Using successional theory to guide restoration of invasive plant dominated rangeland
by Jennifer Lisa Anderson

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Land Rehabilitation
Montana State University

Abstract:
Invasive plant management must progress from simply treating symptoms to modifying processes that cause plant community dynamics. The overall goal of this research was to test a theoretical framework for developing successional weed management strategies on rangeland. I hypothesized that by increasingly addressing the three general causes of succession—site availability, species availability, species performance—in a complementary manner, the successional trajectory will be accelerated toward a desired plant community. I tested the influence of two seeding methods (site availability), three seeding rates (species availability), three herbicide treatments (species performance), and two cover crop treatments (species performance) on the establishment of three seeded grasses (Psuedoreogneria spicata, Festuca scabrella, Festuca idahoensis) and the density, richness, and diversity of existing native species. I hypothesized that no-till drill seeding at the highest rate with a cover crop in combination with a picloram application would result in the highest establishment of grasses, but that picloram would negatively impact the native forb community. The study was conducted as a factorially arranged randomized complete block, replicated four times across the study site. Treatments were applied in the fall of 2001 and the summer of 2002. Densities of all species within 0.1m sampling frames were measured in 2002. No-till drill seeding at the highest rate resulted in the highest establishment of seeded grasses. Picloram improved establishment of F. idahoensis over 2,4-D, but neither treatment differed from the control. The addition of a cover crop did not influence grass establishment. Seeding methods, seeding rates, and cover crop did not consistently influence the density, richness, and diversity of the existing plant community, but the herbicide treatments did. In the spring, these parameters were reduced by picloram and in the summer they were most influenced by 2,4-D. This research suggests that establishment of seeded native grasses improves as management techniques increasingly address the three general causes of succession. However, the variation observed in species' response to management techniques, especially the existing plant community, emphasizes the importance of monitoring invasive plant dominated rangeland throughout the restoration process.

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A thesis submitted in partial fulfillment
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# APPROVAL

of a thesis submitted by

Jennifer Lisa Anderson

This thesis has been read by each member the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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# ABSTRACT

Invasive plant management must progress from simply treating symptoms to modifying processes that cause plant community dynamics. The overall goal of this research was to test a theoretical framework for developing successional weed management strategies on rangeland. I hypothesized that by increasingly addressing the three general causes of succession—site availability, species availability, species performance—in a complementary manner, the successional trajectory will be accelerated toward a desired plant community. I tested the influence of two seeding methods (site availability), three seeding rates (species availability), three herbicide treatments (species performance), and two cover crop treatments (species performance) on the establishment of three seeded grasses (*Psuedoroegneria spicata*, *Festuca scabrella*, *Festuca idahoensis*) and the density, richness, and diversity of existing native species. I hypothesized that no-till drill seeding at the highest rate with a cover crop in combination with a picloram application would result in the highest establishment of grasses, but that picloram would negatively impact the native forb community. The study was conducted as a factorially arranged randomized complete block, replicated four times across the study site. Treatments were applied in the fall of 2001 and the summer of 2002. Densities of all species within 0.1m sampling frames were measured in 2002. No-till drill seeding at the highest rate resulted in the highest establishment of seeded grasses. Picloram improved establishment of *F. idahoensis* over 2,4-D, but neither treatment differed from the control. The addition of a cover crop did not influence grass establishment. Seeding methods, seeding rates, and cover crop did not consistently influence the density, richness, and diversity of the existing plant community, but the herbicide treatments did. In the spring, these parameters were reduced by picloram and in the summer they were most influenced by 2,4-D. This research suggests that establishment of seeded native grasses improves as management techniques increasingly address the three general causes of succession. However, the variation observed in species' response to management techniques, especially the existing plant community, emphasizes the importance of monitoring invasive plant dominated rangeland throughout the restoration process.

# CHAPTER 1

# INTRODUCTION

Nonindigenous plants dominate and continue to spread throughout millions of hectares of rangeland in the western United States (Sheley and Petroff 1999). They disrupt the structure and function of prairie ecosystems by displacing native plant species (Belcher and Wilson 1989, Miller et al. 1994), altering soil water dynamics through increased erosion and reduced infiltration (Lacey et al. 1989), disrupting nutrient cycling (Chapin et al. 1997), and altering disturbance regimes like fire frequency (Mack 1981, Olson et al. 1997, Vitousek et al. 1996, Whisenant 1989). Invasive species also have substantial economic impacts. In Montana alone, it is estimated that *Centaurea maculosa* Lam. costs the livestock industry $11 million a year (Hirsch and Leitch 1996), and if allowed to spread to its potential range could cost as much as $155 million (Sheley et al. 2000).

Invasive plant management usually focuses on weed control with little regard for ecological processes and mechanisms promoting invasion and dominance (Hobbs and Humphries 1995). Sheley et al. (1996) proposed that a more appropriate goal for rangeland weed management would be to develop an ecologically healthy plant community that is relatively weed-resistant and meets land-use objectives. A healthy weed-resistant plant community should efficiently captures energy, has properly functioning hydrologic and nutrient cycles, and includes functionally diverse plant species that occupy most of the niches within the community (Chapin et al. 1997, Whisenant 1999). When most niches are occupied, few resources are available for exploitation by invading species (Carpinelli 2000, Dukes 2001, Pyke and Archer 1991). However, weed control procedures are alone often do not result in a desired plant community because the desired species are not available at the site to occupy niches opened by control procedures (Jacobs et al. 1998, James 1992). In order to achieve a desired plant community, invasive plant management must modify the processes and mechanisms directing plant community dynamics and structure (Luken 1997, Pyke and Archer 1991, Sheley et al. 1996).

Successional management recognizes plant communities as dynamic systems and uses successional theory to direct management implementation. Range management has been based on classical successional theory, which suggests succession is unidirectional with a predetermined climax community (Clements 1916). This theory, however, is not helpful in determining invasive plant management practices and is a poor predictor of community response to management (Allen-Diaz and Bartolome 1998, Grime et al. 1988, Noble and Slatyer 1980). Sheley et al. (1996) and Luken (1997) propose using the hierarchical model of succession developed by Pickett et al. (1987b) as a framework to develop management strategies. This model proposes three general causes of succession—site availability, species availability, species performance—controlling processes, and their modifying factors. The value in this theory is that current restoration and weed management techniques can easily be incorporated into the factors that modify processes driving succession (Sheley et al. 1996).

Increasingly, restoring functionally diverse plant communities is being proposed as a means of controlling weeds (Berger 1993, Jacobs and Sheley 1999a). There is broad knowledge on establishing native grasses (Packard and Mutel 1997, Whisenant 1999). Using a no-till drill, native perennial grasses have been successfully established on a highly disturbed mine site in Colorado (Doerr and Redente 1983), permanent pasture in Iowa (Jackson 1999), and retired cropland in California (Montalvo et al. 2002). Native perennial grasses have also successfully established following broadcast seeding combined with tilling (Bakker et al. 2003) and large shovel-sized holes (Chambers 2000a). When seeding into vegetation dominated by invasive species, Velegala (1996) found grass establishment improved as seeding rate increased. Herron et al. (2001) found that seeding a late seral bunchgrass with a species capable of sequestering nitrogen, shifted the competitive advantage from the invasive forb to the desired bunchgrass.

One of the most common reasons for seeding failure is competition from invasive species (Velagala et al. 1997). Methods for controlling invasive plants range from selective herbicides to intensive grazing to controlled fire (Masters and Nissen 1998, Olson et al. 1997, Sheley and Petroff 1999). In western Montana, the invasive perennials *C. maculosa* and *Potentilla recta* L. are two of the most common noxious rangeland weeds (Rice 1991, Sheley et al. 1998, Sheley and Petroff 1999). One of the most effective means of controlling these two species is broadleaf selective herbicides. Picloram, clopyralid, and 2,4-D, offer good control of *C. maculosa,* with picloram providing 3 to 5 years of control (Lacey et al. 1999, McKone et al. 1989). *Potentilla recta* does not respond to clopyralid, but is sensitive to picloram and 2,4-D (Rice 1999).

