment type (Table 4, Fig. 8). All treatments significantly reduced litter depth when compared to controls (approx. 3.18 cm) (Fig. 8); however, the shallowest litter depths occurred in burned plots, (including combination plots, ≤ 0.64 cm) (Fig. 8).

Soil Moisture. Due to the nature of the site's soils, it was impossible to reliably calibrate the moisture meters. However, gravimetric water content from the soil samples obtained for calibration was available for analysis. Treatment did not affect soil moisture at either the 10cm or 30cm depth (Table 4). Linear regression shows that soil moisture significantly increased with decreasing elevation at both depths in fall 2007 (10cm $R^2 = 0.23$, $F_{1,17} = 4.80$, $P < 0.05$; 30cm $R^2 = 0.25$, $F_{1,17} = 5.41$, $P < 0.04$; $\alpha = 0.05$; Fig. 9), but the relationship was only significant at the 10cm depth in summer 2009 (10cm $R^2 = 0.23$, $F_{1,17} = 4.82$, $P < 0.05$; 30cm $R^2 = 0.18$, $F_{1,17} = 3.42$, $P > 0.08$; $\alpha = 0.05$; Fig. 9).

Light Availability. Soil surface PAR availability varied greatly, and significantly, among treatments (Table 4, Fig. 10), although post-hoc tests did not reveal any clear patterns. Although measurements were to be taken on uniformly clear or overcast days, variable cloud cover occasionally occurred on available samplings dates, introducing additional variability into analyses. In general, PAR availability was greatest in combination plots initially (approx. 80%, fall 2007), decreasing as seeded species established (approx. 60%, fall 2008) (Fig. 10). Herbicide plots initially experienced moderate PAR availability (approx. 35-40%, fall 2007), likely due to standing dead material (personal observation). PAR later increased once standing dead material was matted down (approx. 80%, spring 2008) (Fig. 10). Burning and mowing treatments maintained intermediate PAR levels that appeared to decrease and become more similar to controls by the fall of 2009 (Fig. 10).

