AN ABSTRACT OF THE THESIS OF

Valerie A. Fansler for the degree of Master of Science in Rangeland Ecology and Management presented on November 8, 2007.
Title: Establishing Native Plants in Crested Wheatgrass Stands Using Successional Management.

Abstract approved:

____
Jane M. Mangold Michael M. Borman

Crested wheatgrass (*Agropyron cristatum* (L.) Gaertn.) is a nonindigenous perennial grass that was introduced to North America to improve the condition of degraded rangelands. It has proven to be a successful revegetation species due to its superior ease of establishment, strong competitive ability, and ability to tolerate grazing. However, crested wheatgrass is criticized for its ability to form monotypic stands that result in low plant diversity. The main objective of this study was to determine the effect of crested wheatgrass control methods on native plant establishment using a successional-based approach. I also looked at the effects crested wheatgrass control methods and revegetation had on crested wheatgrass and cheatgrass density and cover, and on soil nitrate, ammonium and water contents. I hypothesized that control methodologies and revegetation would decrease crested wheatgrass density and cover, increase the presence of native species, increase cheatgrass and annual forb density and cover, and initially increase soil nitrate, ammonium and water contents. In 2005, at one site in southeastern Oregon, 10 hectares of an established crested wheatgrass stand was treated with two control methods at two intensities: partial mechanical control (once disked), full mechanical control (twice disked), partial herbicide control (1/4 recommended rate of glyphosate), full herbicide control (full recommended rate of glyphosate), and an undisturbed control. In October 2005, one half of each plot was seeded with 10 native species, representing three different functional groups. These same procedures were repeated again in 2006. In June of 2006 and 2007, the density and cover of crested wheatgrass, cheatgrass, seeded species, and any weedy species phenologically competitive with the seeded species was sampled. In the first year the density of seeded species was: 30.1 plants m^{-2} in the partial mechanical control treatment; 43.9 plants m^{-2} in the full mechanical control treatment; 21.0 plants m^{-2} in the partial chemical control treatment; 22.0 plants m^{-2} in the full chemical control treatment; and 18.2 plants m^{-2} in the undisturbed treatment. By the second year all treatments were similar in seeded species density to the undisturbed treatment at 18.2 plants m^{-2}, suggesting that control strategies did not increase the density of seeded species. Crested wheatgrass density increased and cover increased with the control treatments. Cheatgrass and the annual forb alyssum (*Alyssum alyssoides* (L.)) increased in density and decreased in cover with the control treatments. Soil ammonium concentrations and water content increased the first year following control treatments and decreased in the second year. Soil nitrate concentrations increased the second year following control treatments. I believe that by using a successional approach to management, land managers can direct plant community dynamics to increase the establishment of native species and meet resource agency goals.

Establishing Native Plants in Crested Wheatgrass Stands
Using Successional Management

by

Valerie A. Fansler

A THESIS

submitted to

Oregon State University

In partial fulfillment of
the requirements for the
degree of

Master of Science

Presented November 8, 2007
Commencement June 2008

Master of Science thesis of Valerie A. Fansler presented on November 8, 2007.

APPROVED:

Co-Major Professor, representing Rangeland Ecology and Management

Co-Major Professor, representing Rangeland Ecology and Management

Head of the Department of Rangeland Ecology and Management

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Valerie A. Fansler, Author

ACKNOWLEDGEMENTS

I would first like to give sincere thanks to my major professor Dr. Jane Mangold for her guidance, support, encouragement, and conversation over the past two years. I feel very fortunate to have worked with such an inspirational and kind individual.

I am eternally grateful for the love and support my family has always provided me with. My parents have set wonderful examples for me and have always encouraged me to do my best and follow my dreams. I am especially grateful for Joey, my husband, who has always provided me with unconditional love and support and encouraged me to pursue something I love. Thank you.

I thank the USDA Forest Service Rocky Mountain Research Station for the generous funding for this project. Also, I want to give thanks to the Malheur National Wildlife Preserve for allowing the use of their land for the study. I appreciate the help of the staff at the Eastern Oregon Agricultural Research Station and the use of their facilities. I am grateful to Merilynn Hirsh, Chris Gillespie, Sheila Angell, Gerhart Gareis, Jane Jones, Wendy Bull, and Tori Bull, for their assistance in the countless hours of data collection and entry. A special thanks to Clare Poulsen for his assistance, expertise and knowledge of the technical and mechanical aspects of this project.

In addition, I would like to thank my committee: Dr. Michael Borman, Dr. David Pyke and Dr. James Males for their helpful suggestions and contributions. They were always available to answer questions and keep me on the right track.

Lastly, I would like to thank all of those friends that I made in the Range Department, especially those women who were incredibly supportive and made my graduate experience fun, enjoyable, and memorable. Thanks for being such great friends and confidants.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

CHAPTER 1 – INTRODUCTION

Plant community diversity is a key component within an ecosystem. Plant community diversity is usually desired because of its positive relationship with ecosystem functioning (Kinzig et al. 2002). For example, as diversity of an ecosystem increases, there can be enhanced resource capture and cycling, greater community stability in terms of resilience and resistance to disturbance, and better habitat provided throughout the year for livestock and wildlife (Kinzig et al. 2002). Native plant communities within the arid and semi-arid western United States have been experiencing a decrease in species diversity and richness since European settlement due to land use changes and biological invasions of nonindigenous species (D'Antonio and Vitousek 1992).

Prior to European settlement, rangelands in the western United States were composed of a diverse compilation of native grasses, forbs, and shrubs (Mueggler 1950; Laycock 1967). Rangelands throughout the western United States changed dramatically during the late 1800s and early 1900s with land use changes, increased fire suppression, introduction of nonindigenous species, and overgrazing of the land by livestock, all of which led to widespread degradation of the land. Rangeland management during this time focused primarily on providing forage for livestock. By 1900, the vegetation dynamics of many plant communities in the western United States had been severely altered (Monsen 2004). In 1902, Griffiths noted that the available forage for livestock had decreased significantly from previous levels, the number and occurrence of invasive plants had increased, the soils in many areas were severely compacted, and saline soils made the production of hay crops such as alfalfa difficult. Forsling (1932) described the condition of the land in the western United States as "…a marked depletion in the native plant cover and a consequent erosion of the soil on extensive areas…". The condition of rangelands in the western United States became a great concern of land managers in the early 1900s and thus the focus of rangeland management gradually shifted toward management of the overall ecological health of the land. Today rangeland managers are still being heavily challenged with the remnant destruction of the land caused by past land management practices.

Revegetation is an important component of the restoration of seriously damaged rangelands. In 1913 efforts to revegetate rangelands began with attempts to establish native and introduced plant species onto degraded sites (Monsen 2004). Attempts to establish nonindigenous species such as crested wheatgrass (*Agropyron cristatum* (L.) Gaertn.), Siberian wheatgrass (*Agropyron fragile* (Roth) P. Candargy) and Russian wildrye (*Psathyrostachys juncea* (Fisch.) Nevski) were very successful, however early establishment efforts of native species were not as successful (Monsen 2004). Consequently, most of the rangeland revegetation that occurred in the past has been with nonindigenous species. There is debate, however, over the use of nonindigenous species due to their ability to reduce diversity within a plant community. For example, once crested wheatgrass is established it quickly dominates the seedbank and hinders the recruitment and growth of native species (Marlette and Anderson 1986; Henderson and Naeth 2005). For that reason, the use of native species for rangeland revegetation is now advocated to maintain and restore functioning ecosystems with appropriate habitat for wildlife species such as the sage-grouse and pygmy rabbit. Therefore, the ongoing development of more effective seeding equipment, seeding methods and seedbed preparation has been a major focus of rangeland restoration research.

Another important component of rangeland restoration is the more recently proposed ecologically-based, successional style of management for directing plant community dynamics to promote sustainable rangelands (Sheley et al. 1996; Sheley and Krueger-Mangold 2003; Krueger-Mangold et al. 2006). First outlined by Pickett et al. (1987), a successional approach to management is based on ecological principles that focus on the primary causes of succession, which include site availability, species availability, and species performance. The main goal in successional management is that by manipulating these three causes of succession, land managers can shift plant community dynamics toward desired plant communities, to meet resource agency objectives (Sheley et al. 1996). With this being a more recent management concept, little research has been conducted on the subject, but preliminary evidence suggests it may be useful (Sheley et al. 2006).

It has been a goal of some researchers to determine how to promote and maintain diversity within crested wheatgrass stands (Bakker et al. 1997; Cox and Anderson 2004). Attempts to reintroduce native species into crested wheatgrass stands have been made. Bakker et al. (1997) and Cox and Anderson (2004) have concluded that in order to establish diversity in crested wheatgrass stands:

1) crested wheatgrass plants and propagules must be destroyed or severely damaged; and 2) deliberate introduction of native species is required.

In my study, I attempted to determine the feasibility of establishing native plant species in crested wheatgrass stands in the western United States using a successional-based approach. I sought to determine the effect of crested wheatgrass control methods and revegetation on crested wheatgrass, cheatgrass, and native species density and cover. Additionally, I sought to determine the effects of crested wheatgrass control methods and native plant establishment on soil nitrate, ammonium, and water concentrations. I hypothesized that 1) control methods and revegetation would decrease crested wheatgrass density and cover, 2) control methods and revegetation would increase the establishment of native species, 3) control methods would increase cheatgrass density and cover, and 4) control methods and revegetation would initially increase soil nitrate, ammonium, and water concentrations.

CHAPTER 2 - LITERATURE REVIEW

Introduction

Crested wheatgrass (*Agropyron desertorum* (Fisch. ex Link) J.A. Schultes and *Agropyron cristatum* (L.) Gaertn.) is a perennial bunchgrass native to Eurasia. The first recorded introduction of these species to the United States was in 1898 when N.E. Hansen of the Agricultural Experiment Station of South Dakota brought back five collections of seed from the Valuiki Experiment Station in Volgograd, U.S.S.R. (Rogler and Lorenz 1983). Hansen had been sent by the United States Department of Agriculture (USDA) to Russia and Siberia on a "plant exploration trip" to find dry steppe grass species that would be suitable for cultivation in the United States (Rogler and Lorenz 1983).

The search for suitable cultivars at this time coincided with the severe degradation occurring on range and wild lands across the western United States due to a combination of severe drought and overgrazing. A second introduction of crested wheatgrass seed occurred in 1906 when six collections were imported from the Valuiki Experiment Station to the USDA via the Moscow Botanical Gardens; five of these collections were labeled *A. desertorum* and one was labeled *A. cristatum* (Rogler and Lorenz 1983). These seed collections were then distributed among 15 experiment stations across the western United States where the first plantings of crested wheatgrass occurred. Prior to 1950 all crested wheatgrass was referred to as *A. cristatum*. In 1950 a taxonomic distinction was made between cultivars; thereafter the more commonly seeded "Summit" and "Nordan" cultivars were referred to as standard or desert wheatgrass, *A. desertorum*, and the less common "Fairway" cultivar was referred to as crested wheatgrass, *A. cristatum* (Rogler and Lorenz 1983). For ease of discussion, both species of crested wheatgrass will be jointly referred to as crested wheatgrass (*Agropyron cristatum*).

Although the seeding of crested wheatgrass began in 1906, the widespread seeding of this grass in the United States did not begin until the 1930s Dust Bowl era of the Midwest when there was a crucial need for soil stabilization on abandoned farmlands (Rogler and Lorenz 1983; Pellant and Lysne 2005). Severe drought had led to the abandonment of farms and the subsequent loss of soil due to wind erosion. Massive land rehabilitation efforts resulted as did the onset of federal agencies such as the USDA Soil Conservation Service and legislation such as the Taylor Grazing Act of 1934. In the 1940s and 1950s crested wheatgrass was also seeded in efforts to biologically control the poisonous rangeland weed halogeton (*Halogeton glomeratus* (Bieb.) C.A. Mey), increase forage production for livestock, and to reduce the hazard of wildfires (Pellant and Lysne 2005).

The Success of Crested Wheatgrass

Throughout the 1900s, along with crested wheatgrass, many other nonindigenous perennial bunchgrass species such as Siberian wheatgrass (*Agropyron fragile* (Roth) P. Candargy) and intermediate wheatgrass (*Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey) were introduced to North America from Asia to provide feed for livestock and to aid in the stabilization of heavily eroded land that was a direct result of past rangeland management practices. Due to their superior ease of establishment, strong competitive ability, tolerance of heavy grazing and relative palatability, these introduced species quickly met the management objectives for which they were developed (Rogler and Lorenz 1983). The species that has had the greatest impact on the reestablishment of rangelands, however, is crested wheatgrass (Rogler and Lorenz 1983). Crested wheatgrass has been very successful on range and wild lands in the western United States since its introduction and now occupies more than 5 million hectares, suggesting it is well adapted to the western United States (Rogler and Lorenz 1983).

Crested wheatgrass has historically been the species of choice for rangeland revegetation after disturbances such as overgrazing, floods, erosion, fires and abandoned cropland (Hull and Klomp 1966; Rogler and Lorenz 1983; Krzic et al. 2000). Crested wheatgrass continues to be used today for rangeland rehabilitation and forage production for livestock. Hull and Klomp (1966) and Rogler and Lorenz (1983) listed several reasons for the success of crested wheatgrass: 1) crested wheatgrass can persist for many years (40-50) in very adverse and abusive conditions such as cold temperatures, high elevations, severe drought, and intensive grazing; 2) crested wheatgrass establishes easily in a variety of soil types; 3) crested wheatgrass competes readily with native and invasive species; 4) crested wheatgrass is a prolific seed producer; and 5) crested wheatgrass is relatively resistant to disease.

Crested wheatgrass is also regularly selected as a revegetation species due to its wide commercial availability (Bakker et al. 1997). This species is cheaper and more readily available than native species. In revegetation projects, crested wheatgrass may be favored over native species because many native species do not establish as well in adverse conditions. Native grasses are more difficult and expensive to establish than crested wheatgrass because native grasses require more site preparation (Bakker et al. 1997; Wark et al. 2004). Furthermore, native species tend to be more sensitive to climatic conditions during establishment than crested wheatgrass (Hull and Klomp 1966). Many of the conditions under which crested wheatgrass can establish and persist are not as favorable for native plant establishment (Rogler and Lorenz 1983). Even in the natural habitat of native species, the success rate of the establishment of crested wheatgrass is greater than that of the native plant species because of crested wheatgrass' superior establishment characteristics (Rogler and Lorenz 1983; Marlette and Anderson 1986).

In some regions of the United States and Canada crested wheatgrass has been reported to act as an invasive species and exhibit slow rates of expansion into neighboring native plant communities (Hull and Klomp 1966 and 1967; Pyke 1990; Henderson and Naeth 2005). Contrary to this, some studies indicate that crested wheatgrass is an immobile species (Broersma et al. 2000; Krzic et al. 2000). Due to the phenotypic plasticity of this species, crested wheatgrass can demonstrate both invasive and noninvasive characteristics depending on the specific species (*A. cristatum* or *A. desertorum*), cultivar, and variation in environmental conditions of a specific location.

Crested Wheatgrass and Plant Diversity

Numerous studies indicate that as the cover of nonindigenous species increases, native plant diversity decreases (D'Antonio and Vitousek 1992; Tilman et al. 1996; Christian and Wilson 1999; Mooney and Cleland 2001). Crested wheatgrass is considered a nonindigenous species that often forms monotypic stands which exclude native and invasive plant species, creating low plant diversity (Eckert et al. 1961; Kindschy 1991; Bakker et al. 1997; Henderson and Naeth 2005). Low plant diversity in crested wheatgrass monocultures may be due to improper conditions for germination, the lack of seed of other species, or strong competition between seedlings of crested wheatgrass and other species (Bakker et al. 1997). Over time, crested wheatgrass tends to strongly dominate the seed bank, diminishing the establishment of native species thus leading to a stable stand of crested wheatgrass (Marlette and Anderson 1986; Henderson and Naeth 2005). Native species propagules become extremely limited once crested wheatgrass has been seeded and few safe sites are available for seedling establishment (Marlette and Anderson 1986).

Not only is crested wheatgrass criticized for its characteristic nature of forming monotypic stands that reduce native vegetation, but it is also criticized for limiting habitat diversity for wildlife (Kindschy 1991). Animals such as sage-grouse, pygmy rabbits, sage thrashers and sage sparrows are dependent upon the native grasses, forbs, and shrubs of western North America. For example, the decline of sage-grouse populations has been directly associated with the loss of habitat diversity of native sagebrush rangelands (Johnson and Braun 1999; Crawford et al. 2004). In addition, pygmy rabbit populations have also been in decline due in large part to the degradation of big sagebrush (*Artemisia tridentata* Nutt.) dominated rangelands, which is a critical component of its habitat requirement (Thines et al. 2004).

Regardless of crested wheatgrass' tendency to hinder the development of diverse plant communities, crested wheatgrass has and continues to meet the management objectives of the past and present in relation to stabilizing soils against wind and water erosion and providing forage for livestock. Crested wheatgrass has served its purpose well. However, some land management agencies' objectives have changed. Agencies such as the Bureau of Land Management and the US Fish & Wildlife Service are now being mandated to manage for habitat diversity and to actively restore, maintain, and further enhance habitat conditions (USDI USFWS 2001; USDI BLM 2005). Therefore, the topic of diversity is driving many of the rangeland management decisions made today.

Consequences of Plant Diversity

Plant diversity is a critical component in ecosystems in regards to ecosystem functioning, structure, and dynamics (Tilman 1999; Kinzig et al. 2001). More specifically, species composition is an essential component of ecosystems. Species vary in their specific traits and functions and thus, different species drive different ecological processes that are important to ecosystem functioning, structure, and dynamics (Tilman 1999). Therefore, species composition plays a major role in determining such ecosystem traits as invasibility, stability, productivity, and nutrient cycling (Tilman 1999).

Plant functional group richness is also a very important constituent in ecosystem processes such as nutrient retention, plant productivity, as well as resistance and resilience to disturbance (Hooper and Vitousek 1997; Tilman et al. 1997; Lavorel et al. 1999; Symstad 2000; Diaz and Cabido 2001). Communities with diverse plant functional groups have a greater assortment of mechanisms, both spatially and temporally, for capturing and utilizing resources than do less diverse communities (Symstad 2000; Dukes 2001). Some ecologists believe that ecosystem processes depend more on the range in functional groups within a community, rather than on the total number of species present within a community (Tilman et al. 1997; Diaz and Cabido 2001). For example, some evidence suggests that community resistance to invasion by exotic species largely depends on the specific identity of the functional groups present, rather than exclusively on the number of species present in a community (Lavorel et al. 1999; Diaz and Cabido 2001; Pokorny et al. 2005). Results from a study by Pokorny et al. (2005) advocate that communities which contain species that are similar in function to invasive species may be more successful at resisting invasion than those communities that lack functionally similar species. Therefore, monocultures, including those of crested wheatgrass, might not provide long-term ecosystem sustainability due to their lack of both species composition and functional group diversity.

There is much debate about the relationship between ecosystem diversity and stability. It was first proposed by Elton (1958) that greater species diversity leads to greater ecosystem stability in terms of resilience and resistance to disturbance. There have been arguments against this hypothesis that contend that more complex ecosystems lead to less stability in time and space (May 1972; Stohlgren et al. 1999). However, since Elton (1958) hypothesized that diversity and stability were positively correlated, there has been a commonly held agreement among many ecologists as to its acceptance, yet until recently there was little evidence available to support this hypothesis (Levine and D'Antonio 1999). Dukes (2001), Hector et al. (2001), Kennedy et al. (2002), Henderson and Naeth (2005), Pokorny et al. (2005), and others have concluded that as diversity within an ecosystem increases, the system's ability to resist invasion, or stability, also increases.