The long term control provided by picloram limits broadleaf competition with seeded grass species during the critical first two years of establishment (Sheley et al. 2001). Good short term control is provided by 2,4-D, which has a short soil residual (Bussan and Dyer 1999, Jacobs and Sheley 1999b). Incorporating weed control methods into restoration practices is critical in promoting establishment of seeded grasses (Sheley et al. 2001).

While there a considerable knowledge on the ecology and mechanics of controlling invasive species and restoring degraded grasslands, little research has tested proven practices within the framework of current successional theory (Allen-Diaz and Bartolome 1998, Wali 1999). In a cursory study by Anderson et al. (2002), the rate of establishment of two native perennial grasses on invasive plant dominated rangeland improved when the three general causes of succession (Pickett et al. 1987b) were addressed in a complimentary manner during revegetation. More studies are needed that apply our knowledge on the conditions, mechanisms, and processes controlling plant community dynamics, and managing invasive species through the manipulation of successional pathways. The potential of successional theory to guide the development and implementation of effective integrated invasive plant management is substantial, but largely untested.

The overall goal of this research was to test a theoretical framework for developing successional weed management strategies on rangeland. My underlying hypothesis was that as weed management strategies increasingly address the three general causes of succession—site availability, species availability, species performance—in a complementary manner, the successional trajectory will be accelerated toward a desired plant community (Pickett et al. 1987a, Sheley et al. 1996). The study was conducted to meet four objectives and test four hypotheses. The four objectives were:

I. To determine the effects of two different seeding methods, no-till drill seeding and broadcasting over small holes, on the establishment of desired grasses and density, diversity, and richness of existing native vegetation. This objective addressed site availability. As seeding method increased the number of available safe-sites for desired species, seedling establishment would increase to the extent seeds of desired species were available. I hypothesized that seedling establishment would be greatest in plots that were drill seeded and the native forb community would not be affected by the disturbance.

II. To determine at which seeding rate desired grasses most successfully established and how the various seeding rates affected existing vegetation. This objective addressed species availability. By increasing species availability, establishment would increase to the extent of safe-sites availability. I hypothesized establishment would be the most successful with the highest seeding rate and would not affect the density, richness, and Simpson's diversity of the native forb community.

III. To evaluate the effects of using a herbicide to reduce competition between invasive plants and seedlings of desired species and monitor the response of the native plant community to the herbicides. This objective addressed species performance by reducing competition between the desired species and invasive plants to enhance establishment of desired species. I hypothesized that picloram would reduce competition long enough for the desired grasses to successfully establish but would negatively impact the native forb community.

IV. To assess whether or not the addition of a cover crop would enhance seedling establishment or influence existing native species. This objective also addressed species performance. I hypothesized the cover crop would reduce plant available nitrogen giving a competitive advantage to the desired grasses thereby improving their establishment and would not affect the native forb community.

## References Cited

Allen-Diaz, B. and J. W. Bartolome. 1998. Sagebrush-grass vegetation dynamics: comparing classical and state-transition models. Ecological Applications 8(3):795-804.

Anderson, J. L., J. S. Jacobs and R. L. Sheley. 2002. Using successional management to restore invasive plant dominated wildlands. *In* The Ecological Society of America 87th Annual Meeting, Tucson, AZ.

Bakker, J. D., S. D. Wilson, J. M. Christian, X. Li, L. G. Ambrose and J. Waddington. 2003. Contingency of grassland resotration on year, site, and competition form introduced grasses. Ecological Applications 13(1):137-153.

Belcher, J. W. and S. D. Wilson. 1989. Leafy spurge and species composition of a mixed-grass prairie. Journal of Range Management 42:172-175.

Berger, J. J. 1993. Ecological restoration and nonindigenous plant species: a review. Restoration Ecology 1:74-82.

Bussan, A. J. and W. E. Dyer. 1999. Herbicides and Rangeland. *In:* Biology and Management of Noxious Rangeland Weeds (*ed*) R. L. Sheley and J. K. Petroff, pp. 116-132. Oregon State University Press, Corvallis.

Carpinelli, M. F. 2000. Designing weed-resistant plant communities by maximizing niche occupation and resource capture. Thesis (Doctor of Philososhy) Montana State University.

Chambers, J. C. 2000a. Seed movements and seedling fates in disturbed sagebrush steppe ecosystems: implications for restoration. Ecological Applications 10(5):1400-1413.

Chambers, J. C. 2000b. Using threshold and alternative state concepts to restore degraded or disturbed ecosystems. *In* High Altitude Revegetation Workshop no. 14. Information series (Colorado Water Resources Research Institute); no. 91, pp. 134-145. Colorado State University, Colorado State University, Fort Collins, Colorado.

Chambers, J. C. and A. R. Linnerooth. 2001. Restoring riparian meadows currently dominated by *Artemisia* using alternative state concepts--the establishment component. Applied Vegetation Science 4:157-166.

Chapin, F. S., III, , B. H. Walker, R. J. Hobbs, D. U. Hooper, J. H. Lawton, O. E. Sala and T. Tilman. 1997. Biotic control over the functioning of ecosystems. Science 277(25 July):500-504.

Clements, F. E. 1916. Plant succession: an analysis of the development of vegetation., pp. 512. Carnegie Institution of Washington, Washington, D. C.

Doerr, T. B. and E. F. Redente. 1983. Seeded plant community changes on intensively disturbed soils as affected by cultural practices. Reclamation and Revegetation Research 1983(2):13-24.

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

Grime, J. P., J. G. Hodgson and R. Hunt. 1988. Comparative plant ecology: a functional approach to common British species. Unwin Hyman, London, UK.

Herron, G. J., R. L. Sheley, B. D. Maxwell and J. S. Jacobsen. 2001. Influence of nutrient availability on the interaction between spotted knapweed and bluebunch wheatgrass. Restoration Ecology 9(3):326-331.

Hirsch, S. A. and J. A. Leitch. 1996. The impact of knapweed on Montana's economy. *In* Agriculture Economic Report, pp. 44. North Dakota State Universtiy, Fargo, ND.

Hobbs, R. J. and S. E. Humphries. 1995. An integrated approach to the ecology and management of plant invasions. Conservation Biology 9(4):761-770.

Jackson, L. L. 1999. Establishing tallgrass prairie on grazed permanent pasture in the upper midwest. Restoration Ecology 7(2):127-138.

Jacobs, J. S., M. F. Carpinelli and R. L. Sheley. 1998. Revegetating Weed-Infested Rangeland: What We've Learned. Rangelands 20(6):10-15.

Jacobs, J. S. and R. L. Sheley. 1999a. Competition and niche partitioning among *Pseudoroegneria spicata*, *Hedysarum boreale*, and *Centaurea maculosa*. Great Basin Naturalist 59(2):175-181.

Jacobs, J. S. and R. L. Sheley. 1999b. Spotted knapweed, forb, and grass response to 2,4-D and N-fertilizer. Journal of Range Management 52:482-488.

James, D. 1992. Some principles and practices of desert revegetation seeding. Arid Lands Newsletter 32:22-27.

Lacey, C. A., J. R. Lacey, P. K. Fay, J. M. Story and D. L. Zamora. 1999. Controlling Knapweed on Montana Rangeland, pp. 1-17. Montana State University Extension Service, Bozeman.

Lacey, J. R., C. B. Marlow and J. R. Lane. 1989. Influence of spotted knapweed (*Centaurea maculosa*) on surface runoff and sediment yield. Weed Technology 3:627-631.

Luken, J. O. 1997. Management of Plant Inavasions: Implicating Ecological Succession. *In:* Assessment and Management fo Plant Invasions (*ed*) J. O. Luken, pp. 133-144. Springer-Verlag, New York.

Mack, R. N. 1981. Invasion of *Bromus tectorum* L. into western North America: an ecological chronicle. Agroecosystems 7:145-165.