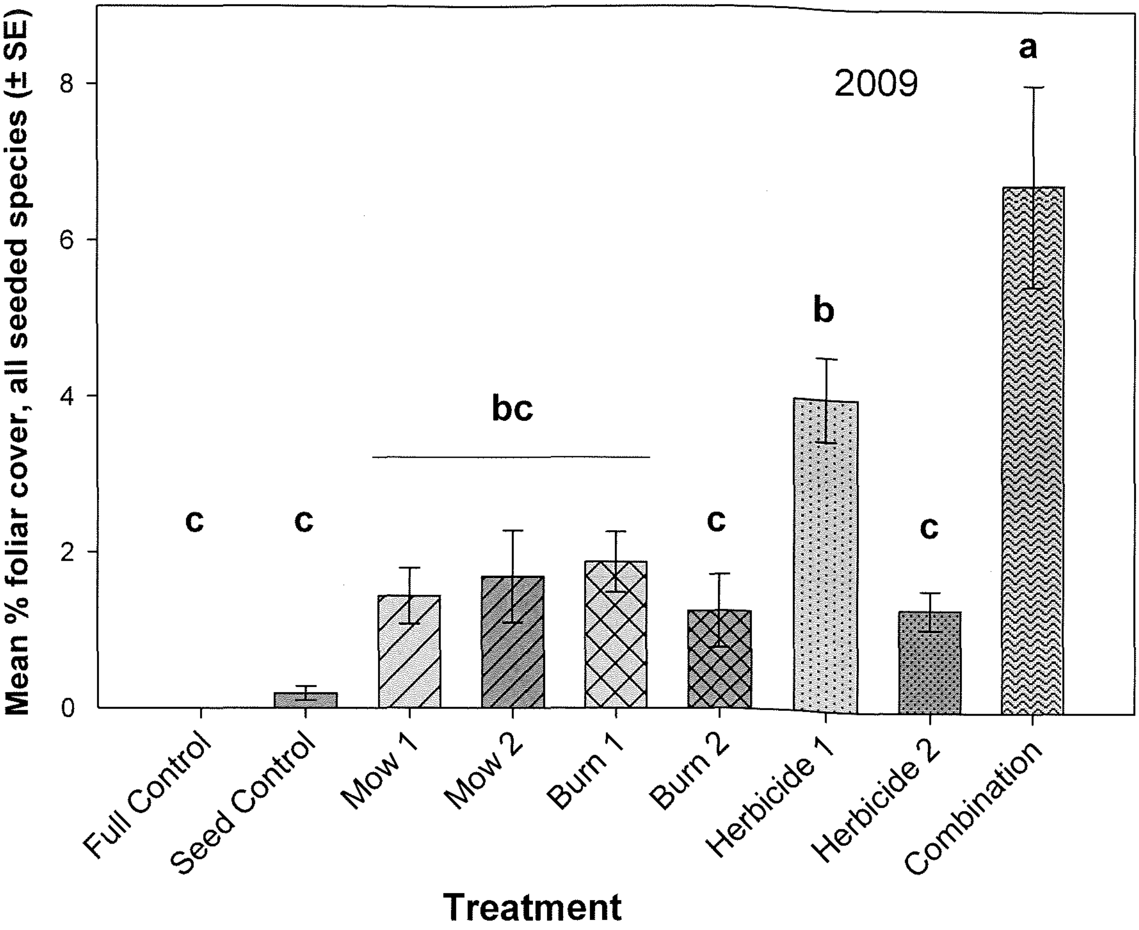

Figure 6. Seeded species cover in experimental plots. Foliar cover shown here was summed and averaged across both the summer and fall sampling periods. Treatments not sharing letters are significantly different from one another in post-hoc tests. Error bars indicate standard error.