Plant diversity has been hypothesized to have a positive impact upon ecosystem productivity (Naeem et al. 1995; Tilman et al. 1996; Tilman and Lehman 2001). The diversity-productivity hypothesis assumes that ecosystem productivity increases with increased diversity because more diverse communities can utilize resources better than less diverse communities (Naeem et al. 1995; Tilman et al. 1996). Therefore, a loss of diversity could negatively impact ecosystem functioning and processes. Another similar hypothesis states that as a result of increased resource capture, more diverse ecosystems experience decreased nutrient losses from leaching (Tilman et al. 1996). These hypotheses, coupled together, are the basis for the diversity-sustainability hypothesis that suggests that plant productivity and nutrient utilization are greatest in communities with higher species diversity (Tilman et al. 1996). Results from Tilman et al. (1996) suggest that plant communities that sustain higher species diversity tend to: 1) exhibit higher levels of production, 2) retain more nutrients, and 3) display higher nutrient utilization by showing a lower loss of soil nitrogen due to leaching. Christian and Wilson (1999) found less available nitrogen, total nitrogen and total carbon in crested wheatgrass monocultures in the Great Plains in comparison to adjacent native mixed-grass prairies. These findings support the hypothesis that a loss of native species diversity can lead to alterations in ecosystem energy flow and nutrient cycling (Naeem et al. 1995; Christian and Wilson 1999).

Crested Wheatgrass Management

Much attention has been paid to diversifying the species composition in crested wheatgrass monocultures as a means to increase soil nitrogen supplies, increase forage protein, improve wildlife habitat, increase plant diversity, and extend the grazing season (Marlette and Anderson 1986; Pendery and Provenza 1987; Bakker et al. 1997). Marlette and Anderson (1986) conducted a study on native species propagule dispersal and establishment in crested wheatgrass stands and determined that without seeding native species, chances for recruitment in crested wheatgrass stands are extremely low. In order to reestablish diversity in crested wheatgrass stands, a deliberate introduction of desired species is required, as well as the control of crested wheatgrass plants and propagules (Marlette and

Anderson 1986; Bakker et al. 1997; Cox and Anderson 2004; Henderson and Naeth 2005).

A study in southwestern Saskatchewan attempted to establish blue grama (*Bouteloua gracilis* (HBK.) Lag) in crested wheatgrass monocultures (Bakker et al. 1997). Blue grama established when it was seeded at a high rate and crested wheatgrass was controlled by chemical spraying. Crested wheatgrass density was much lower in plots that were tilled and broadcast seeded compared to drilled or unseeded plots due to an increased survivorship of blue grama seedlings. Most importantly, establishment of additional species in crested wheatgrass monocultures was possible only when the desired species were seeded and crested wheatgrass growth was controlled (Bakker et al. 1997).

Crested wheatgrass has been proposed as an aid in diversifying invasive annual grass-dominated rangelands by means of "assisted succession" (Cox and Anderson 2004). Assisted succession is a two-step approach: the first step is to convert an annual-dominated site to a perennial-dominated site by revegetating with an aggressive perennial species such as crested wheatgrass, and the second step is to restore diversity by reintroducing native species into the now perennial-dominated site. The objective is not to eliminate crested wheatgrass, but to make it part of a diverse matrix (Cox and Anderson 2004). Two sites in Utah were seeded with native species, a cheatgrass-dominated site that had been revegetated with crested wheatgrass, and a second site dominated by cheatgrass. Native species were drill or broadcast seeded after a disturbance treatment of tilling, harrowing, or herbicide. Native seedlings established more readily on the site dominated by crested wheatgrass compared to the site dominated by cheatgrass. Disturbance (tilling, harrowing, or herbicide treatment) was required for native seedlings to establish in crested wheatgrass. The two treatments that proved to be the most efficient for establishing native seedlings were tilling followed by drill seeding (Cox and Anderson 2004). The study that is the focus of this thesis may help to clarify the feasibility of increasing the establishment of native species following the conversion of an annual grass-dominated site to a crested wheatgrass-dominated site during "assisted succession".

Rangeland Revegetation

Often times after major disturbances such as overgrazing, fire, severe erosion, drought, mining, or weed infestations, public and private land managers make attempts to rehabilitate these areas to sustainable, properly functioning ecosystems. Prior to the 1930s, many attempts to repair and revegetate deteriorated arid and semi-arid ecosystems were successful in the short-term and failures in the long term (Whisenant 1999). Historically, revegetation projects in the western United States used conventional agricultural methods and were largely unsuccessful due to inadequate site preparation and seeding methods and the use of plant materials that were incompatible with the arid and semi-arid conditions (Stoddart and Smith 1955). In the 1930s, however, with the ongoing development of improved plant materials, seedbed preparation, seeding equipment, and seeding methods, rapid progress was made in rangeland revegetation.

Inappropriate plant materials were and still are a major cause of failed revegetation projects (Whisenant 1999). Whisenant (1999) discussed some important considerations that would help to select the appropriate plant materials for a revegetation project. First, clear and attainable goals and objectives of the project must be determined. It is important to set goals and objectives that are site specific, practical, include time frames and consider the ecological and economic impacts. Second, select plant materials that are adapted to the climatic and microclimatic conditions, successional stage, soil status and disturbance regime of the site in which they are to be planted. Plant materials should help repair the damaged ecosystem processes within a system. Whether the plant materials are native or not depends on the objectives of the project. Lastly, the mixture of species chosen for a project should improve site conditions by quickly stabilizing the site and initiating the repair of damaged ecosystem processes while still providing functional diversity. Compatibility with the landscape and neighboring plant communities should also be a consideration. Once desired species have been selected, it is up to the project manager to determine whether to use seeds, seedlings or plant parts in revegetating the site.

Seedbed preparation is one of the most important components of rangeland revegetation and can determine the success or failure of a project. The critical key in seedbed preparation is to create safe sites for the seeds of desired species (Whisenant 1999). Vallentine (1980) describes an ideal seedbed as having the following characteristics: 1) firm soil above and below the seeding depth; 2) friable and thoroughly tilled soil; 3) no compacted or cloddy soil; 4) free from competitive established plants, especially weeds; 5) devoid of a significant presence of weeds in the seedbank; and finally, 6) covered by sufficient plant residue or mulch on the surface. The seedbed can be prepared in variety of ways that include mechanical, chemical, fire, biological and mulch methods (Whisenant 1999). The specific methods used will be dictated by obstructions associated with the terrain, cost limitations and availability of specialized equipment.

The use of seeds is more commonly used in revegetation projects than the transplanting of seedlings or plant parts because seeds are cheaper and easier to collect, purchase, store and transport (Whisenant 1999). When using seeds it is critical to consider: 1) seed preparation, such as breaking the dormancy of the seed or inoculating the seed; 2) planting seed at the appropriate time prior to a long period of optimum growing conditions; 3) calculating an appropriate seeding rate that is most cost effective while allowing the production of the desired density; 4) planting seed at an appropriate depth that is favorable for germination and growth of the seed; and 5) methods of seeding to be used (Whisenant 1999). The two most common methods of seeding are drill and broadcast. Drill seeding is the most uniform method of seeding and places seeds directly into the soil while accounting for seeding density, depth, and spacing. Broadcast seeding disperses seeds across the soil surface and can be done quicker than drill seeding and at a lower cost. There are many advantages and disadvantages to both drill and broadcast seeding. The best method of seeding is determined by the project objectives, funding and available equipment.

Rangeland revegetation is expensive, site specific and risky (Holecheck et al. 2001). Before implementing a revegetation project, land managers must first outline the desired goals and objectives specific to the project. To reduce the probability of failure, special attention must be paid to selecting the appropriate plant materials, seedbed preparation methods, seeding methods and seeding equipment (Vallentine 1980; Whisenant 1999). It is also important to look at past revegetation projects and see what did or did not work so that the mistakes of yesterday are not made today or tomorrow.

Successional Management

The management and restoration of deteriorated lands dominated by nonindigenous species is an immense concern of sustainable rangeland management today. Invasions by nonindigenous species can alter ecosystem functioning, structure, and dynamics (D'Antonio and Vitousek 1992) and thus are not desirable in the ecosystems they invade. The primary management goal for these infested lands is to bring about a shift in the vegetation towards a more desirable plant community. Traditionally, managers of nonindigenous-dominated rangelands focused on controlling unwanted species by utilizing methods such as grazing, fire, herbicides, chaining, and revegetation practices (Sheley and Krueger-Mangold 2003). These management strategies are successful at temporarily controlling plant infestations, yet are unsuccessful at developing and maintaining a healthier, invasion-resistant plant community (Sheley et al. 1996; Sheley and Krueger-Mangold 2003). Recent studies indicate that directing vegetation change may be achieved by integrating an ecologically-based successional management framework into the management and restoration of deteriorated lands and those infested by nonindigenous species (Sheley et al. 1996; Krueger-Mangold et al. 2006).

First outlined by Pickett et al. (1987), a successional approach to management primarily involves looking at three causes of succession: site availability, species availability, and species performance. These three causes of succession influence the pace and direction of vegetation change (Whisenant 1999). The main proposal in successional management is that by manipulating these three causes of succession, land managers can direct ecological succession to meet resource agency objectives. For example, we can initiate vegetation change by creating disturbances to make a site available for different species, induce species availability by seeding or transplanting, and implement management practices that increase the performance of desired species (Sheley et al. 1996; Whisenant 1999; Sheley and Krueger-Mangold 2003). In order for successional management to be used properly, managers must view the process as ongoing, transitioning from one step of succession to the next or replicating one step through time (Sheley et al. 1996).

The first step in directing vegetation change is to make a safe site available for the desired species. The primary process that determines site availability is disturbance, and the size, severity, time interval, patchiness, and predisturbance history are the modifying factors (Pickett et al. 1987; Sheley et al. 1996). Land managers can implement a designed disturbance to create a safe site by utilizing one or a combination of the following activities: plowing, disking, chaining, herbicides, fire (Sheley and Krueger-Mangold 2003), shallow tillage, or grazing with a variety of livestock types (Krueger-Mangold et al. 2006).

The second step in directing vegetation change is to ensure that the desired species are available at the site. Dispersal and propagation are the two most important ecological components in determining species availability and the factors that can modify these components include: dispersal mechanisms, landscape configuration, land use, disturbance interval, and species' life histories (Picket et al. 1987; Sheley et al. 1996). Some activities that land managers can use to ensure species availability include: monitoring dispersal vectors, seedbed preparation to capture desirable propagules, seeding at intervals to increase dispersal frequency, assessing the propagule pool to determine what species are present, and applying a seed coating to enhance establishment (Picket et al. 1987; Krueger-Mangold et al. 2006). After establishment, the species present on the site may inhibit the invasion of additional species by utilizing, and thus limiting, the available resources until another disturbance occurs or until the site is no longer suitable for those species (Krueger-Mangold et al. 2006).

The third step in directing vegetation change involves species performance, which relates to interactions between two or more species. The processes and components that influence the performance of a species include: availability of resources, species' ecophysiology, species' life history strategies, environmental stresses, competition, allelopathy, herbivory, disease, and predation (Picket et al. 1987; Whisenant 1999). In addition, there are numerous factors that can modify these processes and components. The management practices that can be incorporated to boost species performance include: determining what resources that plant assemblages on the site will require and at what quantities; assessing the available resources in the soil and supplementing with resources the plant community might need; comparing and contrasting between an invasive nonindigenous species' native and introduced environments; utilizing seed-priming to enhance germination; performing sensitivity analyses on the life history of invasive plant species to determine when it will be most susceptible to control strategies; seeding with species-rich mixtures; identifying biotic and abiotic stressors that could potentially hamper establishment; establishing cover crops to act as a buffer to shift interference mechanisms such as competition; and considering the use of assisted succession where practical (Krueger-Mangold et al. 2006).

With the use of the ecologically-based successional management framework, land managers can manipulate the following three causes of succession to direct vegetation change: site availability, species availability, and species performance. In essence, land managers can utilize ecological principles to manage and restore lands infested with invasive nonindigenous species to more desirable plant assemblages. In doing this, land managers will not be attempting to temporarily relieve the problem, but will be attempting to solve the problem. Active successional management will not necessarily render quick results; land managers must not be tempted to abandon the successional framework after a short period of limited success. It must be understood that vegetation change takes time. Utilization of a successional management approach may be useful for increasing diversity of native species in monotypic stands of crested wheatgrass.

CHAPTER 3 - MATERIALS & METHODS

Site Location and Condition

The study site was located about 80 km south of Burns, Oregon on the Malheur National Wildlife Refuge. The mean minimum temperature is 0.3˚C and the mean maximum temperature is 17.3˚C. Daily temperature extremes have been recorded to be as low as -35.6˚C and as high as 40˚C. The mean annual precipitation is 280-300 mm, with annual extremes as low as 161mm and as high as 403mm (WRCC 2007). The elevation of the site is 1400 m. The soils on the study site consist of the Raz-Brace complex which consists of soils in the Raz and Brace soil series. Raz soils are loamy, mixed, frigid, shallow Xeric Haplodurids and Brace soils are fine-loamy, mixed, frigid Xeric Argidurids.

This site was planted with a mixture of *Agropyron cristatum* and *A. desertorum* by the Bureau of Land Management around 1981 following a fire. The site was dominated by crested wheatgrass, cheatgrass, and *Alyssum* sp. According to the USDI NRCS (1994) ecological site description for loamy soils in a 250-300 mm precipitation zone, the dominant native vegetation would consist of Wyoming big sagebrush (*Artemisia tridentata* spp. *wyomingensis* Nutt.), bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) A. Löve), Sandberg's bluegrass (*Poa secunda* Presl), Thurber needlegrass (*Achnatherum thurberianum* (Piper) Barkworth), bottlebrush squirreltail (*Elymus elymoides* (Raf.) Swezey), and Indian ricegrass (*Stipa hymenoides* Roemer & Schultes).

Study Design

A randomized block (n=5), split-plot design was used to test the effects of the following treatments on vegetation, soil, and seedbank attributes: 1) undisturbed crested wheatgrass (no control applied), 2) partial chemical crested wheatgrass control, 3) full chemical crested wheatgrass control, 4) partial mechanical crested wheatgrass control, and 5) full mechanical crested wheatgrass control. Within each of these five main plots, plots were split into seeded and unseeded sub-plots. Treatments were replicated in 5 blocks at the site. The study was replicated for two years. Each block consisted of one row of the first year plots and another row of the second year plots. The placement of the first and second year plot rows was randomized for each block.

Procedures

In June 2005, ArcMap software was used to place GPS points into a grid system and hand-held GPS units were used to locate each plot. Steel T-posts were placed on each sub-plot corner. Each sub-plot was 30m x 70m with a 30m buffer between each block. Some blocks had to be split due to space restrictions. Each 0.4-hectare whole plot (undisturbed, partial and full chemical control, partial and full mechanical control), was divided into 2 – 0.2 hectare seeded or unseeded sub-plots (5 x 2 = 10 – 0.2 hectare sub-plots or 2 hectares per block). Five blocks per year for two years were treated for a total of 20 hectares treated over two years.

Prior to seeding, the ammonium and nitrate concentration (ppm) of the soil was sampled and the crested wheatgrass control treatments were applied.

Chemical control treatments for 2005 and 2006 plots were applied July 12, 2005 and May 3- 8, 2006. For full chemical control, glyphosate was applied at the full recommended rate of 4.8 L^{-ha} (44 $oz.^{-ac}$). For partial chemical control, glyphosate was applied at one-fourth the recommended rate of 1.2 L^{-ha} (10 $oz.^{-ac}$). Glyphosate was applied using an ATV-mounted boom sprayer which was calibrated for the appropriate rate of delivering 95 L^{-ha} (10 gal^{-ac}) of water in addition to the glyphosate.

Mechanical control methods were applied to the 2005 and 2006 plots on October 17-18, 2005 and May 15, 2006. A tractor-mounted 4.2m (14 feet) off-set disk with 50cm (20 inch) disks was used for the mechanical treatment. Full mechanical control plots were disked twice and the partial mechanical control plots were disked once.

Seeding

All seeds were purchased from commercial growers with seed collections that were grown as close as possible to the study site. The seeds were sent to the Natural Resource Conservation Service (NRCS) Plants Materials Center in Aberdeen, ID, where they were mixed at the appropriate rates and rice hulls were added to improve flow through the seeder. Two seed mixes were produced; one large-seeded and the other small-seeded. Large seeds were put into a cool-season box while small seeds were put into a fluffy seed box. Alternating drops were used from the cool-season and fluffy boxes. The cool-season box fed the seeding disks, and the fluffy box dropped seeds onto the soil surface where they were rolled over by Brillion® wheels. The large-seeded mix included four-wing saltbush (*Atriplex canescens* (Pursh) Nutt.), Lewis flax (*Linum lewisii* Pursh), Munro globemallow (*Sphaeralcea munroana* (Dougl.) Spach), bluebunch wheatgrass, bottlebrush squirreltail, and Indian ricegrass. The small-seeded mix included Wyoming big sagebrush, white-stemmed rabbitbrush (*Chrysothamnus nauseosus* spp. *albicaulis* (Pall.) Britt.), western yarrow (*Achillea millefolium* L.), and Sandberg's bluegrass. Species, cultivar, commercial source and seeding rates are listed in the Appendix. The 2005 and 2006 plots were seeded by the NRCS using a modified Truax® Rough Rider no-till drill on October 31 – November 1, 2005 and October 30-31, 2006. Seeding conditions in 2005 were approximately 13 ˚C, partly sunny, breezy, and dry and in 2006 conditions were approximately -8˚ C, sunny, and dry.

Data collection

The following data were collected at peak standing crop for two years on plots established in 2005 and for 1 year on plots established in 2006: 1) density of adult crested wheatgrass, cheatgrass, seeded species, any weedy species phenologically competitive with the seeded species, and any other species present, and 2) cover of adult crested wheatgrass, cheatgrass, and any significant weedy species. Five transects 18 m long and 10 m apart were randomly established in each sub-plot, perpendicular to the seeded rows. Percent cover was ocularly estimated in 0.25m² frames (0.5m x 0.5m) using the Daubenmire (1959) cover class method: (1) 0-5%; (2) 6-25%; (3) 26-50%; (4) 51-75%; (5) 76-95%; and (6)

96-100%. The midpoint of each cover class was used as a cover value. The density of individuals was counted in 10 frames per transect. The placement of each frame was randomly selected and the frames were placed 2 m apart and perpendicular to the 5 transects, for a total of 50 frames per sub-plot.

Multiple data were collected for each frame. First, density and cover of adult crested wheatgrass plants within the $.25m^2$ frame: plants with at least 50% or more basal area inside the frame were counted. Second, the number of crested wheatgrass seed heads on culms within the frame and the average length (cm) of all seed heads for use in a regression to estimate the aerial seedbank of the crested wheatgrass within each plot in seeds^{-ha}. Third, density and cover of any additional perennial species, other than the seeded species, within the $.25m^2$ frame. Fourth, density of cheatgrass and any significant weedy species within a .25m x .25m corner of the frame. Fifth, cover of cheatgrass and any significant weedy species within the $.25m^2$ frame. Sixth, density of all seeded species within the $.25m^2$ frame. Distinction between bluebunch wheatgrass, Indian ricegrass, and bottlebrush squirreltail was difficult and therefore they were recorded together in a group called 'seeded perennial species'. The other seeded species could be identified and thus were recorded individually. Finally cover class of rock, litter, and bare ground were estimated. Any other annual species present in the $.25m^2$ frames were noted and counted. Sampling occurred on June 19-28, 2006 and June 4-15, 2007.