Masters, R. A. and S. J. Nissen. 1998. Revegetating Leafy Spurge (*Euphorbia esula*)-Infested Rangeland with Native Tallgrasses. Weed Technology 12:381-390.

McKone, M. B., C. A. Lacey and D. Bedunah. 1989. Evaluation of clopyralid rate and time of application on spotted knapweed (*Centaurea maculosa*). *In* Knapweed Symposium *ed:* P. K. Fay and J. R. Lacey, pp. 83-94. Plant and Soil Science Department and Extension Service, Montana State University, Bozeman, Montana.

Miller, R. F., T. J. Svejcar and N. E. West. 1994. Implications of livestock grazing in the Intermounain sagebrush region: plant composition. *In:* Ecological implications of livestock herbivory in the west (*ed*) M. Vavra, W. A. Laycock and R. D. Pieper. Society of Range Management, Denver, CO.

Montalvo, A. M., P. A. McMillan and E. B. Allen. 2002. The relative importance of seeding method, soil ripping, and soil variables on seeding success. Restoration Ecology 10(1):52-67.

Noble, I. R. and R. O. Slatyer. 1980. The use of vital attributes to predict successional changes in plant communities subject to recurrent disturbances. Vegetatio 43:5-21.

Olson, B. E., R. T. Wallander and J. R. Lacey. 1997. Effects of sheep grazing on a spotted knapweed-infested Idaho fescue community. Journal of Range Management 50:386-390.

Packard, S. and C. F. Mutel. 1997. The Tallgrass Restoration Handbook, pp. 463. Island Press, Washington D. C.

Pickett, S. T. A., S. L. Collins and J. J. Armesto. 1987a. A hierarchical consideration of causes and mechanisms of succession. Vegetatio 69:109-114.

Pickett, S. T. A., S. L. Collins and J. J. Armesto. 1987b. Models, mechanisms and pathways of succession. The Botanical Review 53(3):335-371.

Pyke, D. A. and S. Archer. 1991. Plant-plant interactions affecting plant establishment and persistence on revegetated rangeland. Journal of Range Management 44(2):550-557.

Rice, P. M. 1991. Sulfur Cinquefoil: a new thrreat to biological diversity. Western Wildlands 17:34-40.

Rice, P. M. 1999. Sulfur Cinquefoil. *In:* Biology and Management of Noxious Rangeland Weeds (*ed*) R. L. Sheley and J. K. Petroff, pp. 382-388. Oregon State University Press, Corvallis, Oregon.

Sheley, R. L., J. S. Jacobs and M. F. Carpinelli. 1998. Distribution, biology, and management of diffuse knapweed (*Centaurea diffusa*) and spotted knapweed (*Centaurea maculosa*). Weed Technology 12:353-362.

Sheley, R. L., J. S. Jacobs and D. E. Lucas. 2001. Revegetating spotted knapweed infested rangeland in a single entry. Journal of Range Management 54:144-151.

Sheley, R. L., B. E. Olson and C. Hoopes. 2000. Impacts of noxious weeds on the ecology and economy of Montana. EB 152. Montana State University Extension, Bozeman, Montana.

Sheley, R. L. and J. K. Petroff. 1999. Biology and Management of Noxious Rangeland Weeds, pp. 438. Oregon State University Press, Corvallis.

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.

Velagala, R. P. 1996. Using seed rate and plant densities to enhance intermediate wheatgrass establishment in spotted knapweed dominated rangeland. Thesis (M. S.) Montana State University.

Velagala, R. P., R. L. Sheley and J. S. Jacobs. 1997. Influence of density on intermediate wheatgrass and spotted knapweed interference. Journal of Range Management 50:523-529.

Vitousek, P. M., C. M. D'Antonio, L. L. Loope and R. Westbrooks. 1996. Biological invasions as global environment change. American Scientist 84(5):468-479.

Wali, M. K. 1999. Ecological succession and the rehabilitation of disturbed terrestrial ecosystems. Plant and Soil 213:195-220.

Whisenant, S. G. 1989. Changing fire frequencies on Idaho's Snake River Plains: ecological and management implicaitons. *In* Symposium on cheatgrass invasion, shrub die-off, and other aspects of shrub biology and management. INT-276 *ed.* E. D. McArthur, E. V. Romney, S. D. Smith and P. T. Tueller, pp. 4-10. USDA Forest Service Intermountain Research Station General Technical Report, Las Vegas, NV.

Whisenant, S. G. 1999. Repairing Damaged Wildlands: A Process-Orientated, Landscape-Scale Approach. Cambridge University Press, Cambridge, United Kingdom.

Willson, G. D. and J. Stubbendieck. 2000. A provisional model for smooth brome management in degraded tallgrass prairie. Ecological Restoration 18(1):34-44.

## CHAPTER 2

# USING SUCCESSIONAL THEORY TO GUIDE RESTORATION OF INVASIVE PLANT DOMINATED RANGELAND: ESTABLISHING NATIVE GRASSES

### Introduction

Invasive plants dominate and continue to spread throughout millions of hectares in the western United States (Sheley and Petroff 1999). They alter the structure and function of ecosystems and threaten biological diversity (Randall 1996, Vitousek et al. 1996, Olson 1999). Invasive plants increase soil erosion, reduce infiltration (Lacey et al. 1989), and displace native plant species (Belcher and Wilson 1989, Miller et al. 1994). Economically, weeds cost millions of dollars annually in control and lost production (Hirsch and Leitch 1996, Pimentel 2002). In Montana alone, it is estimated that spotted knapweed (*Centaurea maculosa* Lam.) costs the livestock industry $11 million a year (Hirsch and Leitch 1996), and if allowed to spread to its potential range could cost as much as $155 million (Sheley et al. 2000b).

Current control efforts often focus on the weed rather than the ecological processes and mechanisms promoting invasion and dominance (Hobbs and Humphries 1995). On rangeland where desirable species are not available to occupy niches opened by weed control procedures like herbicides (Davis et al. 1993), herbicides combined with fertilizers (Sheley and Jacobs 1997), natural enemies (Cuda et al. 1989, Story et al. 1991), or sheep grazing (Cox 1989, Olson et al. 1997), long-term control of *C. maculosa* is generally unsuccessful and desired plant communities do not result from these procedures applied alone or in combination (James 1992, Sheley et al. 1996). In order to achieve the desired plant community, invasive plant management must modify processes and mechanisms directing plant community dynamics and structure (Pyke and Archer 1991, Sheley et al. 1996, Luken 1997).

Successional management recognizes plant communities as dynamic systems and uses successional theory to direct management implementation. Range management has been based on classical successional theory, which suggests succession is unidirectional with a predetermined climax community (Clements 1916). This theory, however, is not helpful in determining invasive plant management practices and is a poor predictor of community response to management ( Noble and Slatyer 1980, Grime et al. 1988, Allen-Diaz and Bartolome 1998). Sheley et al. (1996) and Luken (1997) propose using the hierarchical model of succession developed by Pickett et al. (1987b) as a framework to develop management strategies. This model proposes three general causes of succession—site availability, species availability, species performance—controlling processes, and their modifying factors. The value in this theory is that current restoration and weed management techniques can easily be incorporated into the factors that modify processes driving succession (Sheley et al. 1996).

Increasingly, restoring functionally diverse plant communities is being proposed as a means of controlling weeds (Berger 1993, Jacobs and Sheley 1999a). There is broad knowledge on establishing native grasses (Packard and Mutel 1997, Whisenant 1999). Using a no-till drill, native perennial grasses have been successfully established on a highly disturbed mine site in Colorado (Doerr and Redente 1983), permanent pasture in

Iowa (Jackson 1999), and retired cropland in California (Montalvo et al. 2002). Native perennial grasses have also successfully established following broadcast seeding combined with tilling (Bakker et al. 2003) and large holes (Chambers 2000a). When seeding into vegetation dominated by invasive species, Velegala (1996) found grass establishment to improve as seeding rate increased. Herron et al. (2001) found seeding a late seral bunchgrass with a species capable of sequestering nitrogen, shifted the competitive advantage from the invasive forb to the desired bunchgrass. However, one of the most common reasons for seeding failure is competition from invasive species (Velagala et al. 1997).