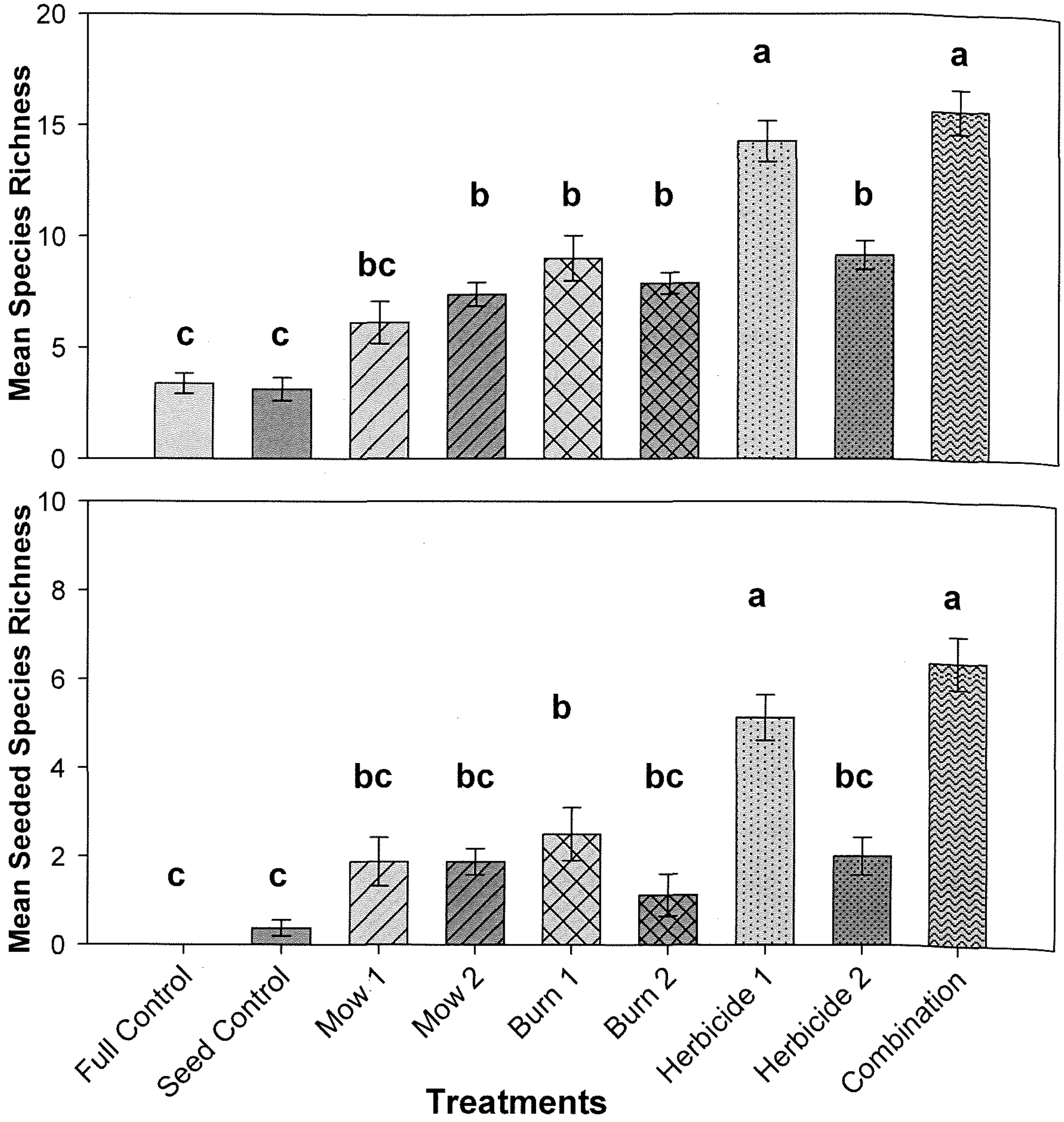

Figure 7. Mean species richness of all (top panel) and seeded (bottom panel) species found in experimental plots. Total mean species richness and mean seeded species richness were calculated by tallying all species present within the plots during the 2009 summer and fall sampling times. Species present during both sampling periods were only counted once. Treatments not sharing letters are significantly different from one another in post-hoc tests. Error bars indicate standard error.

Table 5. Seeded species that had established in experimental plots by the third year of the study (2009). Nomenclature follows Gleason and Cronquist, 1991.

Scientific Name	Common Name	Family	Life History
Graminoids			
Bouteloua curtipendula	Side oats grama	Poaceae	Perennial
Dichanthelium leibergii	Scribner's panic grass	Poaceae	Perennial
Elymus canadensis	Canada wild rye	Poaceae	Perennial
Koeleria macrantha	June grass	Poaceae	Perennial
Schizachyrium scoparium	Little blue stem	Poaceae	Perennial
Forbs			
Chamaecrista fasciculata	Partridge pea	Caesalpiniaceae	Annual
Monarda punctata	Spotted bee balm	Lamiaceae	Biennial
Allium cernuum	Nodding prairie onion	Liliaceae	Perennial
Aster ericoides	Heath aster	Asteraceae	Perennial
Dalea purpurea	Purple prairie clover	Fabaceae	Perennial
Helianthus occidentalis	Western sunflower	Asteraceae	Perennial
Sisyrinchium campestre	Blue eyed grass	Iridaceae	Perennial