Soil sampling

One 2 cm diameter x 15 cm deep soil core was collected from within the center of each of the five transects per plot. The five subsamples per sub-plot were composited and measured for gravimetric water, nitrate, and ammonium concentrations. At the Eastern Oregon Agricultural Research Center in Burns, Oregon, each sample was weighed after collection, oven dried at 30-35 C°, and weighed again to determine the gravimetric water content. Samples were then frozen until they could be sent to the Oregon State University Central Analytical Lab in Corvallis, Oregon for inorganic nitrogen analysis. Soil sampling occurred twice per year, once in early April and once in September.

Seedbank analysis

Surface soil and litter seedbank samples were collected in the spring and fall of each year and bioassayed for any species. Surface soil and litter for each plot were collected using a 2cm deep x 5cm across x 5cm wide (50cm^3) scoop. Five subsamples were collected from each sub-plot and composited into one sample per sub-plot. Samples were kept frozen until analysis. Samples were spread across a sand base in 19cm x 14cm x 5cm trays in the greenhouse at the Eastern Oregon Agricultural Research Center. The first trial of the seedbank analysis for the pre (taken June 29-30, 2005) and post (taken May 10-11, 2006) treatment samples of the 2005 plots and the pre-treatment samples from the 2006 plots (taken May 10-11, 2006) was initiated on May 16, 2006. The samples were kept moist for six weeks followed by watering each sample with 100ml of 1000 ppm giberrellic acid solution once per week for three weeks. The giberellic acid solution was applied to stimulate germination of seeds that hadn't already germinated. Emergent seedlings were recorded on June 16, 2006 and July 19, 2006. After seedlings were recorded they were removed so that they were only recorded once. A second trial of the seedbank analysis was initiated on July 24, 2007. In this trial, post-treatment samples from the 2005 and 2006 plots taken April 11, 2007 were analyzed. The same procedures as the first trial were used.

Statistical Analysis

Within each sub-plot 50 frames were assessed; each frame represented one sample (n=50). Since this was a randomized experiment, one may infer that the difference in density and cover of crested wheatgrass, alyssum, cheatgrass and seeded species was caused by the difference in treatments, seeding levels or both. However, because the site was not selected at random from the western United States, extending this inference to any other site is speculative.

Vegetation and Soil

A proc mixed split-plot analysis was used for all analyses comparing the 2005 and 2006 plots. Fixed effects in this analysis included treatment and seeding level and random effects included year and block. A proc mixed split-split plot analysis was used for all analyses comparing the 2005 plots over a two year sampling period. Fixed effects in this analysis included treatment, year, and seeding level and random effects included block. These analyses were chosen to test for the effects of the five treatments on the density and cover of crested wheatgrass, alyssum, cheatgrass and seeded species. When a significant P value ≤ 0.05 was found, means were separated using Tukey's Honestly Significant Difference (HSD) test (Ramsey and Schafer 2002). Residuals for all models were checked for model fit, normality and variance homogeneity. The statistical software used in all data analyses was SAS version 9.1 (SAS Institute 2003).

Seedbank

No statistical analysis was undertaken for seedbank data due to a lack of seedling emergence which suggested a very depleted seedbank was present. These results may be indicative of possible problems with seedbank analysis procedures.

Weather Data

Monthly average minimum and maximum temperatures and precipitation data from 1948-2007 were gathered from the Western Regional Climate Center (WRCC 2007). Weather observations were taken from the P-Ranch Station located near Frenchglen, Oregon, approximately 24 km from the study site.

CHAPTER 4 – RESULTS

Climate (Average Temperature and Precipitation)

Average monthly temperatures for the study site were within the historical average maximum and minimum values (Figure 1). Average monthly precipitation in 2005-2007 was generally similar to the long-term average except in May 2005 and November – December 2005 when average monthly precipitation was two or three-fold higher than the historical average (Figure 2).

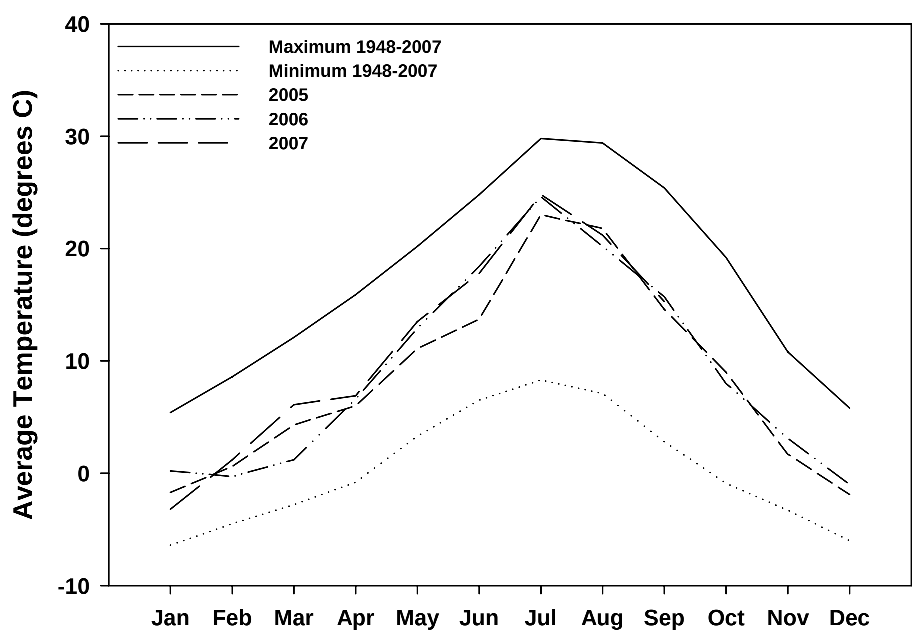

Figure 1. Long-term monthly average maximum and minimum temperatures and average monthly temperatures for 2005, 2006 and 2007.

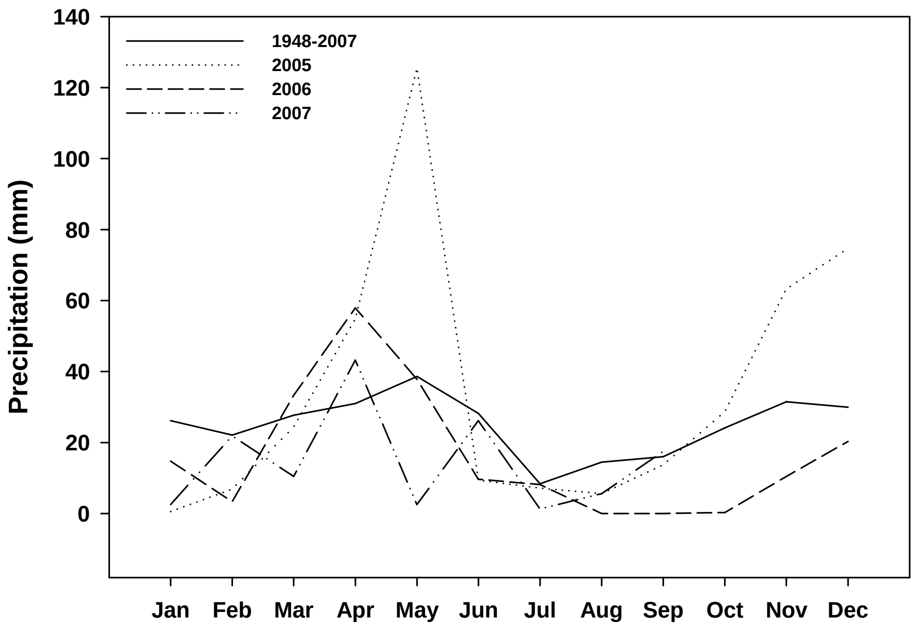

Figure 2. Long-term average monthly precipitation and average monthly precipitation for 2005, 2006 and 2007.

Crested Wheatgrass

Crested Wheatgrass Density – 2005 Plot Comparison by Year

Treatment and year were the main effects that influenced crested wheatgrass densities (Table 1). The full control mechanical (FCM) treatment yielded a higher number of plants m^{-2} than the full control herbicide (FCH), partial control herbicide (PCH), partial control mechanical (PCM) and the control treatments (UD) (11.0 plants m^{-2} vs. 6.5 plants m^{-2}, 6.8 plants m^{-2}, 7.5 plants m^{-2} and 6.7 plants m^{-2}, respectively). Crested wheatgrass density increased in the 2005 plots between year 1 and year 2 (6.5 plants m^{-2} vs. 8.8 plants m^{-2}).

Treatment and year interacted to affect crested wheatgrass density ($P<0.0001$; Table 1; Figure 3). In general, crested wheatgrass density increased from year 1 to year 2. The only exception was in the UD treatment, which remained constant at 6.7 plants m^{-2}. In year 1 none of the treatments differed from the UD treatment. The FCM treatment in year 1 (7.7 plants m^{-2}) displayed a higher density than the FCH, PCH and PCM treatments in year 1 (5.7 plants m^{-2}, 6.6 plants m^{-2} and 6.4 plants m^{-2}, respectively). Otherwise, all treatments resulted in similar densities. After two years, the FCM treatment resulted in the highest crested wheatgrass density at 14.3 plants m^{-2}. This density was roughly two times higher than any other treatment. Lastly, with 8.5 plants m^{-2} the PCM treatment in year 2 was higher in density than the FCH (7.2 plants m^{-2}) and UD treatments in year 2.

Table 1. P-values and degrees of freedom (Df) for main effects and interactions in a 2005 plot comparison by year for crested wheatgrass density, cover and seed head density.

Source	**Df**	**Density**	**Cover**	**Seed Head Density**
treatment (t)	4	0.0003	0.0406	0.2490
seeded (s)	1	0.7425	0.1159	0.3762
t * s	4	0.5451	0.3507	0.0322
year (y)	1	<0.0001	<0.0001	<0.0001
t * y	4	<0.0001	<0.0001	<0.0001
s * y	1	0.0972	0.9100	0.0521
t * s * y	4	0.8655	0.6238	0.0850

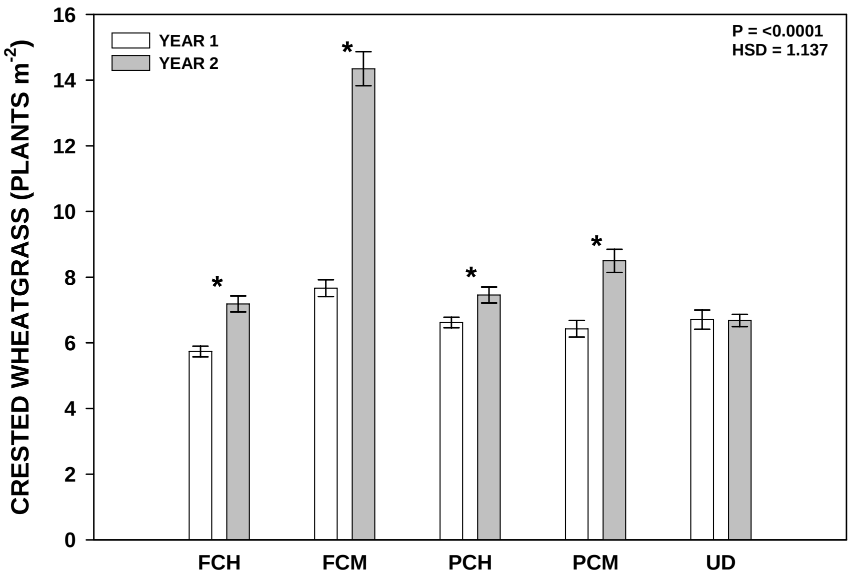

Figure 3. Crested wheatgrass density (plants m^{-2}) as affected by treatment and year in a 2005 plot comparison by year (natural log transformation). Actual means are presented. The * denotes differences across years within a treatment. HSD separates means between treatments within a year. Error bars equal ± 1.0 SE. FCH = full control herbicide. FCM = full control mechanical. PCH = partial control herbicide. PCM = partial control mechanical. UD = undisturbed.

Crested Wheatgrass Cover – 2005 Plot Comparison by Year

Similar to density, crested wheatgrass cover was affected by the main effects of treatment and year (Table 1). Overall the PCH and UD treatments exhibited the greatest crested wheatgrass cover (17.1% and 17.2%, respectively) as compared to the FCH, PCM and FCM treatments (14.0%, 12.1% and 11.3%, respectively). Crested wheatgrass cover decreased from year 1 (15.3%) to year 2 (13.3%).

Treatment and year interacted to affect crested wheatgrass cover ($P<0.0001$; Table 1; Figure 4). Except for the FCM treatment, all other treatments in year 1 were higher in crested wheatgrass cover than those treatments in year 2. In year 1 the FCM treatment demonstrated the lowest crested wheatgrass cover compared to all other treatments at 9.9%, but increased in year 2 to 12.6%. The FCH and PCM treatments (15.7% and 13.4%, respectively) resulted in lower cover than the PCH and UD treatments in year 1 (18.7% and 18.8%). This trend remained consistent in year 2. In the second year the UD treatment was greater in cover than both mechanical treatments.

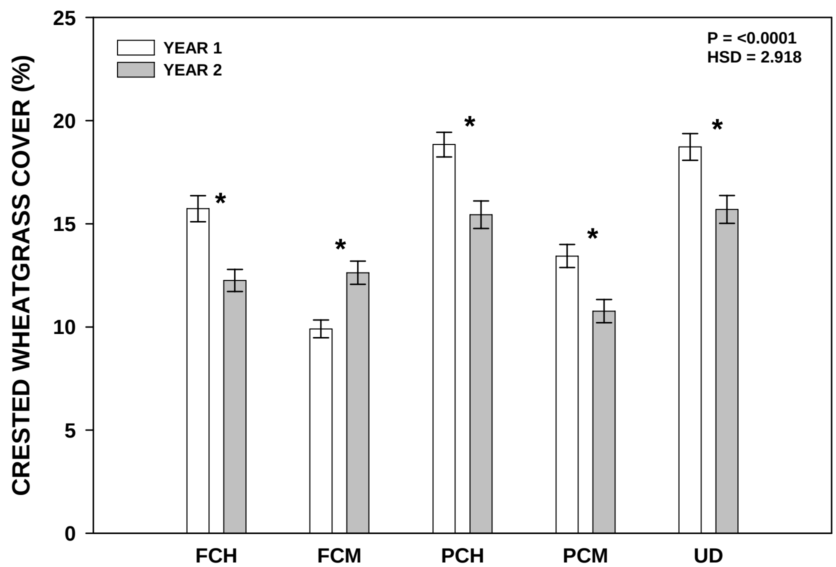

Figure 4. Crested wheatgrass cover (%) as affected by treatment and year in a 2005 plot comparison by year (natural log transformation). Actual means are presented. The * denotes differences across years within a treatment. HSD separates means between treatments within a year. Error bars equal ± 1.0 SE. See Figure 3 for explanation of treatment abbreviations.

Crested Wheatgrass Seed Head Density – 2005 Plot Comparison by Year

Year was the only main effect that influenced crested wheatgrass seed head density ($P < 0.0001$; Table 1). The number of seed heads decreased in year 2 (7.1 seed heads m^{-2}) compared to year 1 (14.0 seed heads m^{-2}). An interaction between treatment and year influenced crested wheatgrass seed head density ($P < 0.0001$; Table 1; Figure 5). Except in the FCH treatment, all other treatments in year 1 displayed about two times higher densities in crested wheatgrass seed heads than in year 2. The FCH treatment in the first and second year was similar in seed head density with 7.6 seed heads m^{-2} and 7.3 seed heads m^{-2}, respectively. With the highest crested wheatgrass seed head densities in year 1, the PCH, PCM and UD treatments (16.0 seed heads m^{-2}, 16.5 seed heads m^{-2} and 17.1 seed heads m^{-2}, respectively) were greater in seed head density than the FCH and FCM (12.7 seed heads m^{-2}) treatments. In year 1 the FCM treatment had higher seed head density than the FCH treatment. Finally, seed head densities in the second year were similar between treatments.

Treatment and seeding level interacted to influence crested wheatgrass seed head densities (P = 0.0322; Table 1; Figure 6). Crested wheatgrass seed head densities were higher in seeded plots as compared to unseeded plots in the FCH and PCM treatments (9.1 vs. 5.8 seed heads m^{-2} and 13.6 vs. 10.8 seed heads m^{-2}, respectively). Seeded plots in the FCM treatment were lower in seed head density with 8.0 seed heads m^{-2} as compared to unseeded plots that exhibited 12.3 seed heads m^{-2}. The PCH and UD treatments displayed similar seed head densities in seeded and unseeded plots with 11.6 vs. 11.7 seed heads m^{-2} and 12.3 vs. 10.2 seed heads m^{-2}, respectively. The FCM and FCH (9.1 seed heads m^{-2}) treatments had lower seed head densities than the PCM and UD treatments (13.6 and 12.3 seed heads m^{-2}, respectively) within seeded plots. Seeded plots within the FCM treatment were also lower in seed head density than seeded plots of the PCH treatment. In the unseeded plots, the FCH treatment with 5.8 seed heads m^{-2} was lower in seed head density than all other treatments.

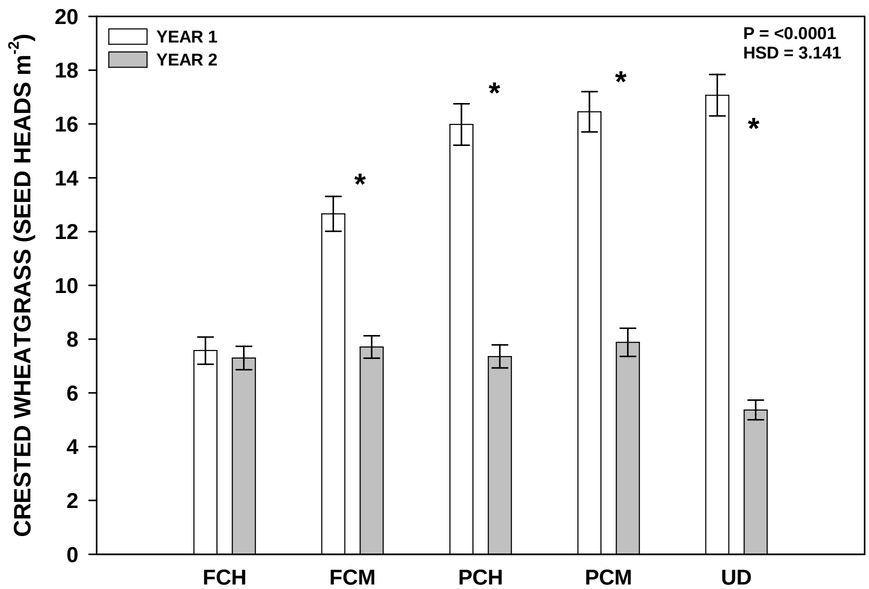

Figure 5. Crested wheatgrass seed head density (seed heads m^{-2}) as affected by treatment and year in a 2005 plot comparison by year (natural log transformation). Actual means are presented. The * denotes differences across years within a treatment. HSD separates means between treatments within a year. Error bars equal ± 1.0 SE. See Figure 3 for explanation of treatment abbreviations.