Methods for controlling invasive plants range from selective herbicides to intensive grazing to controlled fire ( Olson et al. 1997, Masters and Nissen 1998, Sheley and Petroff 1999). In western Montana, the perennials *C. maculosa* and *Potentilla recta* L. are two of the most common noxious rangeland weeds (Rice 1991, Sheley et al. 1998, Sheley and Petroff 1999). One of the most effective means of controlling these two species is broadleaf selective herbicides. Picloram, clopyralid , and 2,4-D, provide good control of *C. maculosa,* with picloram providing 3 to 5 years of control ( McKone et al. 1989, Lacey et al. 1999). *Potentilla recta* does not respond to clopyralid, but is sensitive to picloram and 2,4-D (Rice 1999). The long term control provided by picloram limits competition with seeded grass species during the critical first couple years of establishment (Sheley et al. 2001). Two,4-D provides good short term control and has a low soil residual (Bussan and Dyer 1999, Jacobs and Sheley 1999b). Incorporating weed control methods into restoration practices is critical in promoting establishment of seeded grasses (Sheley et al. 2001).

Little research has tested management practices within the framework of current successional theory (Allen-Diaz and Bartolome 1998, Wali 1999). In a cursory study by Anderson et al. (2002), the rate of establishment of two native perennial grasses on invasive plant dominated rangeland improved when the three general causes of succession (Pickett et al. 1987b) were addressed in a complimentary manner during revegetation. More studies are needed that apply our knowledge about the conditions, mechanisms, and processes controlling plant community dynamics and managing invasive species through manipulating successional pathways. The potential of successional theory to guide the development and implementation of effective integrated invasive plant management is substantial, but largely untested.

The overall goal of this study was to test a theoretical framework for developing successional weed management strategies on rangeland. My underlying hypothesis was that as weed management strategies increasingly address the three general causes of succession—site availability, species availability, species performance—in a complementary manner, the successional trajectory will be accelerated toward a desired plant community (Pickett et al. 1987a, Sheley et al. 1996). There were four objectives to this study. The first objective tested the effect of three seeding methods had on native grass establishment. This objective addressed site availability through two seeding methods, no-till drill and broadcast over small depressions. I hypothesized that drill seeding would increase the likelihood of a seed ending up in a site suitable for germination and emergence, thereby increasing establishment. The second objective tested the influence of seeding rate on grass establishment. Species availability was addressed by this objective. I seeded a native grass seed mix at three rates and hypothesized that, to the extent safe sites were available, establishment would be most successful at the highest rate. Objective three tested the influence of two broadleaf selective herbicides, picloram (4-amino-3,5,6 trichloropicolinic acid) and 2,4-D amine (2,4-dichlorophenoxyacetic acid, dimethylamine salt), on grass establishment. This objective attempted to manipulate species performance. I hypothesized that picloram would reduce competition long enough for the desired grasses to successfully establish. Species performance was also addressed in the fourth objective, seeding with and without a cover crop. The effect of including a cover crop on grass seedling establishment was tested by this objective. I hypothesized that an early seral species would reduce plant available nitrogen.

## Methods

### Study Site

This study was conducted on the Kicking Horse Wildlife Mitigation Area south of Ronan, Montana (47° 29 N, 114° 5 W). The site was a *Festuca scabrella/Pseudoroegneria spicata* habitat type interspersed with ephemeral prairie pothole wetlands (Mueggler and Stewart 1980). It was dominated by various non-native plant species including *C. maculosa* and *P. recta* . The most common exotic grasses were *Poa compressa* L., *Poa pratensis* L., *Bromus tectorum* L., and *Dactylis glomerata*

L. There were remnant stands of native plants, including *Achillea millifolium* (L.), *Anemone cylindrica* Gray, *Antennaria* spp., *Arnica sororia* Greene, *Castilleja pallescens* (Gray) Greene, *Danthonia intermedia* Vasey, *Festuca idahoensis* Elmer., *Geum triflorum* Pursh, *Koeleria cristata* Pers., *Lomatium triternatum* (Pursh) Coult. & Rose, and *Poa sandbergii* Vasey. Historical disturbances associated with this site were grazing by cattle, limited agricultural practices, and intense meadow vole (*Microtis pennsylvanicus*) activity. The more palatable grasses of this habitat type, *F. scabrella* and *P. spicata*, were far less common than the less palatable species, *F. idahoensis*, *P. sanbergii*, and *Danthonia intermedia* Vasey.

The soil is a Post-Ronan-Water complex. It is a deep, well drained silt loam and silty clay loam (glaciolacustrine deposits) with sodic properties within the top 76 cm. The slope varies from 2 to 15 percent and the elevation is 940 m. The average annual precipitation ranges from 350-450 mm per year and the average temperature is 7.6 °C.

## Experimental Design

The study was conducted as a factorially (3 herbicides x 2 cover crops x 3 seeding rates x 2 seeding methods=36) arranged randomized complete block. Replications were located in three locations across the landscape, with one location containing two blocks. I established 144 plots (11.0 x 36.6 m each), 36 in each of four blocks. The 36 treatment combinations were randomly assigned and applied as whole plot treatments. The three herbicide treatments were picloram at 0.28 kg a.i. ha$^{-1}$, 2,4-D amine at 2.2 kg a.i. ha$^{-1}$, and a control with no herbicide. The cover crop treatments included seeding with and without a cover crop of winter wheat (*Triticum aestivum* L.). I seeded a mix of three native grasses (bluebunch wheatgrass [*Pseudoroegneria spicata* (Pursh) Scribn. and Smith], Idaho fescue [*Festuca idahoensis* Elmer], and rough fescue [*Festuca scabrella* Torrey ex Hook.]) at three rates; low (977 pure live seed (PLS) $m^{-2}$), intermediate (1322 PLS $m^{-2}$), and high (1557 PLS $m^{-2}$) (Velagala 1996). The two different seeding methods utilized were no-till drill seeding and broadcast seeding following soil surface disturbance.

## Procedures

During the first week of November 2001, picloram was applied using a pick-up truck mounted with a chemical injection sprayer having a boom width of 12.0 m. Approximately 241 L $ha^{-1}$ of solution was applied with a single pass over the plot. Conditions were overcast, wind <8 km $hr^{-1}$, 70% humidity, and a temperature of 6.4 °C. Because of the lack of precipitation during August and September (Figure 2.1), very few adult *C. maculosa* or *P. recta* plants initiated fall regrowth. Since these were target weed species, the 2,4-D treatment was postponed until the following summer. When the seeded grass species reached the 3- to 6-leaf growth stage in the second week of July 2003, 2,4-D amine was applied using an ATV mounted pressurized sprayer with a spray width of 3.6 m. The unit delivered approximately 210 L $ha^{-1}$ of solution. Conditions were clear, wind <8 km $hr^{-1}$, 52% humidity, and a temperature of 26 °C.

All plots were seeded immediately following the application of picloram in November 2001. The native seed mix was blended to ensure the same number of live seeds of each species, *P. spicata*, *F. idahoensis*, and *F. scabrella*, per kilogram of the seed mix. A Truax® native seed no-till range drill was used for all seeding. The drill was calibrated to dispense roughly 977, 1322, and 1557 PLS m$^{-2}$ for the seeding rates. The cover crop was placed in a separate box of the seed drill designed specifically for smaller hard seeds. This box was calibrated to dispense the cover crop at a rate of roughly 54 seeds m$^{-2}$.