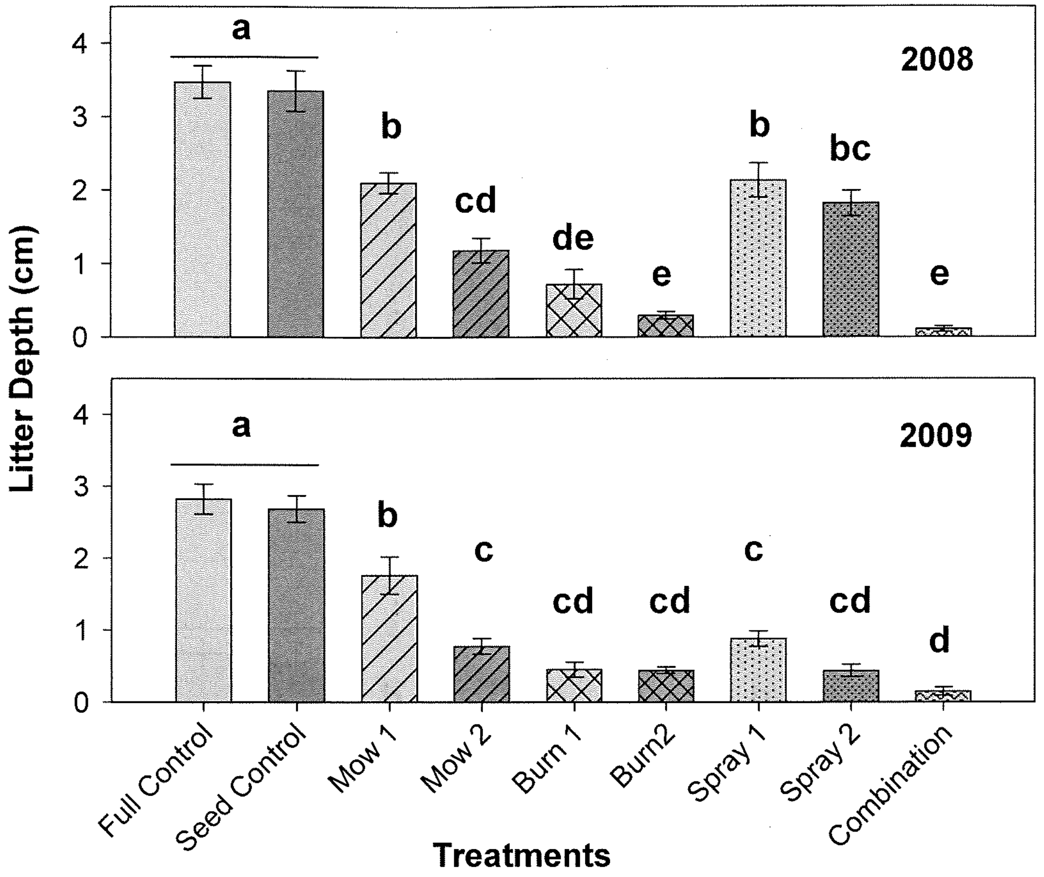

Figure 8. Litter depth in experimental plots during the summers of 2008 (top panel) and 2009 (bottom panel). Litter depth measurements were obtained at eight of the 49 sampling points per plot and averaged. Treatments not sharing letters are significantly different from one another in post-hoc tests. Error bars indicate standard error.