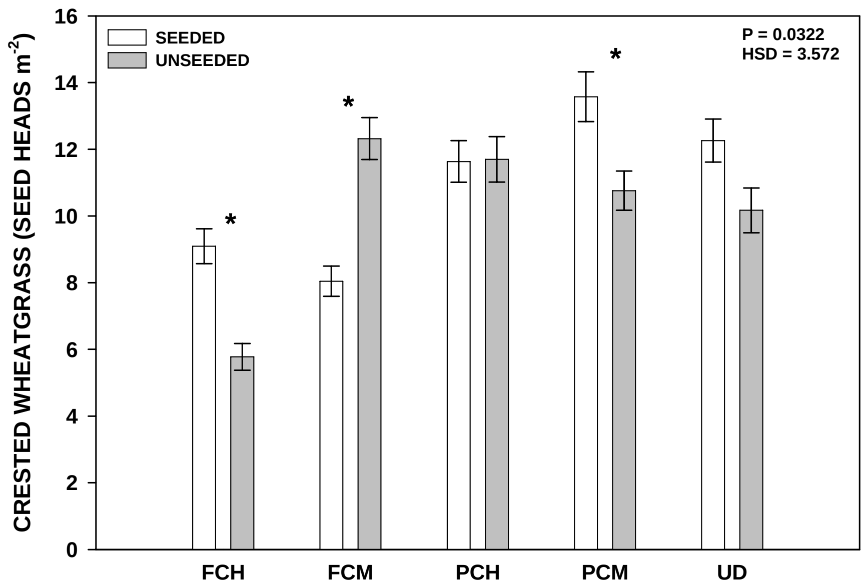

Figure 6. Crested wheatgrass seed head density (seed heads m^{-2}) as affected by treatment and seeding level in a 2005 plot comparison by year (natural log transformation). Actual means are presented. The * denotes differences across seeding levels within a treatment. HSD separates means between treatments within a seeding level. Error bars equal ± 1.0 SE. See Figure 3 for explanation of treatment abbreviations.

Crested Wheatgrass Density – Planting Year Comparison

Crested wheatgrass density was influenced by the main effect of year (P = 0.0007; Table 2). Crested wheatgrass increased from 6.5 plants m^{-2} in the 2005 plots to 9.2 plants m^{-2} in the 2006 plots. Year and seeding level interacted to affect crested wheatgrass densities (P = 0.0017; Table 2; Figure 7). Overall, the density of crested wheatgrass in 2006, regardless of seeding level, was greater than the density of crested wheatgrass in 2005. The crested wheatgrass density in the seeded plots was greater than the unseeded plots in 2006 (9.9 plants m^{-2} vs. 8.5 plants m^{-2}).

Treatment and seeding level interacted to affect crested wheatgrass density ($P = 0.0312$; Table 2; Figure 8). Crested wheatgrass density was similar in all treatments between seeded and unseeded plots except in the FCH treatment where seeded plots were higher in density with 9.6 plants m^{-2} than unseeded plots with 7.3 plants m^{-2}. In the seeded plots, all treatments displayed similar crested wheatgrass densities except for the FCH and FCM (9.7 plants m^{-2}) treatments which were higher in density. The highest crested wheatgrass density in unseeded plots occurred in the FCM treatment with 9.5 plants m^{-2}. Finally, unseeded plots of the PCM treatment were higher in crested wheatgrass density than the unseeded plots of the UD treatment (8.0 plants m^{-2} vs. 6.3 plants m^{-2}).

Table 2. P-values and degrees of freedom (Df) for main effects and interactions in a planting year comparison for crested wheatgrass density, cover and seed head density.

Source	**Df**	**Density**	**Cover**	**Seed Head Density**
treatment (t)	4	0.1405	<0.0001	0.0346
seeded (s)	1	0.5396	0.1222	0.0912
t * s	4	0.0312	0.0301	<0.0001
year (y)	1	0.0007	0.0032	0.0184
t * y	4	0.2438	0.9866	0.0493
s * y	1	0.0017	0.0074	0.0246
t * s * y	4	0.7850	0.0079	0.0006

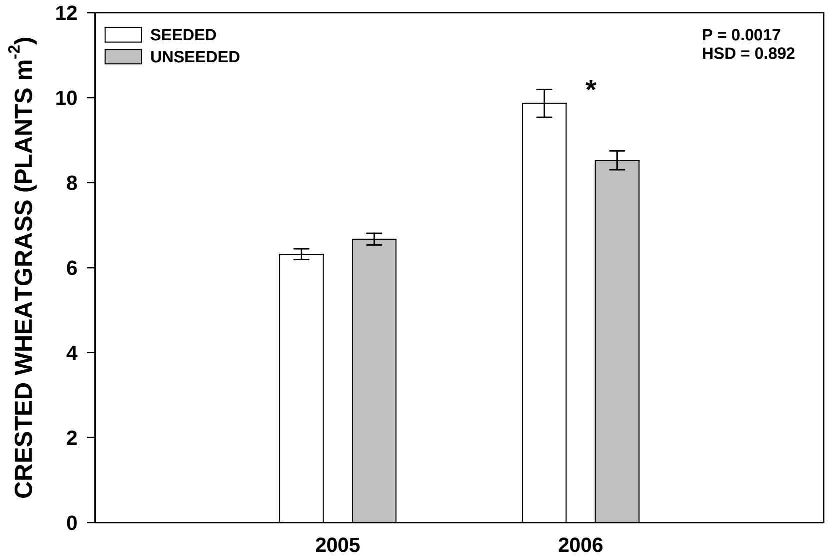

Figure 7. Crested wheatgrass density (plants m^{-2}) as affected by year and seeding level in a planting year comparison (natural log transformation). Actual means are presented. The * denotes differences across seeding levels within a year. HSD separates means across years within a seeding level. Error bars equal ± 1.0 SE. See Figure 3 for explanation of treatment abbreviations.

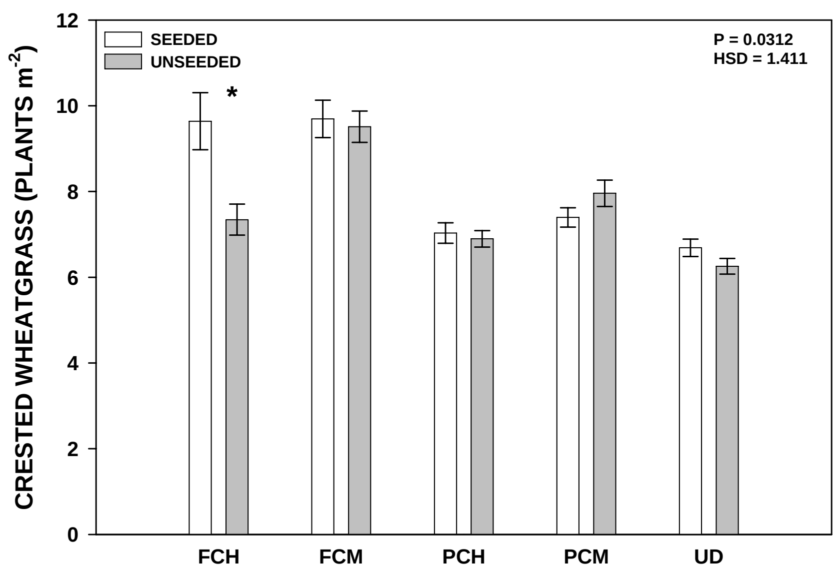

Figure 8. Crested wheatgrass density (plants m^{-2}) as affected by treatment and seeding level in a planting year comparison (natural log transformation). Actual means are presented. The * denotes differences across seeding levels within a treatment. HSD separates means between treatments within a seeding level. Error bars equal ± 1.0 SE. See Figure 3 for explanation of treatment abbreviations.

Crested Wheatgrass Cover – Planting Year Comparison

The main effects of treatment and year affected crested wheatgrass cover (Table 2). Overall, the PCH (16.6%) and UD (16.5%) treatments resulted in the highest cover of crested wheatgrass and the FCM treatment (8.3%) resulted in the lowest cover. The cover of crested wheatgrass decreased from 15.3% in the 2005 plots to 11.2% in the 2006 plots.

The three-way interaction among treatment, seeding level and year affected crested wheatgrass cover (P = 0.0079; Table 2; Figure 9). This interaction suggested that seeded and unseeded PCH and UD treatments in the 2005 plots and the unseeded PCH and seeded UD treatments in the 2006 plots resulted in greater crested wheatgrass cover than all other treatments. All treatments in the 2005 plots, regardless of seeding level, were higher in cover than those same treatments in the 2006 plots except in the seeded FCM treatment. In general, both the 2005 and 2006 plot cover values for each treatment were similar between the seeded and unseeded plots. Exceptions to this included: in the FCM treatment in the 2005 plots, seeded plots had lower crested wheatgrass cover than unseeded plots (8.0% vs. 11.8%); in the UD treatment in the 2005 plots, seeded plots displayed a lower cover value than unseeded plots (17.9% vs. 19.6%); in the PCH treatment in the 2006 plots, seeded plots resulted in lower cover than unseeded plots (12.4% vs. 16.3%); and finally in the UD treatment within the 2006 plots, seeded plots were greater in cover than unseeded plots (15.9% vs. 12.5%).

In the 2005 plots, the seeded FCH treatment had an intermediate crested wheatgrass cover value of 16.1% between seeded PCH and UD treatments and seeded FCM and PCM (13.5%) treatments. In addition, the seeded FCM treatment was lower in cover than the seeded PCM treatment. The unseeded plots showed the same trend in the 2005 plots.

In the 2006 plots, the seeded and unseeded FCM treatments were lower in crested wheatgrass cover than all other seeded and unseeded treatments. Both unseeded FCH and PCM treatments (10.7% and 9.8%, respectively) displayed median cover values between unseeded PCH and UD treatments and the unseeded FCM treatment. The unseeded UD treatment was higher in crested wheatgrass cover than both the unseeded FCH and PCM treatments.

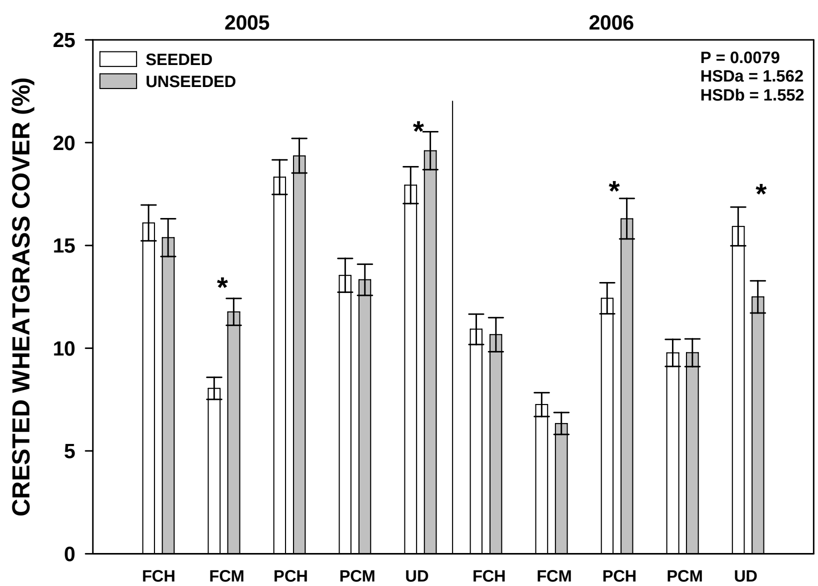

Figure 9. Crested wheatgrass cover (%) as affected by treatment, seeding level and year in a planting year comparison (natural log transformation). Actual means are presented. The * denotes differences between seeding levels within a treatment within a year. HSDa separates means between the same treatments and seeding levels across years. HSDb separates means between treatments across and within years. Error bars equal ± 1.0 SE. See Figure 3 for explanation of treatment abbreviations.

Crested Wheatgrass Seed Head Density – Planting Year Comparison

The density of crested wheatgrass seed heads was influenced by the main effects of treatment and year (Table 2). The FCH treatment displayed the lowest seed head density with 8.6 seed heads m^{-2} when compared to the PCH treatment (12.5 seed heads m^{-2}), PCM treatment (12.8 seed heads m^{-2}) and the UD treatment (11.9 seed heads m^{-2}) ($P = 0.0346$; Table 2). The 2005 plots averaged 13.9 seed heads m^{-2} and the 2006 plots averaged 8.6 seed heads m^{-2} ($P < 0.0001$; Table 2).

The three-way interaction between treatment, seeding level and year affected crested wheatgrass seed head density ($P = 0.0006$; Table 2; Figure 10). With few exceptions, the treatments in the 2005 plots, regardless of seeding level, were higher in seed head densities than the same treatments in the 2006 plots. The exceptions to this included: the seeded FCH treatments in the 2005 and 2006 plots were similar with 10.1 and 9.9 seed heads m^{-2}, respectively; the seed head density in the unseeded FCH treatment in the 2005 plots was lower than in the 2006 plots (5.1 vs. 9.4 seed heads m^{-2}); and seeded FCM treatment in the 2005 plots was similar in seed head density with the 2006 plots (10.1 vs. 7.5 seed heads m^{-2}).

In the 2005 plots, seeded plots tended to exhibit higher seed head densities than unseeded plots except in the FCM and PCH treatments. The FCM treatment was higher in seed head density in unseeded plots compared to seeded plots (15.2 vs. 10.1 seed heads m^{-2}) and seed head density in seeded and unseeded plots in the PCH treatment were similar (15.9 vs. 16.1 seed heads m^{-2}). The lowest seed head densities in seeded plots were displayed in the FCH and FCM treatments (both

10.1 seed heads m^{-2}). Similarly, in the unseeded plots, the lowest seed head density was in the FCH treatment, whose density was about one third of that of the FCM, PCH, PCM and UD treatments.

In the 2006 plots, crested wheatgrass seed head densities were generally similar between treatments and seeding levels. Exceptions to this included: seeded plots in the FCM treatment were lower in seed head density than unseeded plots (7.5 vs. 9.6 seed heads m^{-2}); seeded plots in the UD treatment were higher in seed head density than unseeded plots (7.7 vs. 5.7 seed heads m^{-2}); and finally, the unseeded FCM treatment was higher in seed head density than the unseeded UD treatment.

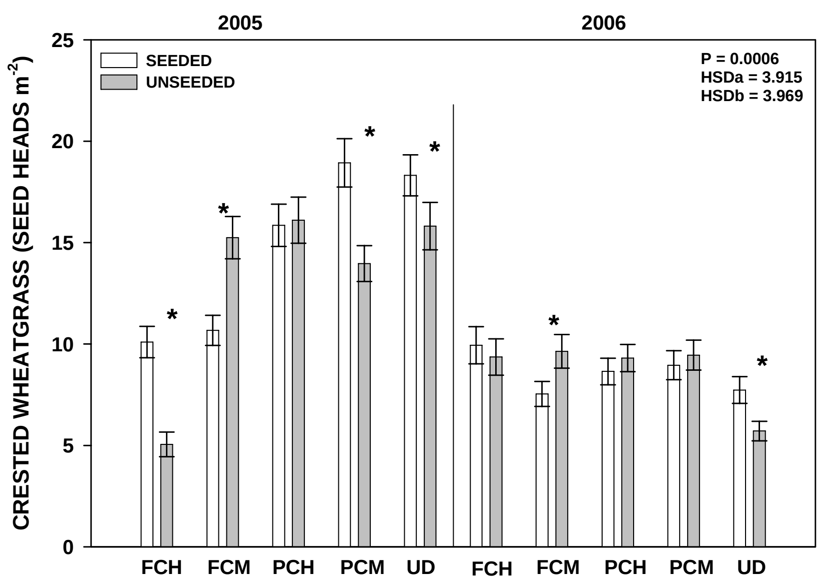

Figure 10. Crested wheatgrass seed head density (seed heads m^{-2}) as affected by treatment, seeding level and year in a planting year comparison (natural log transformation). Actual means are presented. The * denotes differences between seeding levels within a treatment within a year. HSDa separates means between treatments and seeding levels within a year. HSDb separates means between treatments and seeding levels across years. Error bars equal ± 1.0 SE. See Figure 3 for explanation of treatment abbreviations.

Cheatgrass

Cheatgrass Density – 2005 Plot Comparison by Year

Cheatgrass density was influenced by the main effect of year (P <0.0001; Table 3). The 2005 plots increased in cheatgrass density from year 1 (77.3 plants m^{-2}) to year 2 (85.9 plants m^{-2}). Treatment and year interacted to affect cheatgrass density (P <0.0001; Table 3; Figure 11). Except in the PCH and UD treatments, which were similar across years, cheatgrass density tended to increase between the first and second years. In the first year, cheatgrass densities were similar except in the FCM treatment which exhibited a lower density than the PCM treatment (52.0 vs. 104.3 plants m^{-2}). In the second year all cheatgrass densities were similar except for the PCM treatment, which was higher than the UD treatment (116.4 vs. 66.8 plants m^{-2}).

Table 3. P-values and degrees of freedom (Df) for main effects and interactions in a 2005 plot comparison by year for cheatgrass density and cover.

Source	**Df**	**Density**	**Cover**
treatment (t)	4	0.4679	0.6772
seeded (s)	1	0.7769	0.6359
t * s	4	0.7695	0.6131
year (y)	1	<0.0001	0.0086
t * y	4	<0.0001	0.0006
s * y	1	0.0784	0.9257
t * s * y	4	0.2951	0.0225

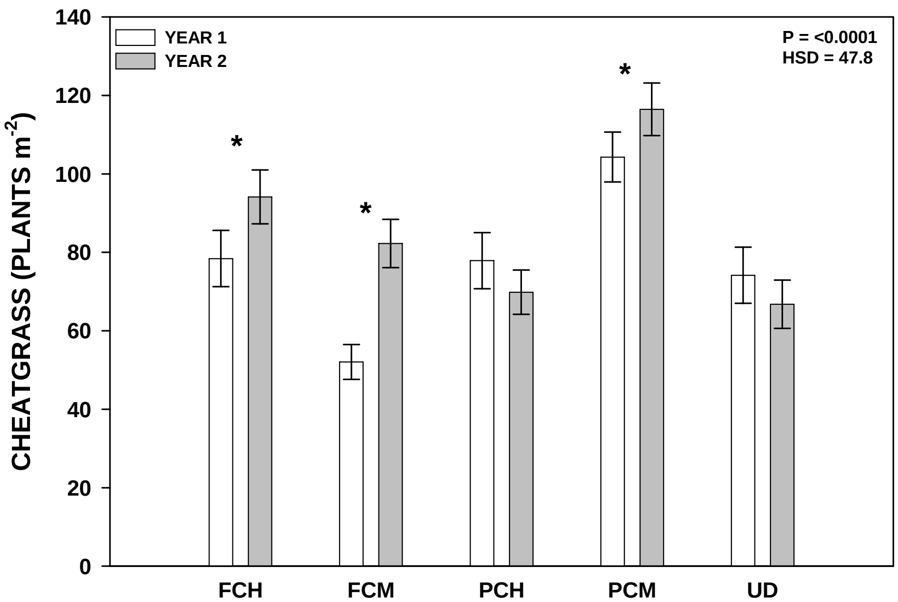

Figure 11. Cheatgrass density (plant m^{-2}) as affected by treatment and year in a 2005 plot comparison by year (natural log transformation). Actual means are presented. The * denotes differences across years within a treatment. HSD separates means between treatments within a year. Error bars equal ± 1.0 SE. See Figure 3 for explanation of treatment abbreviations.

Cheatgrass Cover – 2005 Plot Comparison by Year

Year influenced cheatgrass cover (P = 0.0086; Table 3). Cheatgrass cover decreased from 3.5% in year 1 to 3% in year 2. Cover of cheatgrass was also affected by the three-way interaction of treatment, seeding level and year (P = 0.0225; Table 3; Figure 12). Depending on seeding level, about half of the treatments between the two years did not differ in cheatgrass cover. Those treatments and seeding levels that did differ between years had higher cover values in the first year; these treatments included the unseeded FCH (6.0% vs. 3.5%) and UD (3.2% vs. 2.4%) treatments and the seeded PCH (3.4% vs. 2.5%) and PCM (3.7% vs. 2.9%) treatments. The only treatment that increased in cheatgrass cover from year 1 to year 2 was the unseeded FCM treatment (2.5% vs. 3.2%).