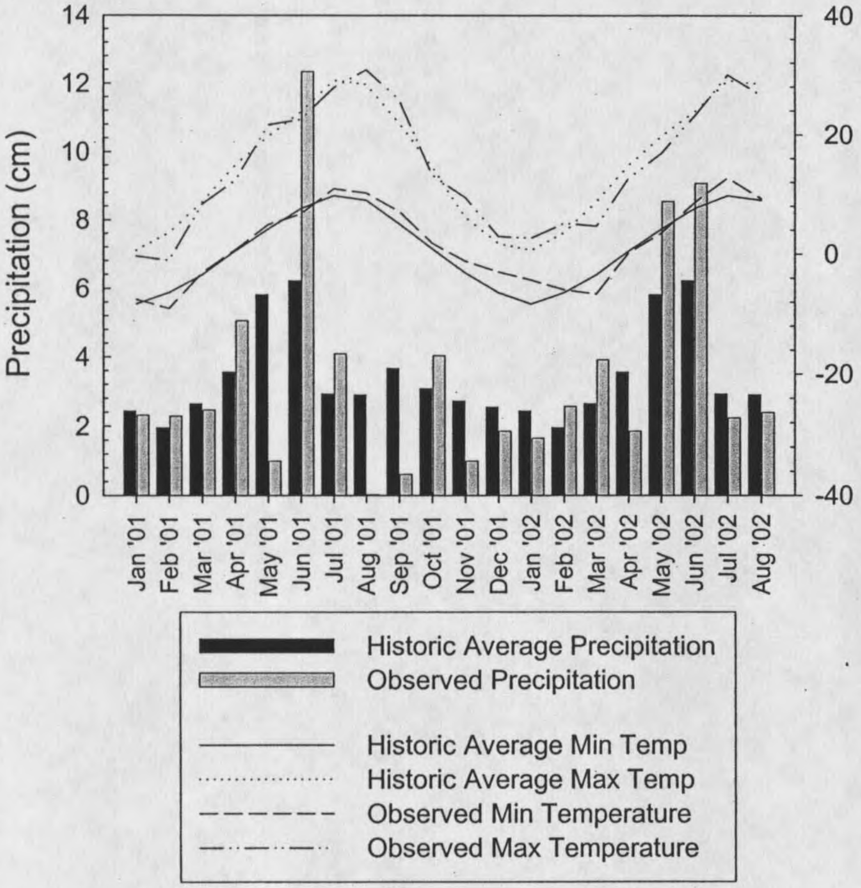

Figure 2.1. The historic and observed temperature and precipitation for the United States Bureau of Reclamation Agrimet station in St. Ignatius, Montana, 22 km south of the study site.

To disturb the soil, an AerWay® was pulled behind a tractor making approximately 18-9x9x10 cm holes per square meter of soil to collect moisture during spring rains.

Seeds were then broadcast over the plots. The drill was modified to broadcast seeds by disconnecting the feed tubes between the seed box and discs just above the discs. Using hose clamps, 15 cm lengths of metal pipe were attached to the hose ends. The weight of the pipe prevented the tubes from bouncing and directed seeds toward the ground. The no-till drill planted seeds to a depth of 6 to 12 mm by opening a furrow, dropping seeds into the furrow, then rolling it closed. Within a seeding method, plots without the cover crop were seeded first, followed by plots receiving the cover crop.

## Sampling

For sampling purposes, plots were divided into three equal subplots in an attempt to capture variation within the plot. All sampling was done block by block to minimize the influence of the time required to sample these larger plots. Pre-treatment percent cover of *C. maculosa* and *P. recta* was determined by ocular estimation of the whole subplot in August 2001. Density was counted during peak standing crop of the native grasses (July 15-27, 2002). Density was determined by randomly placing two 0.2 x 0.5 m Daubenmire frames in each subplot. All species within each frame were counted. Grass density was determined by counting each tiller within the frame.

Volumetric water content in the upper 15 cm of the soil profile was measured three times throughout the growing season of 2002; May 18-26, June 27-July 1, and August 19-23, using Time Domain Reflectometry (TDR) with a 15 cm three pronged probe. The accuracy of TDR is within +/- 0.01 to 0.02 volumetric soil moisture (Or et al. 2002). Each subplot was measured three times for a total of nine sub-samples per plot.

Soil nitrate concentration within the upper 15 cm of the profile was also determined. I collected soil samples during 13-15 August 2002, just after peak standing crop for the grasses. Three cores, 15 cm long with a 1.7 cm diameter, were collected from each subplot and combined to generate one composite sample. The samples were kept cold, dried to a constant weight at 49 °C, ground, and analyzed for inorganic soil nitrate concentrations using 1 M KCl extraction (Mulvaney 1996). The MSU Soils Analytical Laboratory analyzed the samples and reported an accuracy of +/- 0.2 mg kg$^{-1}$.

### Analysis

A five-way analysis of variance was used to determine the effects of block, seeding method, seeding rate, herbicide, and cover crop on summer density of each seeded grass, adult *C. maculosa*, juvenile *C. maculosa*, adult *P. recta*, juvenile *P. recta*, exotic grasses, and soil moisture. Since plots were randomly located on the landscape, subplots were treated as random effects and all treatments were nested within subplots. The complete ANOVA model included all main effects, two- and three-way interactions. To meet the assumptions of homogeneity of variance and normality, square root transformations were used on all plant densities. Soil moisture was not transformed. After using the complete model, the dependent variables were divided into three groups; seeded grasses, exotic species, and soil moisture. Within each group, three-way interactions that were not significant were removed from the model. The Bonferroni multiple comparison test for pairwise comparisons was used to compare means associated with main effects and interactions using $\alpha$=0.05.

Analysis of covariance was used to analyze density of seeded grasses using pre-treatment cover of *C. maculosa* and P. *recta* as the covariates. Block effects and all treatment effects were treated as fixed effects, and pre-treatment cover of either *C. maculosa* or *P. recta* were included as covariates. All main effects, two- and three-way interactions among main effects, and two-way interactions with the covariate were included in the initial model. Square root transformations were used to meet the assumptions of homogeneity of variance and normality. The model was checked for collinearity and interactions involving the covariate exhibiting collinearity were systematically removed. The model was further reduced by removing three-way interactions that were not significant for any seeded grasses. The Bonferroni multiple comparison test for pairwise comparisons was used to compare means associated with main effects and interactions at four values of the covariates; 12.5, 37.5, 62.5, and 87.5% cover using $\alpha$=0.05.

Linear regression was used to test the dependence of seeded grass density on the densities of *C. maculosa*, *P. recta*, and exotic grasses. The densities of *P. spicata*, *F. scabrella*, and *F. idahoensis* were the dependent variables. Independent variables included the densities of adult and juvenile *C. maculosa* and *P. recta*, and exotic grasses. The model was a poor fit; indicating densities were not related.

Soil nitrate concentrations were analyzed using a five-factor factorial model including all main effects and two- and three-way interactions. To meet the assumptions of homogeneity of variance and normality, the data were square root transformed. The model was reduced by removing non-significant three-way interactions following the initial analysis. The Bonferroni multiple comparison test for pairwise comparisons was used to compare means associated with main effects and interactions using $\alpha=0.05$. All statistical analyses were performed using SAS (SAS 2001). Non-transformed means are presented with statistical comparisons based on transformed data.

## Results

### *Psuedoroegneria spicata*

*Psuedoroegneria spicata* tiller density depended on seeding rate and seeding method ($p<0.001$). When *P. spicata* was drill seeded at the highest seeding rate, tiller density was at least twice as high as all other rate/method combinations (Figure 2.2A). There were no differences in tiller density among the three seeding rates when broadcast seeded. Drill seeding at the lowest seeding rate (14.9 tillers $m^{-2}$) increased *P. spicata* tiller density only when compared to broadcast seeding at the lowest rate (5.1 tillers $m^{-2}$) and intermediate rate (5.3 tillers $m^{-2}$). *Psuedoroegneria spicata* density was higher when drill seeded at the intermediate seeding rate than broadcast at any rate.