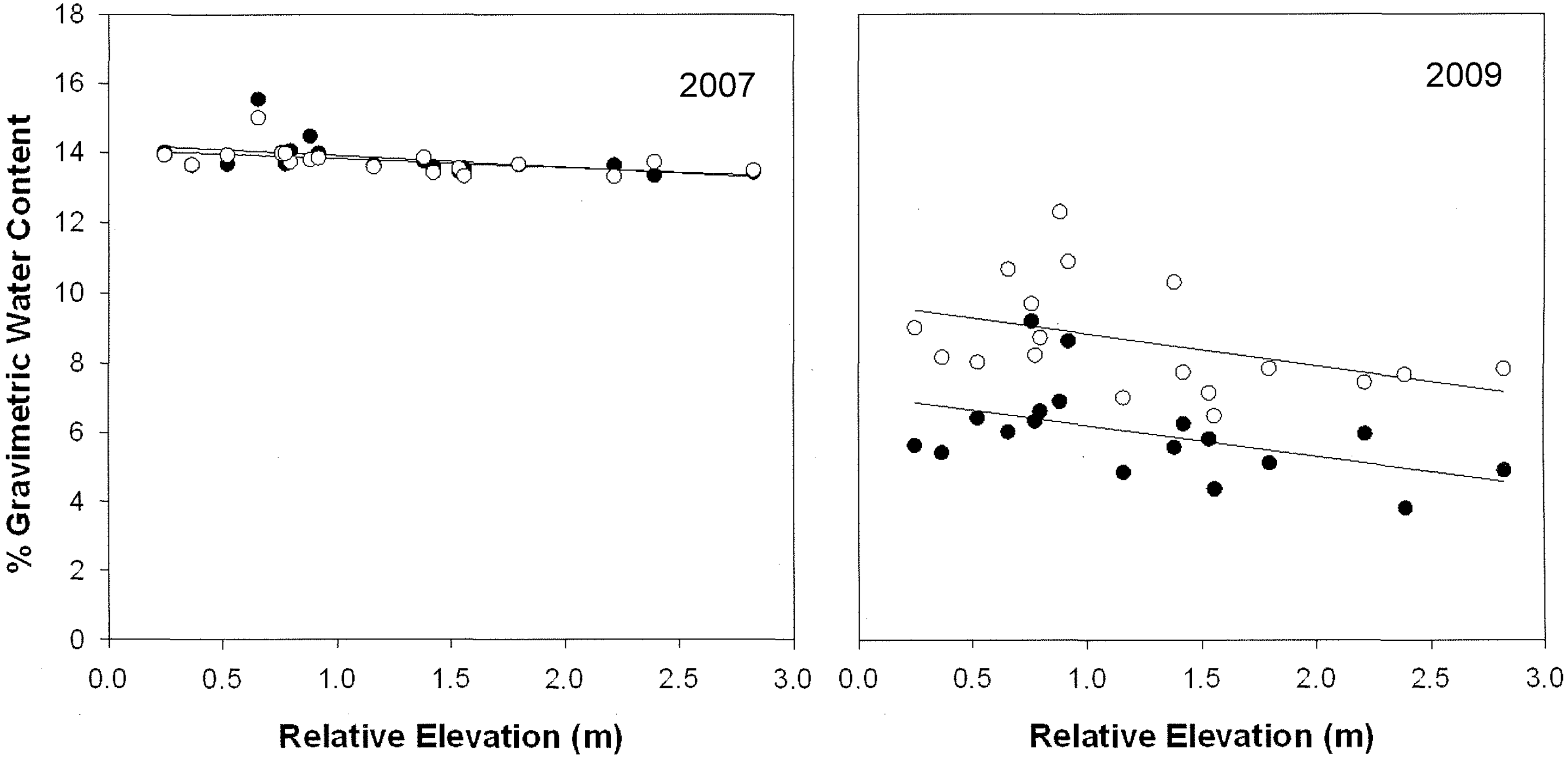

Figure 9. Gravimetric water content in a subset of experimental plots across the site's elevation gradient in Fall 2007 (left panel) and Summer 2009 (right panel). Soil samples from two depths, 10cm (black circles) and 30cm (white circles), were analyzed for each plot included in the subsample. Soil moisture significantly increased with decreasing elevation at both depths in Fall 2007, but the relationship was only significant at the 10cm depth in summer 2009. See text for regression statistics.