In the first year there were no differences within treatments between seeding levels except in the FCH treatment (2.9% vs. 6.0%).   There were no differences between treatments in the seeded plots. In the unseeded plots the FCH treatment was higher in cheatgrass cover than all other treatments. Finally, in the second year cheatgrass cover of all plots, regardless of seeding level, differed only slightly between 2.3% and 3.7%.

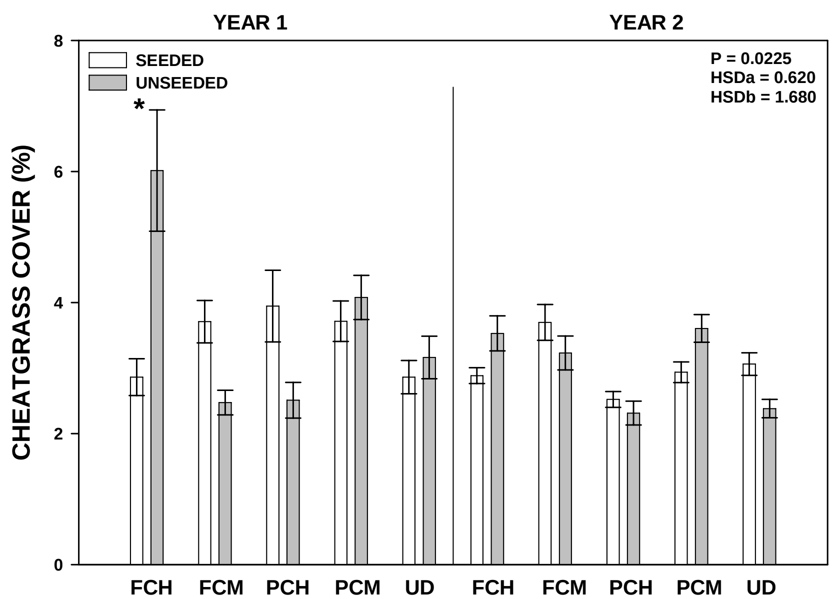

Figure 12. Cheatgrass cover (%) as affected by treatment, seeding level and year in a planting year comparison (natural log transformation). Actual means are presented. The * denotes differences between seeding levels within a treatment within a year. HSDa separates means between the same treatments and seeding levels across years. HSDb separates means between treatments across and within years. Error bars equal ± 1.0 SE. See Figure 3 for explanation of treatment abbreviations.

Cheatgrass Density – Planting Year Comparison

The main effect of year influenced cheatgrass density (P = 0.0092; Table 4). Cheatgrass density decreased from 77.3 plants m^{-2} in the 2005 plots to 29.4 plants m^{-2} in the 2006 plots. Treatment, seeding level and year interacted to affect cheatgrass density (P <0.0001; Table 4; Figure 13). About half of the treatments, regardless of seeding level, had cheatgrass densities similar to one another across the 2005 and 2006 plots. The other half of the treatments, regardless of seeding level, had greater densities in the 2005 plots than the 2006 plots; these treatments included the unseeded FCH treatment (106.3 vs. 21.1 plants m^{-2}), unseeded PCH treatment (78.1 vs. 14.5 plants m^{-2}), seeded PCM treatment (100.1 vs. 44.4 plants m^{-2}), unseeded PCM treatment (108.4 vs. 40.5 plants m^{-2}) and seeded UD treatment (75.5 vs. 18.5 plants m^{-2}).

In the 2005 plots, cheatgrass density within treatments between seeded and unseeded plots were similar except in the FCH and FCM treatments. In the FCH treatment cheatgrass density in unseeded plots more than doubled that of seeded plots (106.3 vs. 50.5 plants m^{-2}). The FCM treatment showed opposite results in which seeded plots were greater in cheatgrass density than unseeded plots (59.6 vs. 44.5 plants m^{-2}). Within the seeded plots, the PCM treatment was higher in density than the FCH (50.5 plants m^{-2}) and FCM treatments. The FCM treatment in the unseeded plots yielded a lower cheatgrass density than the unseeded FCH and PCM treatments seed heads m^{-2}).

Between seeding levels within treatments in the 2006 plots, cheatgrass densities were generally similar except in the UD treatment where seeded plots displayed less than half the density as that of unseeded plots (18.5 vs. 60.2 plants m^{-2}). In the 2006 plots, the seeded plots of all treatments were similar. In the unseeded plots, however, the UD treatment more than doubled the FCH, FCM and PCH treatments (21.1, 21.0 and 14.5 plants m^{-2}, respectively).

Table 4. P-values and degrees of freedom (Df) for main effects and interactions in a planting year comparison for cheatgrass density and cover.

Source	Df	Density	Cover
treatment (t)	4	0.0993	0.0734
seeded (s)	1	0.0624	0.4771
t * s	4	<0.0001	<0.0001
year (y)	1	0.0092	0.0516
t * y	4	0.6053	0.4324
s * y	1	0.1490	0.0039
t * s * y	4	<0.0001	<0.0001

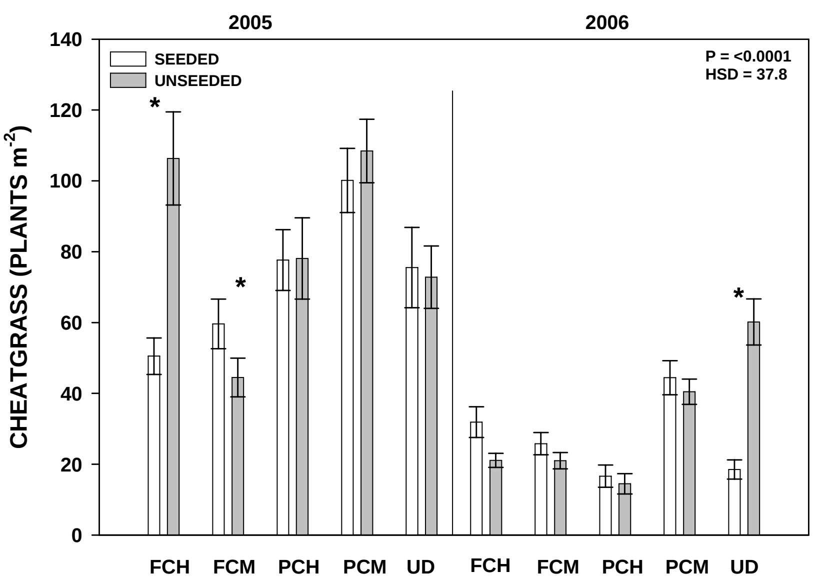

Figure 13. Cheatgrass density (plants m^{-2}) as affected by treatment, seeding level and year in a planting year comparison (natural log transformation). Actual means are presented. The * denotes differences between seeding levels within a treatment within a year. HSD separates means between treatments across and within years. Error bars equal ± 1.0 SE. See Figure 3 for explanation of treatment abbreviations.

Cheatgrass Cover – Planting Year Comparison

Cheatgrass cover was affected by the three-way interaction between treatment, seeding level and year (P <0.0001; Table 4; Figure 14). Regardless of seeding level, cheatgrass cover between the same treatments was similar in the 2005 and 2006 plots, except for a few treatments with higher cover in the 2005 plots than the 2006 plots. These exceptions included the unseeded FCH treatment (6.0% vs. 2.8%), the seeded PCH treatment (3.9% vs. 1.2%) and the unseeded PCM treatment (4.1% vs. 2.6%).

In the 2005 plots, seeded FCM and PCH treatments were higher in cheatgrass cover than unseeded FCM and PCH treatments (3.7% vs. 2.5% and 3.9% vs. 2.5%, respectively). Alternately, the seeded plots in the FCH treatment were lower in cover than the unseeded plots (2.9% vs. 6.0%). Cheatgrass cover among seeded plots was similar across treatments. In unseeded plots, the FCH treatment was higher in cheatgrass cover than all other treatments. In addition, the unseeded PCM treatment had a higher cheatgrass cover than the unseeded FCM and PCH treatments.

Overall in the 2006 plots, cheatgrass cover of different seeding levels within each treatment were similar except in the UD treatment where seeded plots displayed lower cover with 1.6% as compared to unseeded plots with 2.6% cover. With a cheatgrass cover of 1.2% in the seeded plots, the PCH treatment was lower in cover than the seeded FCH, FCM and PCM treatments (3.2%, 2.7% and 2.7%, respectively). In addition, the seeded UD treatment (1.6%) was lower than the FCH treatment. Finally, in the unseeded plots, all treatments displayed similar cheatgrass cover except for the FCH treatment with 2.8% compared to the PCH treatment with 1.3%.

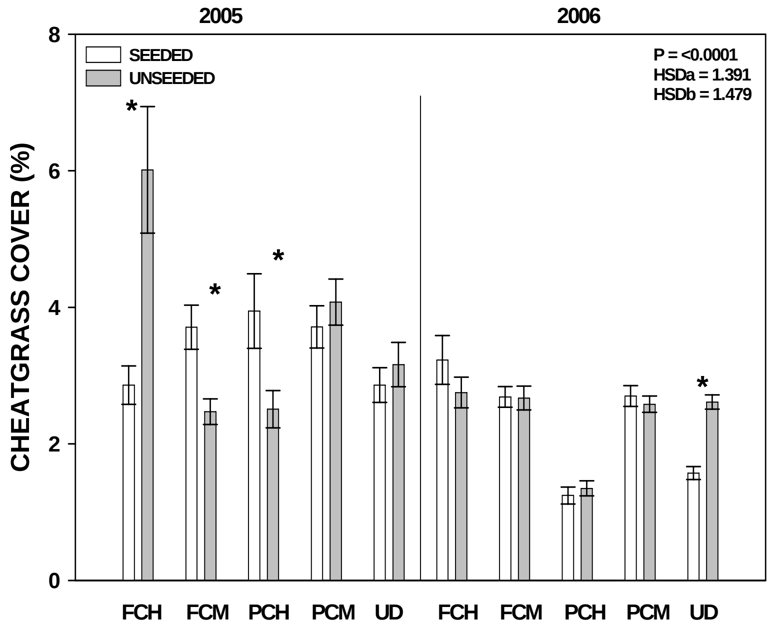

Figure 14. Cheatgrass cover (%) as affected by treatment, seeding level and year in a planting year comparison (natural log transformation). Actual means are presented. The * denotes differences between seeding levels within a treatment within a year. HSDa separates means between treatments and seeding levels within a year. HSDb separates means between treatments and seeding levels across years. Error bars equal ± 1.0 SE. See Figure 3 for explanation of treatment abbreviations.

Alyssum

Alyssum Density – 2005 Plot Comparison by Year

The main effect of year influenced alyssum density (P <0.0001; Table 5). Alyssum density decreased from 137 plants m^{-2} in year 1 to 35.1 plants m^{-2} in year 2. Treatment, seeding level and year interacted to affect alyssum density (P = 0.0387; Table 5; Figure 15).

In the first year, alyssum density in seeded plots was higher in the FCM treatment with 190.2 plants m^{-2} than the PCH (62.8 plants m^{-2}) and UD treatments. In the unseeded plots, the UD treatment displayed lower alyssum density with 46.5

plants m^{-2} compared to the FCH, FCM and PCM treatments (258.4, 209.5 and 166.6 plants m^{-2}, respectively). In addition, the PCH treatment (99.1 plants m^{-2}) had the second lowest alyssum density in unseeded plots and was lower than the FCH and FCM treatments. In the second year, all treatments, regardless of seeding level, exhibited relatively similar alyssum densities. As a general trend, the UD treatments in years 1 and 2 yielded lower alyssum densities than other treatments.

Table 5. P-values and degrees of freedom (Df) for main effects and interactions in a 2005 plot comparison by year for alyssum density and cover.

Source	**Df**	**Density**	**Cover**
treatment (t)	4	0.4928	0.4110
seeded (s)	1	0.3867	0.1702
t * s	4	0.9236	0.8556
year (y)	1	<0.0001	<0.0001
t * y	4	0.3322	0.1196
s * y	1	0.9323	0.0465
t * s * y	4	0.0387	0.1149

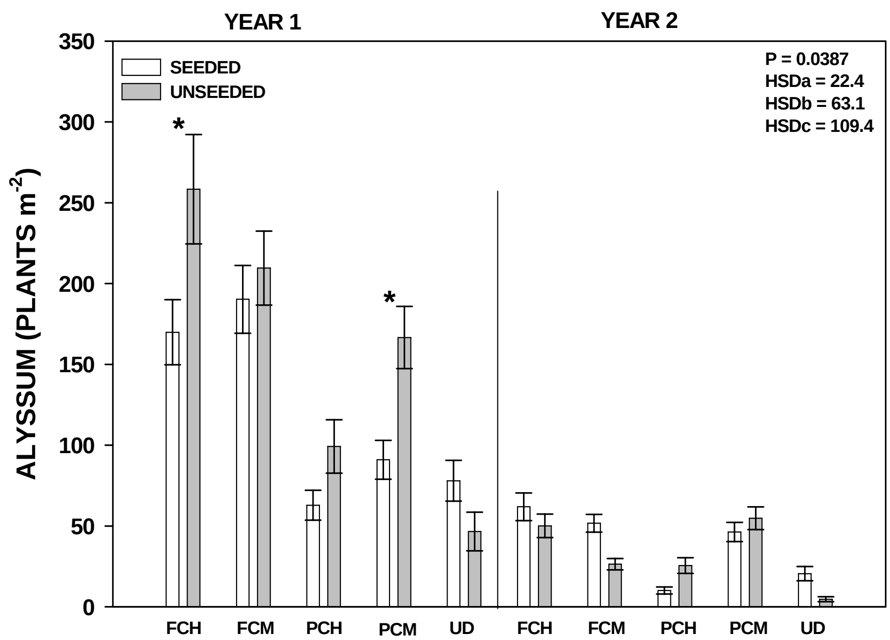

Figure 15. Alyssum density (plants m^{-2}) as affected by treatment, seeding level and year in a 2005 plot comparison by year (natural log transformation). Actual means are presented. The * denotes differences between seeding levels within a treatment within a year. HSDa separates means between the same treatments and seeding levels across years. HSDb separates means between the same treatments with different seeding levels across years. HSDc separates means between treatments and seeding levels across and within years. Error bars equal ± 1.0 SE. See Figure 3 for explanation of treatment abbreviations.

Alyssum Cover – 2005 Plot Comparison by Year

Alyssum cover was influenced by the main effect of year (P <0.0001; Table 5). Alyssum cover was 2.3% in the first year and decreased to 1.2% in the second year. Year and seeding level interacted to affect alyssum cover (P = 0.0465; Table 5; Figure 16). Seeded and unseeded year 1 plots (2.6% and 2.1%) were higher in cover than seeded and unseeded plots in year 2 (1.2% and 1.1%).

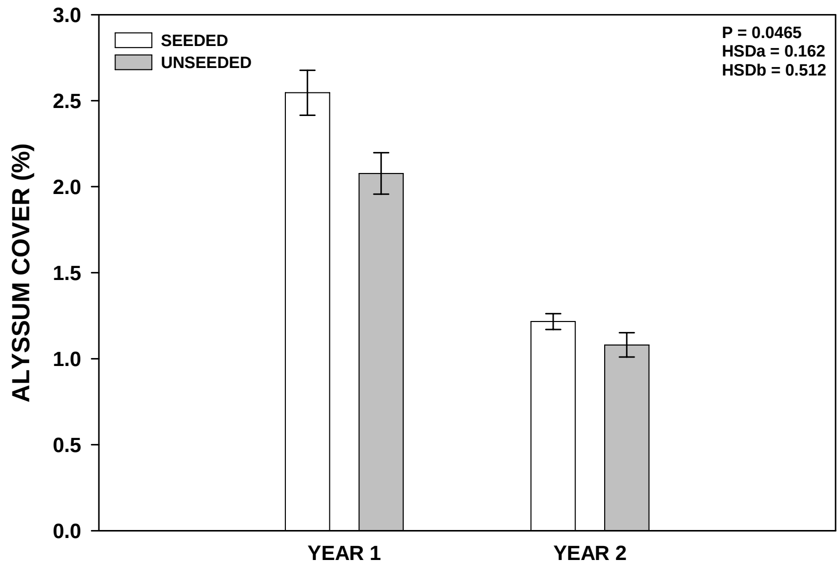

Figure 16. Alyssum cover (%) as affected by year and seeding level in a 2005 plot comparison by year (natural log transformation). Actual means are presented. HSDa separates means between the same seeding level across years. HSDb separates means between seeding levels across years. Error bars equal ± 1.0 SE. See Figure 3 for explanation of treatment abbreviations.

Alyssum Density – Planting Year Comparison

The main effect of seeding level affected alyssum density ($P = 0.0178$; Table 6). With 87.8 plants m^{-2}, unseeded plots had higher alyssum density than seeded plots with 68.2 plants m^{-2}. The three-way interaction between treatment, seeding level and year affected alyssum density ($P < 0.0001$; Table 6; Figure 17). Half of the treatments in the 2005 plots showed higher alyssum densities than those in the 2006 plots. These treatments included the seeded FCH treatment (170.0 vs. 11.8 plants m^{-2}), unseeded FCH treatment (258.4 vs. 17.2 plants m^{-2}), seeded FCM treatment (190.2 vs. 10.7 plants m^{-2}), unseeded FCM treatment (209.5 vs. 5.9 plants m^{-2}) and unseeded PCM treatment (166.6 vs. 13.7 plants m^{-2}).

In the 2005 plots, alyssum densities were generally higher in unseeded plots than seeded plots, except in the UD treatment where seeded plots had higher densities than unseeded plots (78.0 vs. 46.5 plants m^{-2}) and in the FCM treatment where seeded and unseeded plots were similar in density. Seeded plots in the first year were similar to one another except in the comparison between the FCM and PCH (62.8 plants m^{-2}) treatments. The UD treatment displayed a low alyssum density in unseeded plots, which was about 65% lower than the FCH, FCM and PCM treatments. Additionally, the unseeded FCH treatment was higher in alyssum density than the unseeded PCH treatment (99.1 plants m^{-2}). Lastly, in the 2006 plots, alyssum density of all treatments and seeding levels were similar.

Table 6. P-values and degrees of freedom (Df) for main effects and interactions in a planting year comparison for alyssum density and cover.

Source	**Df**	**Density**	**Cover**
treatment (t)	4	0.9436	0.5679
seeded (s)	1	0.0178	<0.0001
t * s	4	0.0033	<0.0001
year (y)	1	0.2609	0.3416
t * y	4	0.3916	0.5644
s * y	1	0.0073	<0.0001
t * s * y	4	<0.0001	<0.0001

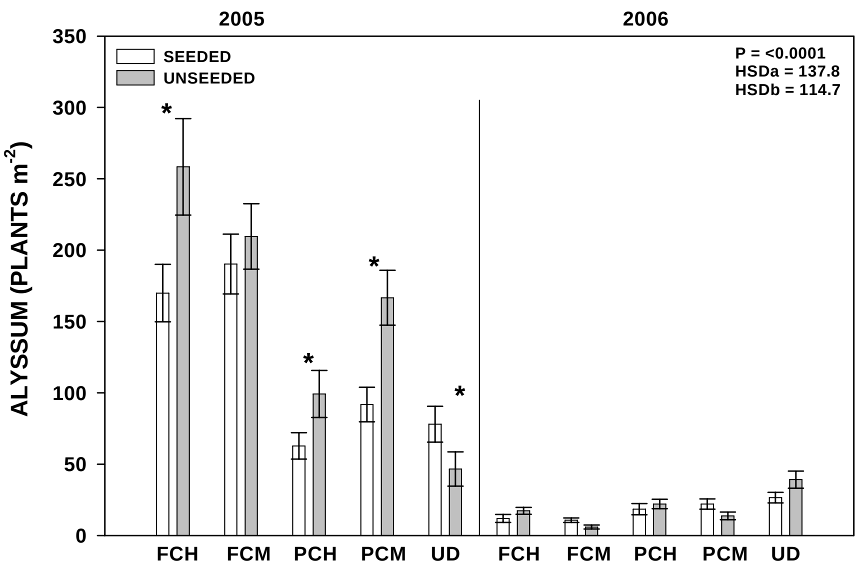

Figure 17. Alyssum density (plants m^{-2}) as affected by treatment, seeding level and year in a planting year comparison (natural log transformation). Actual means are presented. The * denotes differences between seeding levels within a treatment within a year. HSDa separates means between the same treatments with different seeding levels across years. HSDb separates means between treatments and seeding levels across and within years. Error bars equal ± 1.0 SE. See Figure 3 for explanation of treatment abbreviations.