The influence of seeding rate on *P. spicata* density depended upon herbicide and cover crop ($p=0.025$). All treatments yielded similar *P. spicata* density at the two lowest seeding rates (Figure 2.3). At the highest seeding rate, the cover crop reduced *P. spicata* density below that of treatment without the cover crop where 2,4-D was applied. All other treatments at the highest seeding rate produced similar *P. spicata* density.. In addition, seeding at the intermediate rate with picloram and no cover crop, yielded similar *P. spicata* density to the highest yielding treatments seeded at 1500 seeds $m^{-2}$.

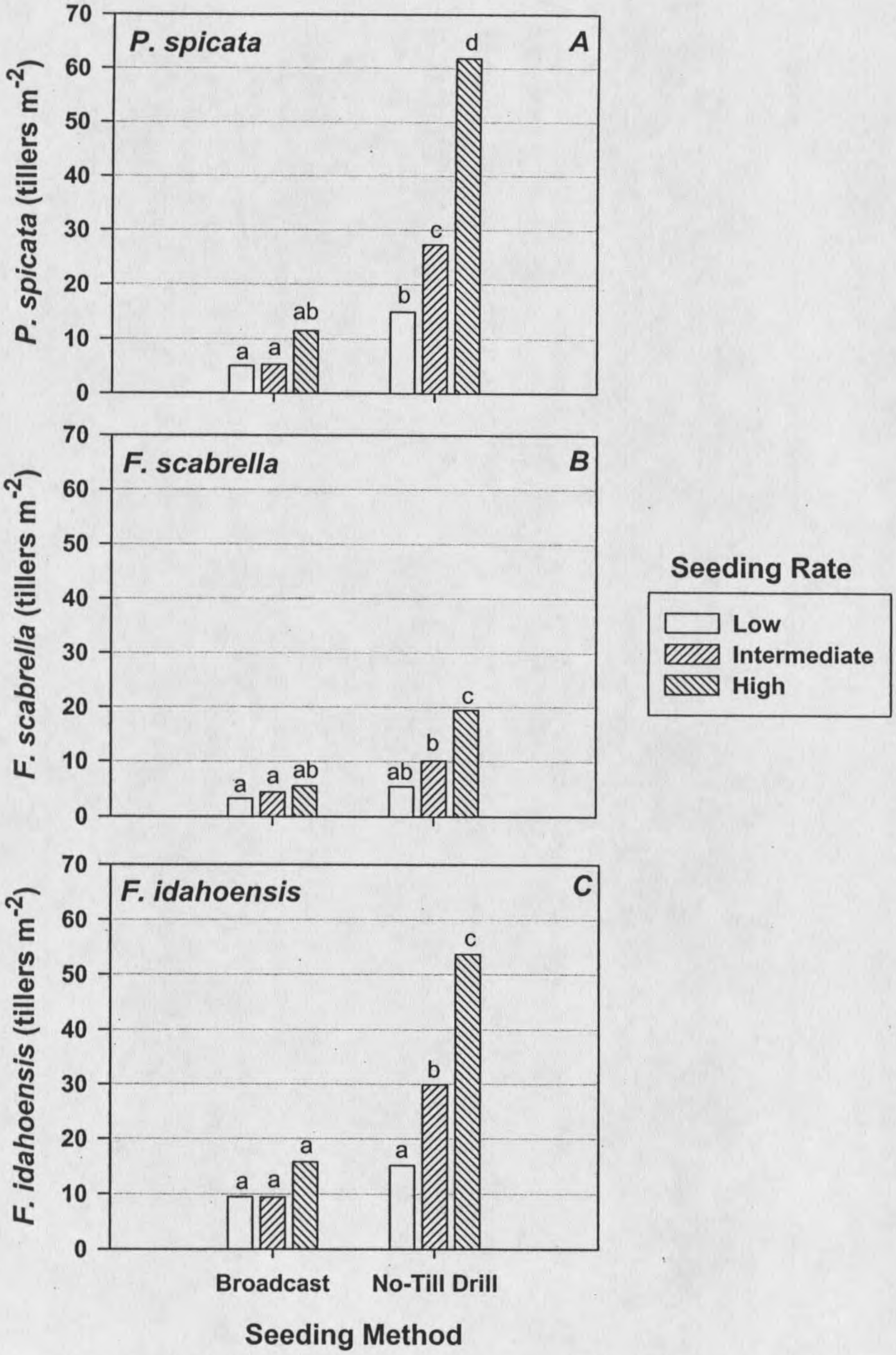

Figure 2.2. The effect of seeding rate and seeding method on the density of A) *P. spicata*, B) *F. scabrella*, and C) *F. idahoensis*. Means followed by the same letters represent similarities ($\alpha<0.05$) among treatments within species.

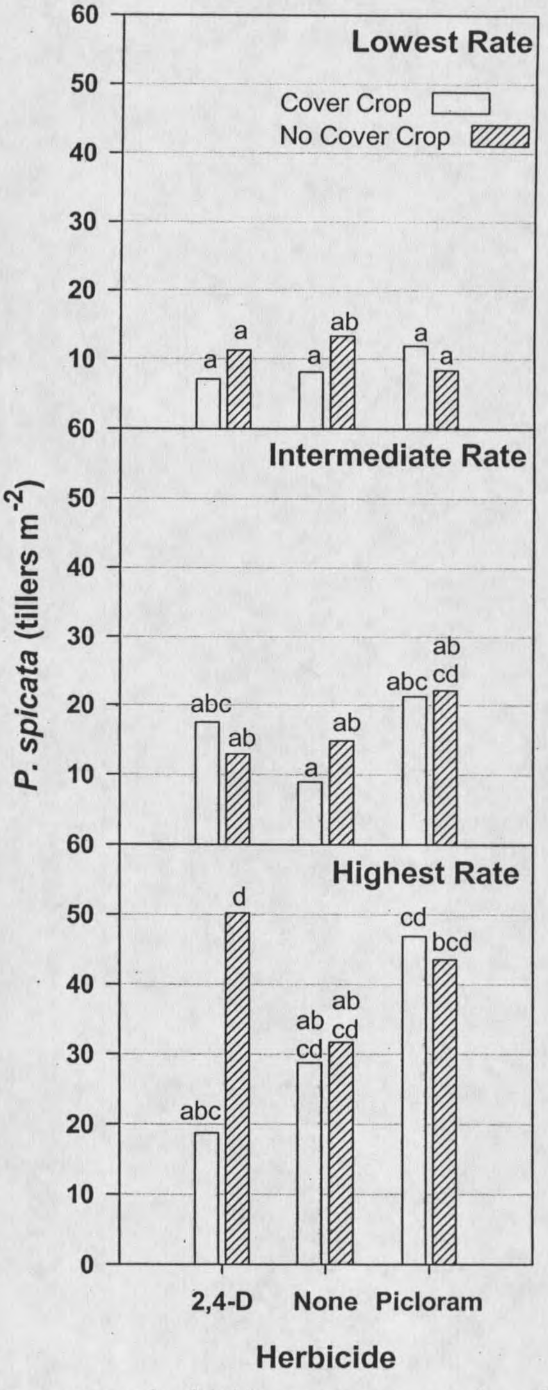

Figure 2.3. *P. spicata* response to herbicide, cover crop, and seeding rate treatments. Means followed by the same letters represent similarities ($\alpha<0.05$) among all herbicide/cover crop/seeding rate combinations.

Pre-treatment cover of *C. maculosa* and *P. recta* did not affect *P. spicata* density. Further, *P. spicata* density was not dependent on the density of *C. maculosa, P. recta*, or exotic grass.

### Festuca scabrella

The tiller density of *F. scabrella* was influenced by seeding method and seeding rate (p=0.017). Drill seeding at the highest rate yielded the highest density which was at least double that of any other treatment (Figure 2.2B). The density of *F. scabrella,* when drill seeded at the intermediate rate, was similar to drill seeding at the lowest rate and broadcast seeding at the highest rate. Tiller density did not differ among seeding rates when broadcast seeded.