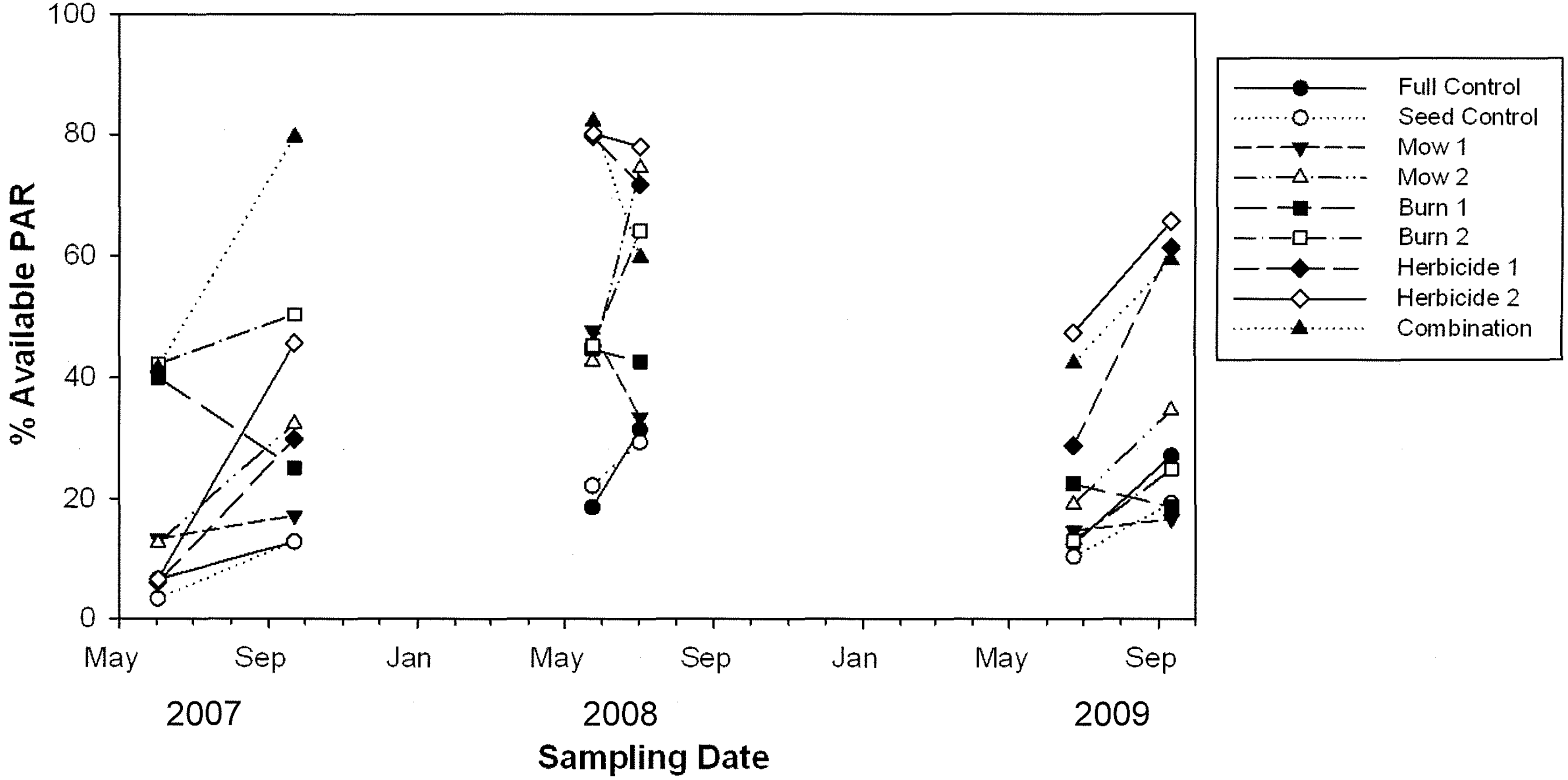

Figure 10. Percent available PAR near the soil surface. PAR measurements on each sampling date were divided by the highest measurement on that date. Sampling dates occurred before and after treatment application in 2007 and 2008; however, initial burning treatments had just occurred prior to spring 2007 sampling. Significant differences exist among treatments at each sampling date (see Table 4); however, post-hoc differences among treatments were complex.

Discussion

Side-by-side comparisons of multiple treatments are still rare in restoration ecology, making it difficult to know if contrasting results are driven by treatment, site or natural climatic differences (Weiher, 2007). This experiment was designed to compare multiple treatment methods, under real-world restoration conditions, and to generate concrete suggestions for restoration practitioners. It seems fitting, then, to open the discussion with several of the clearest patterns in the data presented above that relate directly to the control of smooth brome in a restoration context.

First, herbicide applications (whether a single or repeated sprayings, alone or in combination with fire) were extremely successful at reducing the cover of smooth brome and, indeed, appear to have eliminated resident plants from those plots. Other control efforts (mowing and burning) reduced smooth brome cover to varying degrees, but failed to reduce stem densities. Whether the observed decrease in smooth brome productivity is enough to open a window for native species to become sufficiently established and competitive remains to been seen; the three year period this experiment encompasses is the very beginning of the restoration process. More time is needed to fully assess success vs. failure.

Second, seeding alone was not enough to re-establish sand prairie species. Restoration treatments that decrease the competitive dominance of smooth brome are required, agreeing with Wilson and Gerry's (1995) work concluding a neighbor-free site is important for seedling establishment. The seed control plots, in which seed additions were performed in the absence of smooth brome control efforts, were indistinguishable from full controls at all time points, both in terms of brome cover and of prairie plant establishment. Litter removal was also important for seeded species establishment. Seeded species cover was greatest in combination plots, where both smooth brome and litter were absent. Seeded species richness did not differ between single herbicide and combination treatments, but foliar cover of seeded species was significantly greater in combination plots, suggesting the litter present in herbicide plots delayed or suppressed seedling establishment (Jutila and Grace, 2002; Maret and Wilson, 2005).

Lastly, repeated treatments may not provide the presumed advantage over single treatments. Except for repeated mowing, the effects of repeated burning and herbicide treatments on smooth brome were not different from single treatments. Seeded species establishment appeared to be reduced in repeatedly burned and herbicided plots when compared to once-burned or once-herbicided plots. As of the third year of the experiment, both seeded species richness and foliar cover in repeatedly burned and herbicided plots were not different from controls. Repeated broadcast herbicide application is not recommended on a large scale, but can be useful as a spot spray treatment if localized populations of smooth brome or other problem plants remain. Conversely, repeatedly mowing significantly reduced smooth brome cover when compared to once-mowed plots. However, all measures of prairie plant establishment were very similar between the two mowing treatments.