Alyssum Cover – Planting Year Comparison

Seeding level influenced alyssum cover ($P < 0.0001$; Table 6). At 1.8% alyssum cover, seeded plots were higher in cover than unseeded plots with 1.6%. Treatment, seeding level and year interacted to affect alyssum cover ($P < 0.0001$; Table 6; Figure 18). In general, 2005 plots displayed higher alyssum cover than 2006 plots with the exceptions of the unseeded PCH treatments having the same cover (1.2%) and the unseeded UD treatment having lower cover in the 2005 plots compared to the 2006 plots (0.8% vs. 1.4%).

Within the 2005 plots, in general, seeded plots tended to be higher in alyssum cover than unseeded plots except in the PCM treatment where unseeded plots were higher (3.7% vs. 2.6%). In seeded plots, the FCH and PCM treatments were intermediate in cover (2.7% and 2.6%, respectively) between the FCM treatment (4.1%) and the PCH and UD treatments (1.8% and 1.7%, respectively). Similarly, in unseeded plots, the FCH treatment displayed an intermediate cover (2.0%) between the FCM and PCM treatments (2.7% and 3.7%, respectively) and the PCH and UD treatments (1.2% and 0.8%, respectively). Additionally, the unseeded FCM treatment was lower in alyssum cover than the unseeded PCM treatment.

In the 2006 plots, seeded plots in the FCM treatment were higher in cover than unseeded plots (1.5% vs. 0.8%) and seeded plots in the PCM treatment were higher in cover than unseeded plots (1.7% vs. 0.9%). Unseeded plots in the FCH treatment were higher in alyssum cover than seeded plots (1.3% vs. 0.6%) as were unseeded plots in the UD treatment than seeded plots (1.4% vs. 1.0%). The FCM and PCM treatments displayed the highest cover values in the seeded plots. In unseeded plots the UD treatment was higher in cover compared to the FCM and PCM treatments (0.8% and 0.9%, respectively). Lastly, the unseeded FCH treatment (1.3%) was higher in alyssum cover than the unseeded FCM treatment.

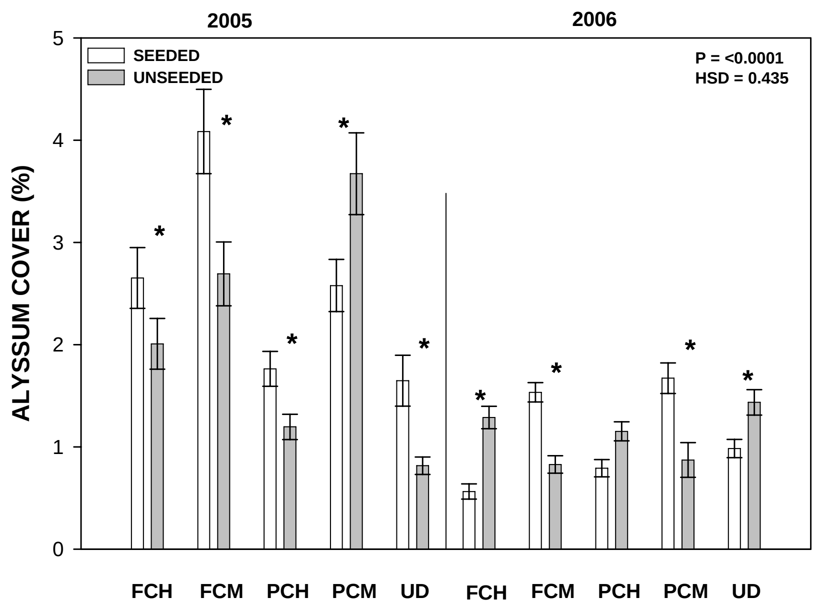

Figure 18. Alyssum cover (%) as affected by treatment, seeding level and year in a planting year comparison (natural log transformation). Actual means are presented. The * denotes differences between seeding levels within a treatment within a year. HSD separates means between treatments and seeding levels across and within years. Error bars equal ± 1.0 SE. See Figure 3 for explanation of treatment abbreviations.

Seeded Species

Seeded Species Density – 2005 Plot Comparison by Year

Seeded species density was influenced by the main effect of year ($P<0.0001$; Table 7). In the first year, the seeded species density was 27.1 plants m^{-2} and by year 2 the density had decreased to 15.3 plants m^{-2}. Year interacted with treatment to affect seeded species density ($P<0.0001$; Table 7; Figure 19). In all treatments except the UD treatment, year 1 seeded species densities were greater than year 2 densities. The UD treatment resulted in 18.2 plants m^{-2} in year 1 and year 2. In year 1 the FCM and PCM treatments displayed the highest seeded species densities with 43.9 plants m^{-2} and 30.1 plants m^{-2}, respectively. In the first year the FCM treatment was also higher in density than the PCM treatment. By the second year, none of the treatments differed in seeded species density.

Table 7. P-values and degrees of freedom (Df) for for seeded species density main effects and interactions in a 2005 plot comparison by year.

Source	Df	P-Value
treatment (t)	4	0.0540
year (y)	1	<0.0001
t * y	4	<0.0001

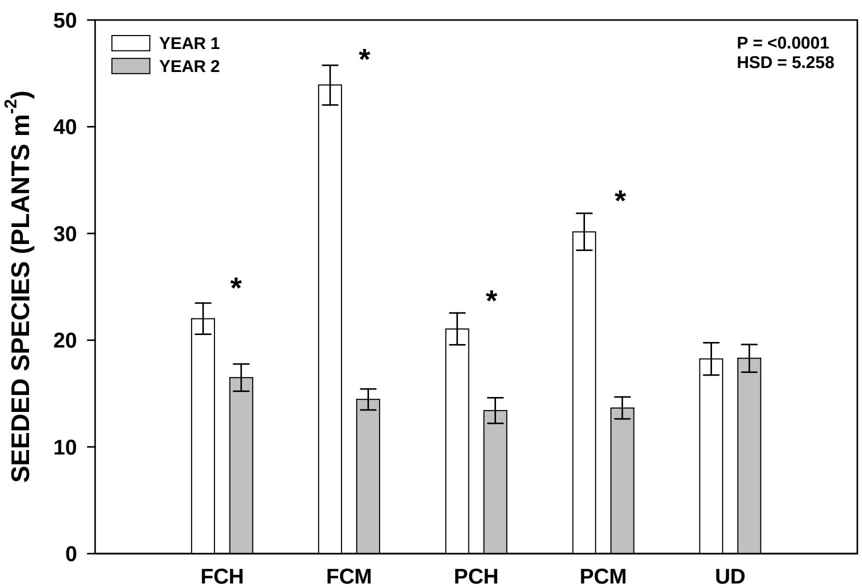

Figure 19. Seeded species density (plants m^{-2}) as affected by treatment and year in a 2005 plot comparison by year (natural log transformation). Actual means are presented. The * denotes differences across years within a treatment. HSD separates means between treatments within a year. Error bars equal ± 1.0 SE. See Figure 3 for explanation of treatment abbreviations.

Seeded Species Density – Planting Year Comparison

Treatment influenced seeded species density (P = 0.0057; Table 8). With 34.9 plants m^{-2}, the FCM treatment was higher in seeded species density than the FCH (24.5 plants m^{-2}), PCH (25.5 plants m^{-2}), PCM (26.4 plants m^{-2}) and the UD

(22.1 plants m^{-2}) treatments. Additionally, the PCM treatment was higher in density than the UD treatment.

Seeded species density was also affected by the interaction between treatment and year (P = 0.0002; Table 8; Figure 20). In the 2005 plots, the FCM and PCM treatments exhibited the highest densities with 43.9 and 30.1 plants m^{-2}. However the FCM treatment was also higher than the PCM treatment in seeded species density. In the 2006 plots, all treatments had similar density values except in the comparison between the PCH and PCM treatments (30 vs. 22.7 plants m^{-2}).

Table 8. P-values and degrees of freedom (Df) for for seeded species density main effects and interactions in a planting year comparison.

Source	**Df**	**P-Value**
treatment (t)	4	0.0057
year (y)	1	0.1498
t * y	4	0.0002

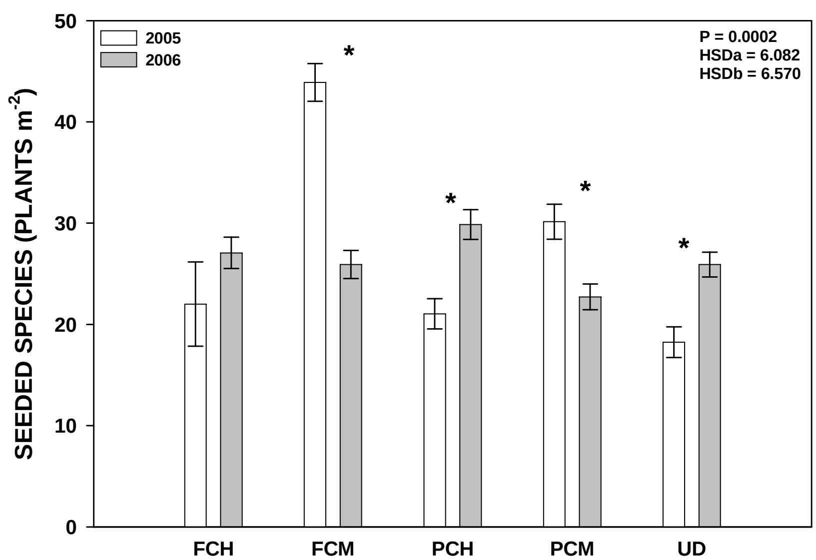

Figure 20. Seeded species density (plants m^{-2}) as affected by treatment and year in a planting year comparison (natural log transformation). Actual means are presented. The * denotes differences across years within a treatment. HSDa separates means between treatments within a year. HSDb separates means between treatments across years. Error bars equal ± 1.0 SE. See Figure 3 for explanation of treatment abbreviations.

Soil Attributes

Soil Ammonium Concentration

Spring Soil Ammonium Concentration – 2005 Plot Comparison by Year

Year was the main effect that affected soil ammonium concentration in the spring (P <0.0001; Table 9). Soil ammonium concentration decreased from 12.5 ppm in year 1 to 4.2 ppm in year 2. Prior to year 1, before treatments were applied, soil ammonium values ranged from 1.2 to 3.6 ppm (mean = 2.0 ppm).

Table 9. P-values and degrees of freedom (Df) for spring soil ammonium concentration main effects and interactions in a plot comparison by year.

Source	Df	2005 Plots	2006 Plots
treatment (t)	4	0.1286	0.3835
seeded (s)	1	0.7963	0.0779
t * s	4	0.8284	0.2145
year (y)	1	<0.0001	0.0020
t * y	4	0.6089	0.2188
s * y	1	0.2097	0.1328
t * s * y	4	0.7140	0.1369

Spring Soil Ammonium Concentration – 2006 Plot Comparison by Year

Spring soil ammonium concentration was affected by the main effect of year (P = 0.002; Table 9). There was an increase in ammonium concentration from year 1 (2.2 ppm) to year 2 (5.8 ppm).

Spring 2006 Soil Ammonium Concentration – Planting Year Comparison

Year affected spring 2006 soil ammonium concentration (P <0.0001; Table 10). The 2005 plots were greater in ammonium concentration with 12.5 ppm compared to the 2006 plots with an ammonium concentration of only 2.2 ppm.

Table 10. P-values and degrees of freedom (Df) for soil ammonium concentration main effects and interactions in a planting year comparison.

Source	Df	Spring 2006	Fall 2006	Spring 2007
treatment (t)	4	0.1461	0.4825	0.5384
seeded (s)	1	0.7214	0.8843	0.0488
t * s	4	0.8839	0.3428	0.3177
year (y)	1	<0.0001	0.8889	0.3048
t * y	4	0.3833	0.3848	0.1769
s * y	1	0.3487	0.3641	0.2778
t * s * y	4	0.8761	0.6426	0.1143

Fall 2006 Soil Ammonium Concentration – Planting Year Comparison

The ammonium concentration of the soil in the fall of 2006 was not affected by year, treatment, or seeding level (Table 10). Ammonium concentration values ranged from 2.4 to 17.9 ppm (mean = 6.1 ppm).

Spring 2007 Soil Ammonium Concentration – Planting Year Comparison

The ammonium concentration of the soil in the spring of 2007 was affected by the main effect of seeding level (P = 0.0488; Table 10). Seeded plots were lower in ammonium concentration with 3.8 ppm as compared to unseeded plots with an average ammonium concentration of 6.2 ppm.

Soil Nitrate Concentration

Spring Soil Nitrate Concentration – 2005 Plot Comparison by Year

Soil nitrate concentration was affected by the main effects of treatment (P = 0.0053) and year (P<0.0001) (Table 11). With 6.4 ppm of nitrate in the soil, the FCM treatment was higher in nitrate concentration than the FCH (4.1 ppm), PCH (4.0 ppm), PCM (4.3 ppm) and UD (3.8 ppm) treatments. Soil nitrate concentration increased from year 1 (0.9 ppm) to year 2 (8.2 ppm) ($P < 0.0001$). Prior to year 1, before treatments were applied, soil nitrate values ranged from 0.6 to 1.8 ppm (mean = 0.9 ppm).

Treatment and year interacted to affect the soil nitrate concentration ($P = 0.0200$; Table 11; Figure 21). Soil nitrate concentration in the second year was higher than in year 1. In the first year, nitrate concentration did not differ between treatments. In the second year, the FCM treatment yielded the highest nitrogen concentration at 11.7 ppm.

Table 11. P-values and degrees of freedom (Df) for for spring soil nitrate concentration main effects and interactions in a plot comparison by year.

Source	**Df**	**2005 Plots**	**2006 Plots**
treatment (t)	4	0.0053	0.2525
seeded (s)	1	0.1871	0.3664
t * s	4	0.6101	0.5957
year (y)	1	<0.0001	<0.0001
t * y	4	0.0200	0.1520
s * y	1	0.0921	0.6163
t * s * y	4	0.5960	0.5439

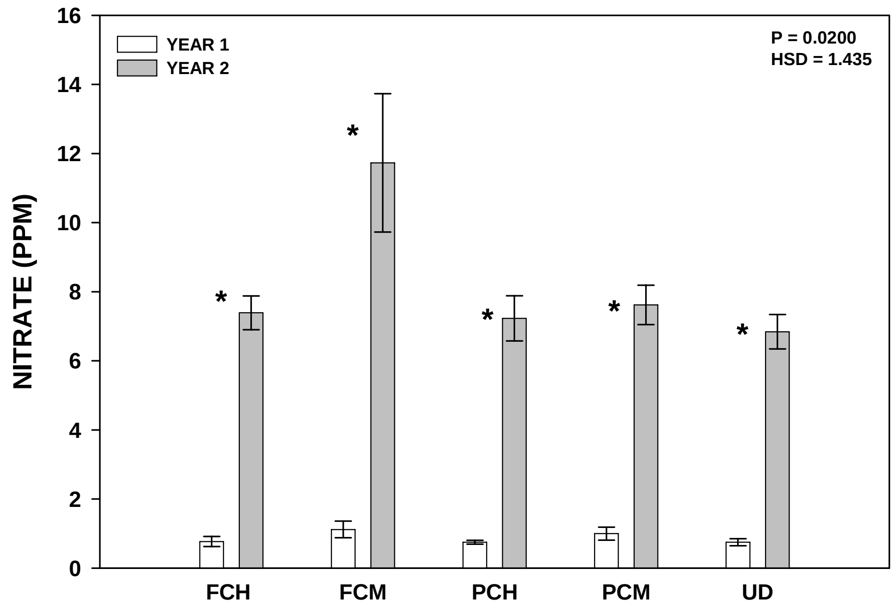

Figure 21. Spring soil nitrate concentration (ppm) as affected by treatment and year in a 2005 plot comparison by year. Actual means are presented. The * denotes differences across years within a treatment. HSD separates means between treatments within a year. Error bars equal ± 1.0 SE. See Figure 3 for explanation of treatment abbreviations.

Spring Soil Nitrate Concentration – 2006 Plot Comparison by Year

Spring soil nitrate concentration was influenced by the main effect of year (P <0.0001; Table 11). Soil nitrate increased from year 1 (1.7 ppm) to year 2 (11.9 ppm).

Spring 2006 Soil Nitrate Concentration – Planting Year Comparison

Seeding level and year were the main effects that influenced soil nitrate concentrations in the spring of 2006 (Table 12). The nitrate concentration of the soil was higher in seeded plots (1.4 ppm) than in unseeded plots (1.2 ppm) (P =

0.0030; Table 12). Soil nitrate concentration was higher in the 2006 plots than the 2005 plots (1.7 vs. 0.9 ppm) (P = 0.0037; Table 16).

Table 12. P-values and degrees of freedom (Df) for soil nitrate concentration main effects and interactions in a planting year comparison.

Source	Df	Spring 2006	Fall 2006	Spring 2007
treatment (t)	4	0.7311	<0.0001	0.0226
seeded (s)	1	0.0030	0.5352	0.9553
t * s	4	0.5189	0.9885	0.4523
year (y)	1	0.0037	0.0008	0.0014
t * y	4	0.3281	0.0045	0.6768
s * y	1	0.2466	0.5758	0.1769
t * s * y	4	0.4761	0.0769	0.6411

Fall 2006 Soil Nitrate Concentration –
Planting Year Comparison

The nitrate concentration of the soil in the fall of 2006 was affected by the main effects of treatment and year (Table 12). With the highest soil nitrate values, the FCM and FCH treatments (5.5 and 4.6 ppm, respectively) were higher in nitrate concentration than the UD (2.1 ppm), PCH (2.7 ppm) and PCM (3.7 ppm) treatments. The FCM treatment was also higher in the concentration of soil nitrate than the FCH treatment. Lastly, the PCM treatment was higher in soil nitrate concentration than the UD and PCH treatments. Soil nitrate concentration was higher in the 2006 plots (4.3 ppm) than the 2005 plots (3.1 ppm).

The interaction between treatment and year affected the concentration of soil nitrate in the fall of 2006 (P = 0.0045; Table 12; Figure 22). In the 2005 plots, soil nitrate concentration was highest in the FCM treatment (4.7 ppm). In addition, with 3.3 ppm the PCM treatment was higher in nitrate concentration than the UD treatment with 2.1 ppm. Lastly, the PCM treatment in the 2006 plots exhibited an intermediate soil nitrate concentration of 4.0 ppm, which was between the FCH and FCM treatments (6.5 and 6.3 ppm, respectively) and the PCH and UD treatments (2.7 and 2.1 ppm, respectively).