Pre-treatment cover of *C. maculosa* and *P. recta* did not influence the establishment of *F. scabrella*. *Festuca scabrella* density was not dependent on *C. maculosa, P. recta,* or exotic grass densities.

### Festuca idahoensis

*Festuca idahoensis* tiller density was dependent on seeding rate and method (p=0.0005). The highest density was produced by drill seeding at the highest rate (Figure 2.2C). Drill seeding at the intermediate rate yielded more tillers than drill seeding at the lowest rate or broadcast seeding at any rate. The density of *F. idahoensis* when drill seeded at the lowest rate was similar to those broadcast at any rate.

Herbicide treatments affected the tiller density of *F. idahoensis* (p=0.002). The application of picloram yielded higher tiller density (29.3 tillers $m^{-2}$) than the application of 2,4-D (16.8 tillers $m^{-2}$). However, the untreated control produced *F. idahoensis* density (20.6 tillers $m^{-2}$) comparable to 2,4-D and picloram treatments.

*Festuca idahoensis* density was not influenced by pre-treatment cover of *C. maculosa* or *P. recta*. *Festuca idahoensis* density was not dependent on the density of *C. maculosa*, *P. recta*, or exotic grasses.

### Centaurea maculosa

Herbicide treatments affected adult and juvenile *C. maculosa* densities ($p<0.0001$). The density of adult and juvenile *C. maculosa* was different for each herbicide treatment. For adult *C. maculosa*, the 2,4-D application resulted in the smallest density (2.5 plants $m^{-2}$) while the untreated control had the highest density (61.2 plants $m^{-2}$). Picloram reduced *C. maculosa* density to about half (32.5 plants $m^{-2}$) found in the untreated control. Juvenile *C. maculosa* responded similarly as density was highest in untreated plots (395.4 plants $m^{-2}$) and lowest in 2,4-D treated plots (37.9 plants $m^{-2}$). Picloram reduced the density (210.1 plants $m^{-2}$) to about half of the untreated control.

### Potentilla recta

The influence of herbicide on adult and juvenile *P. recta* densities depended on the existence of a cover crop ($p=0.046$ adult, $p=0.002$ juvenile). Adult *P. recta* density was reduced the most by 2,4-D (Figure 2.4A). Without the addition of a cover crop, *P. recta* density was similar between untreated plots and picloram plots. However, *P. recta* density was higher in the untreated control with a cover crop, than in picloram plots with or without a cover corp. Within herbicide treatments, adult *P. recta* densities did not differ with or without a cover crop.

Juvenile *P. recta* densities were lowest when treated with 2,4-D (Figure 2.4B). Density was highest when no herbicide was applied and a cover crop was seeded. Picloram yielded juvenile *P. recta* densities similar to non herbicide treated plots without a cover crop. When a cover crop was included, picloram treated plots had densities similar to 2,4-D plots with and without a cover crop.

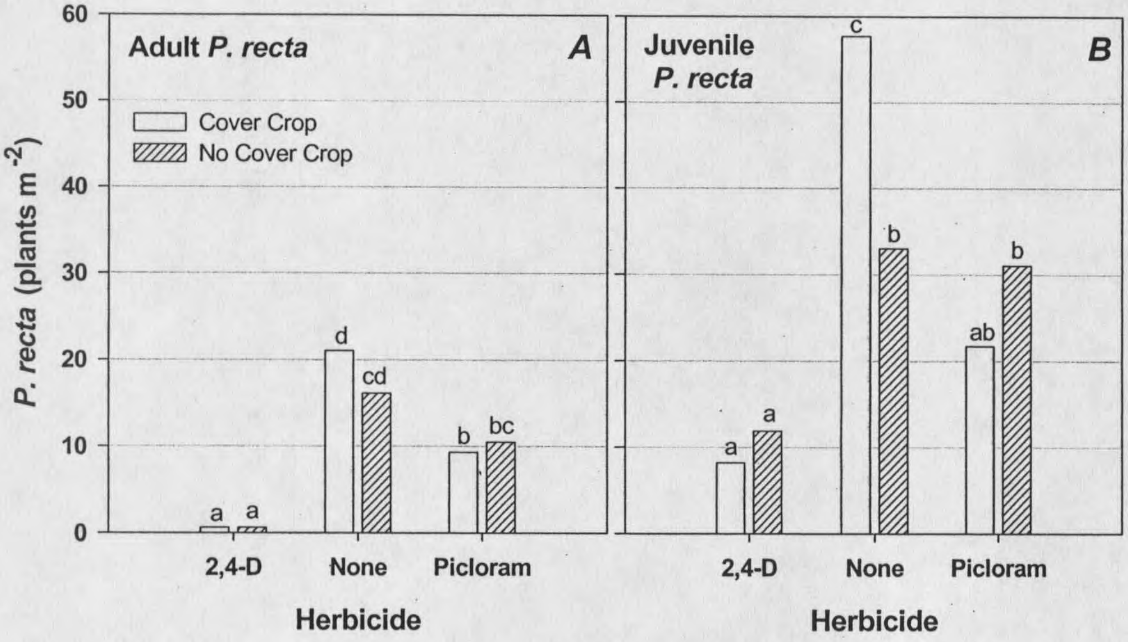

Figure 2.4. The effect of herbicide and cover crop on the density of A) adult *P. recta* and B) juvenile *P. recta*. Means followed by the same letters represent similarities ($\alpha$<0.05) among treatments within age classes.

Exotic Grasses

The effect of herbicide treatments on exotic grass tiller density relied on seeding method (p=0.042). Broadcast seeding and treating with 2,4-D yielded lower tiller densities than treating with picloram, but similar densities to all other herbicide/seeding method combinations (Figure 2.5). Exotic grass tiller density was similar between drill and broadcast seeding in plots treated with picloram. Picloram combined with drill seeding produced tiller densities higher than the other herbicide treatments. However, picloram combined with broadcast seeding produced tiller densities similar to non herbicide treated plots and 2,4-D treated plots that were drill seeded.

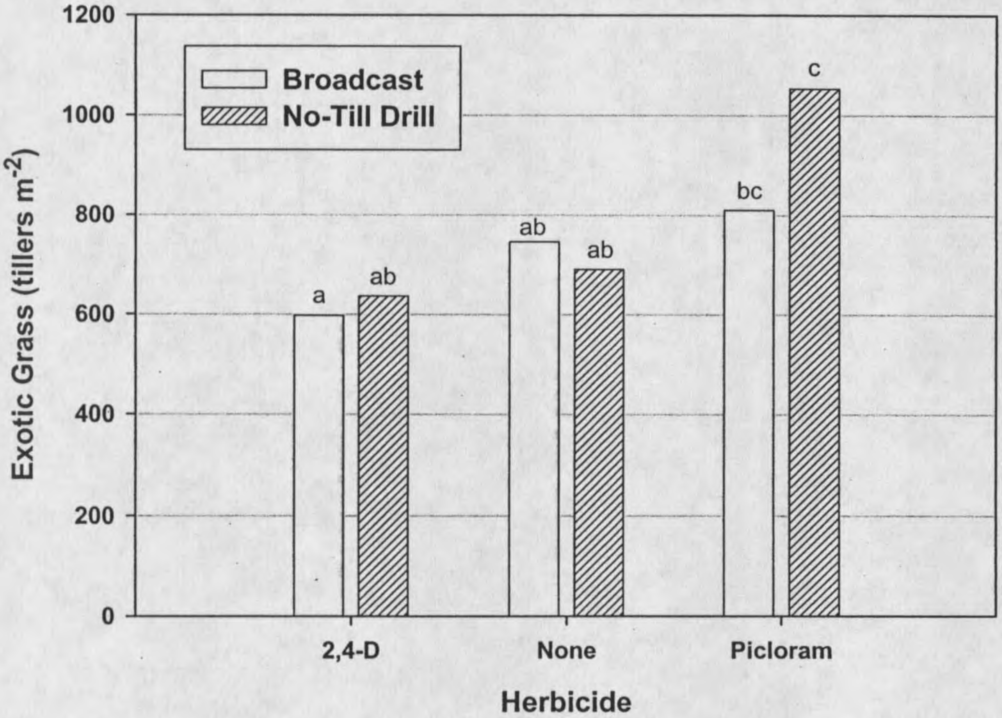

Figure 2.5. The effect of herbicide and seeding method on exotic grass density. Means followed by the same letters represent similarities ($\alpha$<0.05) among treatments.