Management Implications

Based on the results of this experiment, combining prescribed fire and herbicide, in this case a 2% solution of Glyphosate, was by far the most effective treatment for controlling smooth brome and creating the conditions conducive to the establishment of sand prairie species on the site. Managers do use fire in combination with herbicide, but presumably to increase the efficiency of herbicide application by removing litter and standing dead stems. Herbicide alone was just as effective as the combination treatment for removing smooth brome; therefore, burning did not significantly contribute to the combination treatment's effect on smooth brome. However, the combination of neighbor removal (via herbicide) and litter removal (via burning) created the optimal conditions for relatively rapid sand prairie species establishment. Instead of focusing solely on the success or failure to remove an unwanted species, managers should also take into consideration the effect management actions may have on other aspects of a restoration, such as seeded species establishment or the recovery of resident species populations.

Cookie-cutter, or one-size-fits-all, management recommendations are not practical (Brudvig *et al.*, 2007). Although the combination treatment was the most successful, it may not be the preferred method for achieving restoration goals at a site. Either component of the combination treatment may not be management tools available to some managers or practical on other sites. If fire is not an option, grazing or haying followed by herbicide may be the next best option as both actions reduce litter (Knapp *et al.*, 1999; Jutila and Grace, 2002). Burning and mowing were not as successful in this study as the combination and herbicide treatments for controlling smooth brome; however, they are still very useful management tools.

If burning is the treatment of choice, annually repeated burning on nutrient-poor sites may not be worth the time and associated costs. Very limited litter accumulation is available for subsequent burns; therefore fire effects are far less intense than the initial burn. To carry flame into the interiors of the repeat burn plots, all four sides needed to be ignited and no plot managed to burn completely. Observed flame lengths could be described in inches rather than in feet, whereas flame lengths for the initial treatment easily exceeded one foot under very mild conditions. Repeat treatments on richer, mesic sites may be more effective than single treatments as the growth of smooth brome is more vigorous than on sandy sites, such as this one. Waiting for sufficient litter accumulation before re-burning an area is advisable and may give seeded species more time to establish. Sites that have a history of grazing or haying may also see diminished fire effects because of reduced litter accumulation.

If mowing is the preferred treatment, repeated annual mowing after smooth brome tiller elongation at the lowest feasible mower deck setting is recommended to ensure consistent removal of the growing point. Willson and Stubbendieck (1996) suggest 4 cm, whereas some suppressive effect was observed in this study with the blades set to 7.5 cm. It is likely that the mower deck could be set higher as more time elapses between the time plants reach the five leaves stage and the time treatment takes place; the tillers will continue to elongate as the plants move into the boot stage. Treatment effectiveness may or may not be lost, however, as smooth brome replenishes carbohydrate reserves (Willson, 1992). Site by site investigations may be necessary to determine appropriate mower height for the site and therefore appropriate treatment timing. It is unknown whether or not additional mowings per growing season will enhance smooth brome control. Annual spring haying, as a potential alternative, may enhance seeded species establishment through reduction in litter accumulation.

Our study system represents a relatively simple context for restoration. The site is homogenous both in terms of environmental conditions and the dominance of a single invasive species. There are few resident natives to consider in terms of non-target impacts of restoration strategies, and its location and topography make a wide variety of restoration strategies practical. Even so, our results illustrate the complexity of decision-making in a restoration context. Finding the right balance between decreasing brome vigor and the direct harm restoration treatments cause establishing individuals will likely be a key factor in determining restoration success.

Additional study is still necessary. This experiment did not compare the effects of other treatments, such as haying and grazing, or other combinations, such as burning and mowing. Nor did it investigate the differences in spring vs. fall timing of treatment application, which has been discussed in the literature (Sather, 1987). Most importantly, no long-term studies following performance of smooth brome and seeded species under various treatment regimes have been conducted.

Ultimately, how and what treatments are used will depend not only on the efficacy of the treatment, but also on the preserve size and accessibility, management goals, species present, robustness of at-risk populations, human and financial resources, as well as social perception and degree of acceptance. Providing land managers with adequate information and confidence in expected outcome will contribute to sound management decisions and fewer wasted resources.

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