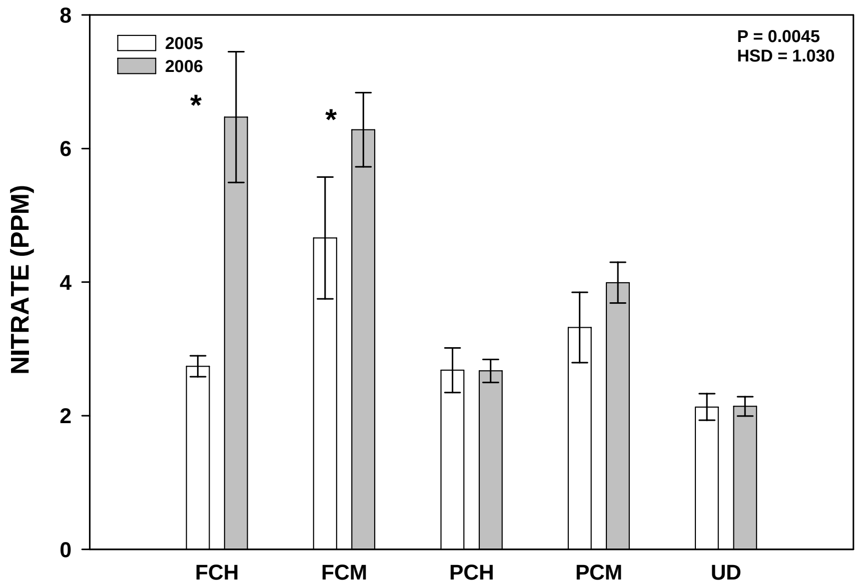

Figure 22. Fall 2006 soil nitrate concentration (ppm) as affected by treatment and year in a planting year comparison. Actual means are presented. The * denotes differences across years within a treatment. HSD separates means between treatments within a year. Error bars equal ± 1.0 SE. See Figure 3 for explanation of treatment abbreviations.

Spring 2007 Soil Nitrate Concentration – Planting Year Comparison

Treatment and year were the main effects that affected the soil nitrate concentration in the spring of 2007 (Table 12). The FCM treatment exhibited the highest soil nitrate content with 13.4 ppm. In addition, the FCH and PCM treatments were higher in soil nitrate concentration than the UD treatment (10.3 and 10.0 vs. 7.3 ppm). The 2006 plots displayed higher soil nitrate concentration with 11.9 ppm than the 2005 plots with 8.2 ppm.

Soil Water Content

Spring Soil Water Content – 2005 Plot Comparison by Year

The soil water content in the spring was influenced by the main effect of year (P <0.0001; Table 13). In year 1 the soil water content was 19.9% compared to 7.9% in year 2.

Table 13. P-values and degrees of freedom (Df) for spring soil water content main effects and interactions in a 2005 plot comparison by year.

Source	Df	P-Value
treatment (t)	4	0.2182
seeded (s)	1	0.7342
t * s	4	0.6038
year (y)	1	<0.0001
t * y	4	0.7383
s * y	1	0.4184
t * s * y	4	0.7246

Fall 2006 Soil Water Content – Planting Year Comparison

Fall 2006 soil water content was not affected by year, treatment, or seeding level (Table 14). Soil water content values ranged from 0.7% to 2.5% (mean = 1.3%).

Table 14. P-values and degrees of freedom (Df) for soil water content main effects and interactions in a planting year comparison.

Source	Df	Fall 2006	Spring 2007
treatment (t)	4	0.7498	0.3959
seeded (s)	1	0.2805	0.8382
t * s	4	0.0624	0.6536
year (y)	1	0.1182	0.5161
t * y	4	0.6496	0.1354
s * y	1	0.8872	0.3594
t * s * y	4	0.8436	0.8027

Spring 2007 Soil Water Content – Planting Year Comparison

Spring 2007 soil water content was not affected by year, treatment, or seeding level (Table 14). Values for the soil water content in the spring of 2007 ranged from 1.6% to 10.7% (mean = 7.7%).

CHAPTER 5 – DISCUSSION

Crested Wheatgrass

The first step in directing vegetation change utilizing successional management is to make safe sites available for desired species. In this study I attempted to prepare the seedbed and create safe sites for seeded species by implementing designed disturbances in the form of mechanical and chemical treatments to control crested wheatgrass. In both the 2005 plot comparison by year analysis and the planting year comparison analysis, I found that the crested wheatgrass density increased with the mechanical treatments (PCM and FCM) as compared with the undisturbed (UD) treatment. The chemical treatments (PCH and FCH) resulted in crested wheatgrass densities that were similar to that of the UD treatment. These findings led me to refute my hypothesis that crested wheatgrass control treatments will decrease crested wheatgrass density.

Alternately, crested wheatgrass cover was found to decrease in the mechanical treatments as compared with the UD treatment. The partial chemical treatment was similar in cover to the UD treatment. I therefore partially accept my hypothesis that crested wheatgrass control treatments will decrease crested wheatgrass cover. It is possible that the decrease in cover was adequate to increase site availability for establishment of native species, even though crested wheatgrass control treatments did not decrease crested wheatgrass density.

The increase in crested wheatgrass density in response to the mechanical treatments is consistent with previous studies conducted on the effects of double-disking in crested wheatgrass stands. Houston (1957) found that the first year after 'renovating' an older crested wheatgrass stand by double-disking and then reseeding with crested wheatgrass, there was a decrease in density and forage production. Two years following the renovation, however, crested wheatgrass density had recovered to pre-treatment levels and forage production had increased. A study by Lodge (1960) indicated that compared to mowing in the fall and burning in the spring and fall, only double-disking in the fall resulted in a significant reduction of crested wheatgrass basal cover when compared to a control. This reduction in crested wheatgrass basal cover was only observed for two years, after which the basal cover returned to pre-treatment levels thus indicating that there was no long-term effect of the double-disking. After conducting a 20-year study on the effects of manuring and disking native Palouse prairie grasslands, Heady (1952) determined that disking tended to increase the yield of the native grasses.

Although previous studies indicate that double-disking crested wheatgrass will in the long term actually stimulate the growth of the plant, the desired outcome is that the first year after disking there is a noticeable decrease in crested wheatgrass density and cover. This noted decrease would hopefully be enough to reduce the competitive ability of crested wheatgrass and allow the establishment of desired species. In this study I did not see a decrease in crested wheatgrass density, however there was a decrease in crested wheatgrass cover. Being a short-term study, it is difficult to say whether or not the disking reduced the competitive ability enough to allow the establishment and persistence of desired species for the long term. I believe that follow up management to affect species performance would probably improve results in the long-term.

It is possible that the increase in crested wheatgrass density was a result of the disks breaking up large tussocks of crested wheatgrass and spreading the seeds, creating several smaller portions of the plant still connected by the roots. I suspect that each of these smaller portions was counted as an individual plant when sampled, thus increasing the actual count of plants per square meter yet also explaining the decrease in crested wheatgrass cover. By the second year the smaller portions of the plants that had been broken up by the disks the year previous seemed to have established into individual plants.

With few exceptions, the chemical treatments were ineffective at controlling crested wheatgrass density and cover. Glyphosate is a non-selective herbicide that stunts or kills an entire plant after contact (Monsanto Company 2004). The effectiveness of the herbicide depends on the quantity and timing of application and the phenological stage of the plant. Previous research has documented the results of applying glyphosate to control perennial grasses. After applying glyphosate to crested wheatgrass in late winter in Utah, Cox and Anderson (2004) concluded that crested wheatgrass cover decreased from 12% to 4% in the first year. However, the application of glyphosate had no effect on the crested wheatgrass in the second year of the study. In a study attempting to seed blue grama into crested wheatgrass stands in Canada, Bakker et al. (1997) found that applying glyphosate in the spring to control the crested wheatgrass prior to seeding resulted in significant reductions in the cover of crested wheatgrass at one of two study sites.

Perhaps in my study the herbicide applications were ineffective at controlling crested wheatgrass due to the timing in which the herbicides were applied. Glyphosate application in July 2005 on the year 1 plots was probably not the most opportune time to apply the herbicides. By July, crested wheatgrass had already set seed and the growth of the plant was starting to slow. Results, however, indicate that the 2005 plots were actually lower in crested wheatgrass density than the 2006 plots which were treated with glyphosate in May of 2006. This evidence suggests that maybe the early May herbicide application was too late an application to have an effect on crested wheatgrass. Perhaps a different outcome might have resulted from a late winter application of herbicides.

In my study the density and cover of crested wheatgrass were very similar between the chemical treatments and the UD treatments, especially in the PCH treatment. The FCH treatment provided the best results for decreasing crested wheatgrass density and cover using herbicides; however decreases were minimal at best. This evidence suggests that when attempting to use herbicides to control crested wheatgrass, more favorable results will occur from utilizing the herbicide at the full recommended rate. It is possible that repeated applications throughout a season or across multiple years might be required to achieve a desired outcome. A combination of mechanical and chemical treatments within the same season might also provide a more desired outcome. Attempts were made in this study to compare the effectiveness of using herbicides at partial and full application rates to determine not only the most effective rate, but also the most economical rate. Therefore, since using glyphosate at the full recommended rate to control crested wheatgrass is more effective, it is probably also the most economical rate of application. Utilizing the herbicide at one-fourth of the recommended rate would probably be a waste of money because it will not effectively control crested wheatgrass.

The crested wheatgrass stand that was used in this study seemed to be a stable, persistent stand that is not invading nearby native rangelands. Native species were present at the site, but at much lower densities compared to the crested wheatgrass. The crested wheatgrass at the site was inhibiting the recruitment of additional native species, which was very apparent in the depleted seedbank and similarly noted in a different study in southeastern Idaho by Marlette and Anderson (1986). Other crested wheatgrass stands, however, have been documented to not inhibit the reestablishment of native species (Broersma et al. 2000; Krzic et al. 2000). Furthermore, in other literature, crested wheatgrass stands have been shown to be very mobile and invasive towards neighboring rangelands (Hull and Klomp 1966 and 1967; Pyke 1990; Henderson and Naeth 2005). An engaging observation in my study is that the undisturbed plots displayed the establishment of just as many seeded species as did the treated plots, suggesting that in this stand, perhaps there is sufficient enough bare ground to allow the establishment of other species and that the real issue is a lack of species availability.

Seeded Species

The major objective of controlling crested wheatgrass in this study was to prepare the seedbed for native species by making safe sites available for the establishment of these species and therefore ultimately restoring proper ecosystem functioning and biological diversity to the site. In the first year following treatment application and the seeding of desired species, there was a noted increase in seeded species establishment in the mechanical treatments (30-43 plants m^{-2}) as compared to the undisturbed plots (18 plants m^{-2}). By the second year, however, seeded species densities had decreased and were not different from those in the undisturbed plots. This evidence suggests that, after two years, the control treatments were ineffective at increasing the establishment of native species, therefore leading me to reject my hypothesis that crested wheatgrass control treatments would increase the establishment of native species. Although crested wheatgrass control treatments were more or less ineffective at increasing the establishment of native species, an average of 15 plants m^{-2} after two years is an acceptable result by many land management agencies. For example, the Bureau of Land Management aims for five perennial bunchgrasses m^{-2} when rehabilitating after fire (Jeff Rose, BLM-Burns, OR district).

The results of this study indicate that in order to establish desired species in crested wheatgrass stands, perhaps control measures are unnecessary and desired species can be directly seeded into the stand. Undisturbed plots in my study yielded 18-22 plants m^{-2}. Contrary to my results, other research in this subject area suggests that in order for desired species to establish at reasonable rates in crested wheatgrass stands, disrupting the growth of crested wheatgrass is a necessary prerequisite to create openings for the desired species (Marlette and Anderson 1986; Bakker et al. 1997; Cox and Anderson 2004; Henderson and Naeth 2005). It was important in these studies to decrease crested wheatgrass somewhat to allow native species establishment. Similar to my results, Cox and Anderson (2004) also found that native seedlings decreased from the first to the second year, however by the second year the density of seeded species in their study was still greater than those of a control. With a poor showing of native species in the seedbank in my study, perhaps all that is needed for the establishment of native species is the availability of species propagules other than those of crested wheatgrass. This study shows that native species establishment is possible with the proper site availability and species availability.

The initial increase in seeded species density in the first year, followed by a 56% decrease in density, may have been attributed to several factors. First, the yearly variation in the amount and timing of precipitation may explain why the seeded species were more successful the first year in the 2005 plots. There were noticeable spikes in precipitation that occurred in October thru December of 2005 and in the spring of 2006. The soil water content in the spring of 2006 was 19.9%, however after a drier summer and fall, the soil water content in the spring of 2007 was down to 7.9%. I speculate that more seeds were able to establish and persist in the first year due to an adequate amount of moisture in the soil. It is difficult to say if the soil water content played a large role in seeded species density since the soil water content at any moment in time can be variable. Interestingly enough, however, there was no difference in the number of species in the first year between the 2005 plots and the 2006 plots, suggesting that the variation in precipitation affected the persistence of the seedlings in the 2005 plots in the second year, but did not have an effect on the establishment of the seedlings in the 2006 plots. Many of those seedlings that emerged the first year, however, were perhaps unable to grow big enough to survive the seasonal drought and persist until the following spring. According to Hyder et al. (1971) and Ries and Svejcar (1991), a seedling is established once it has produced adventitious roots. Hyder et al. (1971) found that crested wheatgrass seedlings have high survival rates due to the initiation of adventitious root production at planting depths of 2cm below the soil surface. Perhaps those seedlings that did not survive in this study were unable to produce deep enough adventitious roots to avoid the harsh environmental conditions at the soil surface.

Second, it is possible that in the first year, the crested wheatgrass control treatments did in fact prepare an adequate seedbed for seeded species by creating more available safe sites and by reducing the competitive ability of crested wheatgrass. With the increase in crested wheatgrass density and cover by the second year, the seeded species may have experienced an increase in competition from crested wheatgrass, therefore decreasing seedling density. It is difficult to say exactly why there was such a large decrease in seeded species density between year 1 and year 2. I suspect that this decrease was a result of the combination of climatic factors as well as the increase in crested wheatgrass competition. A 56% seedling mortality rate after the first year is not unreasonable as compared to other studies that have observed herbaceous perennial seedling mortality rates of 80% or more after the first year (Thomas and Dale 1975; Hawthorne and Cavers 1976; Bishop et al. 1978; Silvertown and Dickie 1981).

It is worth mentioning that most all of the seeded species that established in this study were perennial grasses and Lewis flax. Very few seeded shrubs emerged. These results indicate that grasses and forbs are easier to establish than shrubs, which is consistent with previous research. Cox and Anderson (2004) found that after seeding a diverse mixture of native grasses and shrubs in Utah, native grass emergence was 2-5 times greater than that of the shrubs. Also, when studying seedling establishment characteristics in sagebrush steppe ecosystems, Chambers (2000) found that from a diverse mixture of several seeded native grass, forb and shrub species, the grasses and forbs displayed the highest emergence. Some shrubs are episodic in establishment; perhaps conditions in my study we not favorable for shrub establishment.

As previously mentioned, assisted succession is an attempt to diversify annual-infested rangelands (Cox and Anderson 2004). It is a two-step approach that first looks at converting an annual dominated site to a perennial dominated site by revegetating with an aggressive perennial such as crested wheatgrass. The second step is to revegetate the site with native species in subsequent years. I believe that my study has provided promising results in the second step of assisted succession. Based on my findings, I believe that native species establishment is possible in crested wheatgrass stands using a successional-based approach. Further research is needed, however, before assisted succession can become a standard operating procedure in rangeland management.

Weedy Annual Species and Soil Attributes

As predicted, cheatgrass density increased, after crested wheatgrass control treatments were applied. Weedy species tend to increase in disturbed areas due to increased resource availability (Davis et al. 2000). Resource availability increases when a pulse in resource supply occurs and/or resource uptake declines. Therefore, after a disturbance, resource uptake can decline due to damage or mortality to the resident species, or resource supply can increase due to the decomposition of dead plant material and chemical transformations (Vitousek et al. 1997). Evidence from my study supports this conviction. In my study there was an initial increase in the spring ammonium concentration of the soil the year following crested wheatgrass control treatments in the 2005 plots, however, the increase in spring soil nitrate concentrations occurred in the second year following treatments. This evidence leads me to partially accept my hypothesis concerning the soil nitrate and ammonium concentrations. I do not believe that the soil water content was affected by the treatments or the seeding but was merely a result of the variation in precipitation amount and timing.

After crested wheatgrass control treatments were applied there was a flush in the density and cover of weedy annual species (cheatgrass, alyssum and other annual forbs). These results are consistent with other experimental and observational studies that conclude that the removal of perennial grasses via herbicides, fire, grazing or cultivation leads to an increase in cheatgrass biomass and density (Anderson and Inouye 2001; West and York 2002; Beckstead and Augspurger 2004; Chambers et al. 2007). By the second year after the treatments were applied, cheatgrass density continued to increase while the alyssum density sharply decreased, suggesting that alyssum is more pulse driven than cheatgrass. Cheatgrass is an opportunist species that has the ability to germinate after autumn rains or in early spring (Stewart and Hull 1949); since there was less precipitation in the fall of 2006 thru the spring of 2007 than the previous year, cheatgrass may have been able to utilize the limited moisture in the second year before many of the other species and therefore not allow species such as alyssum adequate resources to survive. Cheatgrass density seems to fluctuate spatially and temporally across a landscape depending on the variation in environmental conditions (Mack and Pyke 1983).

The decrease in alyssum the second year might have been from increased competition for resources with the seeded species, the increasing crested wheatgrass, and the increasing cheatgrass. Additionally, there was slightly less precipitation that occurred in the winter and spring before alyssum emergence in the second year than there was in the first year. I noted a 50% or greater decrease in available soil water by the second year.

I speculate that the initial flush of weedy annual species was in large part a combination of the following: a response to the opening of safe sites for new seedling recruitment; more available resources due to less competition from the crested wheatgrass; an increase in precipitation the previous fall and spring of the first year as compared to the historical average; advantageous earlier seedling emergence of weedy species; and finally, increased seed dispersal from mechanized disturbances (i.e. tractor with disks, four-wheeler with herbicide sprayer and tractor with seeder). In studies attempting to revegetate and renovate rangelands, a flush of weedy annual species was detected the first year after seedbeds were prepared by either mechanical (Heady 1952; Houston 1957; Nelson et al. 1970) or chemical methods (Nelson et al. 1970). By the second year after the seedbed preparation, the density of weedy annual species had decreased (Heady 1952; Houston 1957). Nelson et al. (1970) found that due to the early emergence of cheatgrass and annual forbs, seeded species had difficulties establishing due to intense competition for resources. Further, it was found that as a direct result to the decrease in competition from prior established species, weedy annual species rapidly increased.

In a 13-year study conducted by Bates et al. (2005) looking at the long-term successional patterns following juniper cutting, cheatgrass densities were found to spike during a five-year above-average precipitation pattern. After the above-average precipitation pattern, rainfall levels decreased to below-normal levels and within four years, cheatgrass densities dropped significantly to pre-cutting levels. This evidence suggests that although cheatgrass is responsive to increased precipitation in the short-term, it may be more responsive to increased precipitation in the long-term. Therefore, to really know what will happen with the cheatgrass density in my study in the future, long-term monitoring and evaluation will be necessary.

Alyssum cover and cheatgrass density tended to be greater in the mechanical treatments, especially cheatgrass in the PCM treatment. In an effort to reinvigorate crested wheatgrass stands by double-disking and harrowing, Houston (1957) found that those renovation measures tended to encourage weed invasion. The results of my study and Houston (1957) could have been attributed to the large disturbance on the soil surface created by the mechanical treatments. The mechanical treatments generated diverse microtopography on the soil surface, resulting in more suitable safe sites for seedling establishment. Most species rely on the characteristics of the seedbed, especially soil microtopography, for establishment and persistence (Chambers and MacMahon 1994; Chambers 2000), including cheatgrass (Evans and Young 1984). Alyssum density tended to be greatest in the unseeded plots and in the FCH and FCM treatments. Although the chemical treatments did prepare the seedbed for the desired species by reducing competition and making resources more readily available, these treatments did not greatly alter the microtopographical characteristics of the soil. Interestingly enough, the density of weedy species did not increase in the UD treatment, yet seeded species were able to readily establish.

The most important resources that drive ecosystem processes in arid and semiarid environments, such as the study location, are water (Noy-Meir 1973) and nitrogen (Krueger-Mangold et al. 2004). In the 2005 plots, there was a significant increase in ammonium concentrations in the soil the first year after the crested wheatgrass control treatments were applied, which is consistent with the theory of fluctuating resources (Davis et al. 2000). Additionally, these results coincide with those of Chambers et al. (2007) where removal of perennial grasses led to a "pulse" of nitrogen that was most apparent the year following removal treatments. Nitrogen pulses of this kind can be attributed to the reduction in plant uptake and the breakdown and decomposition of dead plant material (Vitousek et al. 1997). Weedy annual grasses such as cheatgrass can take advantage of these elevated nitrogen levels by increasing in size and seed production with higher rates of growth than perennial grasses (Monaco et al. 2003).

In summary, I have discussed the short-term outcomes of an attempt to establish native species in a crested wheatgrass stand using a successional-based approach. I have concluded that crested wheatgrass control methods may be unnecessary and that the direct seeding of desired species into a crested wheatgrass stand can lead to the establishment of native species. Since this was a short-term study, however, predicting the success or failure of these methods in the long-term is nearly impossible. To fully understand the plant community dynamics of this study, ongoing monitoring and careful evaluation will be required.

CHAPTER 6 – CONCLUSIONS AND MANAGEMENT IMPLICATIONS

The main objective of this research study was to investigate the feasibility of establishing native species in crested wheatgrass stands using a successional-based approach. Second, I wished to determine the effects of crested wheatgrass control methods and revegetation on crested wheatgrass, cheatgrass and native species density and cover. Lastly, I sought to determine if soil nitrate, ammonium and water concentrations were affected by crested wheatgrass control methods and revegetation. I hypothesized that 1) control methods and revegetation would decrease crested wheatgrass density and cover, 2) control methods and revegetation would increase the establishment of native species, 3) control methods and revegetation would increase cheatgrass density and cover, and 4) control methods and revegetation would initially increase soil nitrate, ammonium, and water concentrations.

I found that control methods and revegetation increased crested wheatgrass density and decreased crested wheatgrass cover. Control methods did not increase the establishment of native species as compared to the UD treatment and therefore led me to refute my second hypothesis. As predicted, cheatgrass density increased after control methods and revegetation yet cheatgrass cover decreased. The density of weedy species did not increase in the UD treatment. Finally, soil ammonium concentrations initially increased after control methods and revegetation. Soil nitrate concentrations were similar to pre-treatment levels initially following control methods and revegetation and then sharply increased in the second year, therefore partially supporting my hypothesis. By the second year both the soil ammonium concentration had decreased. I do not believe that the soil water content was affected by control methods or revegetation.

There have been proposals and in some cases mandates to restore and direct crested wheatgrass stands into more ecologically-healthy, diverse and sustainable plant communities that meet multiple land-use objectives. Land managers, however, are reluctant to invest time and money into revegetation projects due to the probability of failure. This study has shown that with an ecologically-based successional style of management that addresses site availability and species availability, native plant establishment in crested wheatgrass stands can be enhanced by directly seeding native species into a well prepared seedbed. This approach is not only efficient but cost effective since crested wheatgrass control is unnecessary. Land managers must be prepared, however, for an increase in weedy annual species that will result from disturbances such as crested wheatgrass control methods and seeding methods. These issues can be addressed with the long-term management of species performance.

Since this was a short-term study it is hard to predict the success or failure of such a revegetation project in the long-term. It is important to note that any revegetation project will require ongoing monitoring and evaluation to understand plant community dynamics. In the future the performance and persistence of the seeded species should be evaluated as should the status of crested wheatgrass and any weedy annual species.

BIBLIOGRAPHY

Anderson, J.E., and R.S. Inouye. 2001. Landscape-scale changes in plant species abundance and biodiversity of a sagebrush steppe over 45 years. Ecological Monographs. 71:531-556.

Bakker, J.D., J.M. Christian, S. D. Wilson, and J. Waddington. 1997. Seeding blue grama in old crested wheatgrass fields in southwestern Saskatchewan. Journal of Range Management. 50:156-159.

Bates, J.D., R.F. Miller, and T.J. Svejcar. 2005. Long-term successional trends following western juniper cutting. Journal of Rangeland Ecology and Management. 58:533-541.

Beckstead, J., and C.K. Augspurger. 2004. An experimental test of resistance to cheatgrass invasion: limiting resources at different life stages. Biological Invasions. 6:417-432.

Bishop, G.F., A.J. Davy, and R.L. Jefferies. 1978. Demography of *Hieracium pilosella* in a breck grassland. The Journal of Ecology. 66:615-629.

Broersma, K., M. Krzic, D.J. Thompson, and A.A. Bomke. 2000. Soil and vegetation of ungrazed crested wheatgrass and native rangelands. Canadian Journal of Soil Science. 80:411-417.

Chambers, J.C. 2000. Seed movements and seedling fates in disturbed sagebrush steppe ecosystems: implications for restoration. Ecological Applications. 10:1400-1413.

Chambers, J.C., and J.A. MacMahon. 1994. A day in the life of a seed: movements and fates of seeds and their implications for natural and managed systems. Annual Review of Ecology and Systematics. 25:263-292.

Chambers, J.C., B.A. Roundy, R.R. Blank, S.E. Meyer, and A. Whittaker. 2007. What makes Great Basin sagebrush ecosystems invasible by *Bromus tectorum*? Ecological Monographs. 77:117-145.

Christian, J.M., and S.D. Wilson. 1999. Long-term ecosystem impact of an introduced grass in the Northern Great Plains. Ecology. 80:2397-2407.

Cox, R.D., and V.J. Anderson. 2004. Increasing native diversity of cheatgrass-dominated rangeland through assisted succession. Journal of Range Management. 57:203-210.

Crawford, J.A., R.A. Olson, N.E. West, J.C. Mosley, M.A. Schroeder, T.D. Whitson, R.F. Miller, M.A. Gregg, and C.S. Boyd. 2004. Ecology and management of sage-grouse and sage-grouse habitat. Journal of Range Management. 57:2-10.

D'Antonio, C.M., and P.M. Vitousek. 1992. Biological invasions by exotic grasses, the grass/fire cycle, and global change. Annual Review of Ecology and Systematics. 23: 63-87.

Daubenmire, R.F. 1959. Canopy coverage method of vegetation analysis. Northwest Science 33:43-64.

Davis, M.A., J.P. Grime, and K. Thompson. 2000. Fluctuating resources in plant communities: a general theory of invasibility. The Journal of Ecology. 88:528-534.

Diaz, S., and M. Cabido. 2001. Vive la difference: plant functional diversity matters to ecosystem processes. Trends in Ecology & Evolution. 16:646-655.

Dukes, J.S. 2001. Biodiversity and invasibility in grassland microcosms. Oecologia. 126:563-568.

Egler, F.E. 1954. Vegetation science concepts I. Initial floristic composition, a factor in old field development. Vegetatio 4:412-417.

Elton, C.S. 1958. The ecology of invasions by animals and plants. Methuen, London. UK. 196 pp.

Evans, R.A., and J.A. Young. 1984. Microsite requirements for downy brome (*Bromus tectorum*) infestation and control on sagebrush rangelands. Weed Science. 32(Supplement 1):13-17.

Hawthorne, W.R., and P.B. Cavers. 1976. Population dynamics of the perennial herbs *Plantago major* L. and *P. rugelii* Decne. The Journal of Ecology. 64:511-527.

Heady, H.F. 1952. Reseeding, fertilizing, and renovating in an ungrazed mixed prairie. Journal of Range Management. 5:144-149.

Hector, A., K. Dobson, A. Minns, E. Bazeley-White, and J.H. Lawton. 2001. Community diversity and invasion resistance: an experimental test in a grassland ecosystem and a review of comparable studies. Ecological Research. 16:819-831.

Henderson, D.C., and M.A. Naeth. 2005. Multi-scale impacts of crested wheatgrass invasion in mixed-grass prairie. Biological Invasions. 7:639-650.

Holechek, J.L., R.D. Pieper, and C.H. Herbel. 2001. Range management principles and practices. Fourth Edition. Prentice-Hall, Inc., Upper Saddle River, NJ. 587 pp.

Hooper, D.U., and P.M. Vitousek. 1997. The effects of plant composition and diversity on ecosystem processes. Science. 277:1302-1305.

Houston, W.R. 1957. Renovation and fertilization of crested wheatgrass stands in the Northern Great Plains. Journal of Range Management. 10:9-11.

Hull, A.C., Jr., and G.J. Klomp. 1966. Longevity of crested wheatgrass in the sagebrush-grass type in southern Idaho. Journal of Range Management. 19:5-11.

Hull, A.C., Jr., and G.J. Klomp. 1967. Thickening and spread of crested wheatgrass stands on southern Idaho ranges. Journal of Range Management. 20:222-227.

Hyder, D.N., A.C. Everson, and R.E. Bement. 1971. Seedling morphology and seeding failures with blue grama. Journal of Range Management. 24:287-292.

Johnson, K.H., and C.E. Braun. 1999. Viability and conservation of an exploited sage grouse population. Conservation Biology. 13:77-84.

Kennedy, T.A., S. Naeem, K.M. Howe, J.M.H. Knops, D. Tilman, and P. Reich. 2002. Biodiversity as a barrier to ecological invasion. Nature. 417:636-638.

Kindschy, R.R. 1991. Alfalfa in crested wheatgrass seedings. Rangelands. 13:244-246.

Kinzig, A.P., S.W. Pacala, and D. Tilman (eds.). 2002. The Functional Consequences of Biodiversity. Princeton University Press, Princeton, NJ. 365 pp.

Krueger-Mangold, J., R. Sheley, R. Engel, J. Jacobsen, T. Svejcar, and C. Zabinski. 2004. Identification of the limiting resource within a semi-arid plant association. Journal or Arid Environments. 58:309-320.

Krueger-Mangold, J.M., R.L. Sheley, and T.J. Svejcar. 2006. Toward ecologically-based invasive plant management on rangeland. Weed Science. 54:597-605.

Krzic, M., L. Broersma, D.J. Thompson, and A.A. Bomke. 2000. Soil properties and species diversity of grazed crested wheatgrass and native rangelands. Journal of Range Management. 53:353-358.

Lavorel, S., A.H. Prieur-Richard, and K. Grigulis. 1999. Invasibility and diversity of plant communities: from patterns to process. Diversity and Distributions. 5:41-49.

Levine, J.M., and C.M. D'Antonio. 1999. Elton revisited: a review of evidence linking diversity and invisibility. Oikos. 87:15-26.

Lodge, R.W. 1960. Effects of burning, cultivating, and mowing on the yield and consumption of crested wheatgrass. Journal of Range Management. 13:318-321.

Mack, R.N., and D.A. Pyke. 1983. The demography of *Bromus tectorum*: variation in time and space. The Journal of Ecology. 71:69-93.

Marlette, G.M., and J.E. Anderson. 1986. Seed banks and propagule dispersal in crested-wheatgrass stands. The Journal of Applied Ecology. 23:161-175.

May, R.M. 1972. Will a large complex system be stable? Nature. 238:413-414.

Monaco, T.A., D.A. Johnson, J.M. Norton, T.A. Jones, K.J. Connors, J.B. Norton, and M.B. Redinbaugh. 2003. Contrasting responses of Intermountain West grasses to soil nitrogen. Journal of Range Management. 56:282-290.

Monsanto Company. 2004. Roundup original herbicide: complete directions for use. St. Louis, Missouri.

Monsen, S.B. 2004. History of range and wildlife habitat restoration in the intermountain west. Pages 1-5 *in* Monsen, S.B.; Stevens, R.; Shaw, N.L., comps. Restoring western ranges and wildlands. Gen. Tech. Rep. RMRS-GTR-136-vol-1. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Mooney, H.A., and E. E. Cleland. 2001. The evolutionary impact of invasive species. Proceedings of the National Academy of Sciences of the United States of America. 98:5446-5451.

Naeem, S., L.J. Thompson, S.P. Lawler, J.H. Lawton, and R.M. Woodfin. 1995. Empirical evidence that declining species diversity may alter the performance of terrestrial ecosystems. Philosophical Transactions: Biological Sciences. 347:249-262.

Nelson, J.R., A.M. Wilson, and C.J. Goebel. 1970. Factors influencing broadcast seeding in bunchgrass range. Journal of Range Management. 23:163-170.

Noy-Meir, I. 1973. Desert ecosystems: environment and producers. Annual Review of Ecology and Systematics. 4:25-41.

Pellant, M., and C.R. Lysne. 2005. Strategies to enhance plant structure and diversity in crested wheatgrass seedings. USDA Forest Service Proceedings RMRS-P-38: 81-92.

Pendery, B.M., and F.D. Provenza. 1987. Interplanting crested wheatgrass with shrubs and alfalfa: effects of competition and preferential clipping. Journal of Range Management. 40:514-520.

Pickett, S.T.A., S.L. Collins, and J.J. Armesto. 1987. Models, mechanisms and pathways of succession. The Botanical Review. 53:335-371.

Pokorny, M.L., R.L. Sheley, C.A. Zabinski, R.E. Engel, T.J. Svejcar, and J.J. Borkowski. 2005. Plant functional group diversity as a mechanism for invasion resistance. Restoration Ecology. 13:448-459.

Pyke, D.A. 1990. Comparative demography of co-occurring introduced and native tussock grasses: persistence and potential expansion. Oecologia. 82:537-543.

Ramsey, F.L., and D.W. Schafer. 2002. The statistical sleuth, a course in methods of data analysis. Second Edition. Duxbury Press, Belmont, CA. 768 pp.

Ries, R.E., and T.J. Svejcar. 1991. The grass seedling: when is it established? Journal of Range Management. 44:574-576.

Rogler, G.A., and R.J. Lorenz. 1983. Crested wheatgrass – early history in the United States. Journal of Range Management. 36:91-93.

SAS Institute, Inc. 2002-2003. SAS System for Microsoft Windows. SAS Institute, Cary, North Carolica, USA.

Sheley, R.L., and J.M. Krueger-Mangold. 2003. Principles for restoring invasive plant-infested rangeland. Weed Science. 51:260-265.

Sheley, R.L., J.M. Mangold, and J.L. Anderson. 2006. Potential for successional theory to guide restoration of invasive-plant-dominated rangeland. Ecological Monographs. 76:365-379.

Sheley, R.L., T.J. Svejcar, and B.D. Maxwell. 1996. A theoretical framework for developing successional weed management strategies on rangeland. Weed Technology. 10:766-773.

Silvertown, J.W., and J.B. Dickie. 1981. Seedling survivorship in natural populations of nine perennial chalk grassland plants. New Phytologist. 88:555-558.

Stewart, G., and A.C. Hull. 1949. Cheatgrass (*Bromus tectorum* L.) – an ecological intruder in southern Idaho. Ecology. 30:58-74.

Stoddart, L.A., and A.D. Smith. 1955. Range management. Second Edition. McGraw-Hill, NY. 433 pp.

Stohlgren, T.J., D. Binkley, G.W. Chong, M.A. Kalkhan, L.D. Schell, K.A. Bull, Y. Otsuki, G. Newman, M. Bashkin, and Y. Son. 1999. Exotic plant species invade hot spots of native plant diversity. Ecological Monographs. 69:25-46.

Symstad, A.J. 2000. A test of the effects of functional group richness and composition on grassland invisibility. Ecology. 81:99-109.

Thines, N.J. Siegel, L.A. Shipley, and R.D. Sayler. 2004. Effects of cattle grazing on ecology and habitat of Columbia Basin pygmy rabbits (*Brachylagus idahoensis*). Biological Conservation. 119:525-534.

Thomas, A.G., and H.M. Dale. 1975. The role of seed reproduction in the dynamics of established populations of *Hieracium floribundum* and a comparison with that of vegetative reproduction. Canadian Journal of Botany. 53:3022-3031.

Tilman, D. 1999. The ecological consequences of changes in biodiversity: a search for general principles. Ecology. 80:1455-1474.

Tilman, D., and C. Lehman. 2001. Biodiversity, composition, and ecosystem processes: theory and concepts. Pages 9-41 *in* A.P. Kinzig, S.W. Pacala, and D. Tilman, editors. The Functional Consequences of Biodiversity. Princeton University Press, Princeton, New Jersey. USA

Tilman, D., J. Knops, D. Wedin, P. Reich, M. Ritchie, and E. Siemann. 1997. The influence of functional diversity and composition on ecosystem processes. Science. 277:1300-1302.

Tilman, D., D. Wedin, and J. Knops. 1996. Productivity and sustainability influenced by biodiversity in grassland ecosystems. Nature. 379:718-720.

United States Department of Agriculture, Natural Resource Conservation Service (USDA NRCS). 1996. Ecological site description: loamy 10-12" pz. NRCS OR MLRA: D23.

United States Department of the Interior, Bureau of Land Management (USDI BLM). 2005. Wildlife and fisheries management. BLM Manual Section 6500.1.

United States Department of the Interior, United States Fish and Wildlife Service (USDI USFWS). 2001. National wildlife refuge system: biological integrity, diversity, and environmental health. 601 FW 3.

Vallentine, J.F. 1980. Range development and improvements. Second Edition. Brigham Young University Press, Provo, Utah. 545 pp.

Vitousek, P.M., J.D. Aber, R.W. Howarth, G.E. Likens, P.A. Matson, D.W. Schindler, W.H. Schlesinger, and D. Tilman. 1997. Human alterations of the global nitrogen cycle: sources and consequences. Ecological Applications. 7:737-750.

Wark, D.B., L.K. Gabruch, C. Penner, R.J. Hamilton, and T.G. Koblun. 2004. Revegetating with native grasses in the northern great plains. Ducks Unlimited Canada, Stonewall, Manitoba. 60 pp.

West, N.E., and T.P. York. 2002. Vegetation responses to wildfire on grazed and ungrazed sagebrush semi-desert. Journal of Range Management. 55:171-181.

Whisenant, S.G. 1999. Repairing damaged wildlands. Cambridge University Press, Cambridge, MA. 324 pp.

Western Regional Climate Center (WRCC). 2007. P ranch refuge, Oregon. (Online: http://www.wrcc.dri.edu/summary/Climsmor.html). [August 15, 2007].

APPENDIX

Seeded species, including their origin and commercial source, and seeding rates.

Species	**Kind/ Variety**	**Commercial Source**	**Seeding Rate (lb. PLS/acre)**
Wyoming big sagebrush (*Artemisia tridentata* spp. *wyomingensis* Nutt.)		Maple Leaf	0.20
fourwing saltbush (*Atriplex canescens* (Pursh) Nutt.)		L&H Seed	1.0
white-stemmed rabbitbrush (*Chrysothamnus nauseosus* spp. *albicaulis* (Pall.) Britt.)		L&H Seed	0.25
Lewis flax (*Linum lewisii* Pursh)	Appar	Maple Leaf	0.75
Western yarrow (*Achillea millefolium* L.)	Eagle mountain	Landmark Seed	0.20
Munro globemallow (*Sphaeralcea munroana* (Dougl.) Spach)		Maple Leaf	0.50
bluebunch wheatgrass (*Pseudoroegneria spicata* Pursh)	Anatone	Landmark Seed	3.0
Sandberg's bluegrass (*Poa sandbergii* Vasey)	Mountain Home	Landmark Seed	0.75
squirreltail (*Elymus elymoides* spp. *elymoides* (Raf.) Swezey)	Toe Jam Creek	Landmark Seed	2.0
Indian ricegrass (*Stipa hymenoides* Roemer & Schultes)	Nezpar	Landmark Seed	2.0