Tiller density of exotic grasses was also influenced by the interaction of cover crop and seeding method (p=0.010). In broadcast seeded plots, tiller density was higher with a cover crop (782.0 tillers $m^{-2}$) than without a cover crop (654.2 tiller $m^{-2}$). Broadcast seeding with a cover crop was similar to drill seeding with (791.3 tillers $m^{-2}$) and without

(796.0 tillers $m^{-2}$) a cover crop. Broadcast seeding without a cover crop yielded fewer exotic grass tillers than drill seeding without a cover crop, but a comparable number to drill seeding with a cover crop.

### Soil Moisture

Soil moisture was affected by all treatments—seeding method, seeding rate, herbicide, and cover crop—of which all interacted with the time of sampling. There is some risk in interpretive error as the differences were not always greater than TDR accuracy. Seeding rate, seeding method, and herbicide interacted to influence volumetric soil moisture (p=0.002). Soil moisture was similar among all seeding method/rate combinations within 2,4-D and non-treated plots (Figure 2.6A). Within picloram treated plots, soil moisture was higher when plots were broadcast at the intermediate rate than when broadcast at the lowest or highest rate, or drilled at the highest rate. When plots were broadcast seeded at the intermediate rate, soil moisture was lower when no herbicide was applied than when either picloram or 2,4-D was applied.

Cover crop also interacted with seeding method and herbicide to influence soil moisture (p=0.040). Soil moisture did not differ among herbicide treatments for any given seeding method/cover crop combination (Figure 2.6B). Soil moisture was lower in all seeding method/herbicide combinations without a cover crop, than in plots broadcast with a cover crop and treated with 2,4-D. Plots drill seeded with a cover crop and treated with 2,4-D also had lower soil moisture than plots broadcast with a cover crop and treated with 2,4-D. Soil moisture was higher in picloram treated plots broadcast with a cover

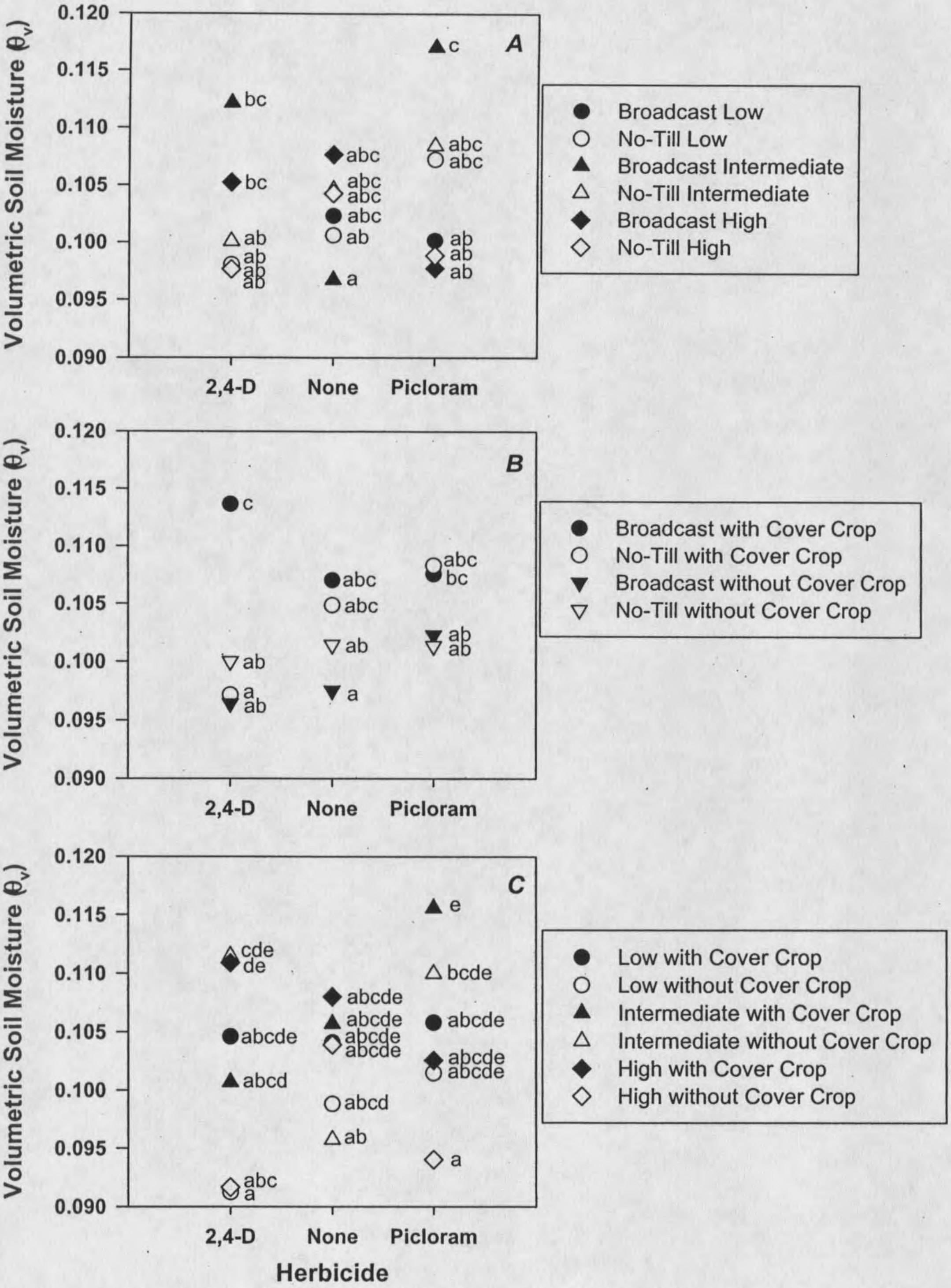

Figure 2.6. The effect of herbicide on volumetric soil moisture as influenced by A) seeding method and seeding rate, B) seeding method and cover crop, and C) seeding rate and cover crop. Means followed by the same letters represent similarities ($\alpha<0.05$) among treatments.

crop, than in 2,4-D treated plots drilled with a cover crop and non herbicide treated plots broadcast without a cover crop.

The effect of seeding rate and cover crop on soil moisture depended on herbicide (p=0.001). Within the 2,4-D treatment, plots seeded at the lowest rate without a cover crop had lower soil moisture than plots seeded at the intermediate rate without a cover crop and plots seeded at the highest rate with a cover crop (Figure 2.6C). Also within the 2,4-D treatment, plots seeded at the highest rate without a cover crop had lower soil moisture than plots seeded at the highest rate with a cover crop. Within picloram treatments, soil moisture was lower in plots seeded at the highest rate without a cover crop than in plots seeded at the intermediate rate with or without a cover crop. There were no differences among seeding rate/cover crop combinations within the non herbicide treated plots. When a cover crop was included at the intermediate seeding rate, soil moisture was lower in the 2,4-D treated plots than in the picloram treated plots. When plots were seeded at the intermediate rate without a cover crop, soil moisture was lower in plots that did not receive a herbicide treatment than in 2,4-D treated plots.

Time of sampling was highly significant for soil moisture. Seeding rate, herbicide, and time of sampling interacted to influence soil moisture (p<0.001). Soil moisture was highest at the first sampling period and lowest for the last sampling period for all seeding rate/herbicide combinations (Figure 2.7A). Within the lowest seeding rate, soil moisture in plots treated with picloram (0.094) was lower than in non treated plots (0.095) during the second sampling phase. Soil moisture did not differ among seeding rates within sampling periods.

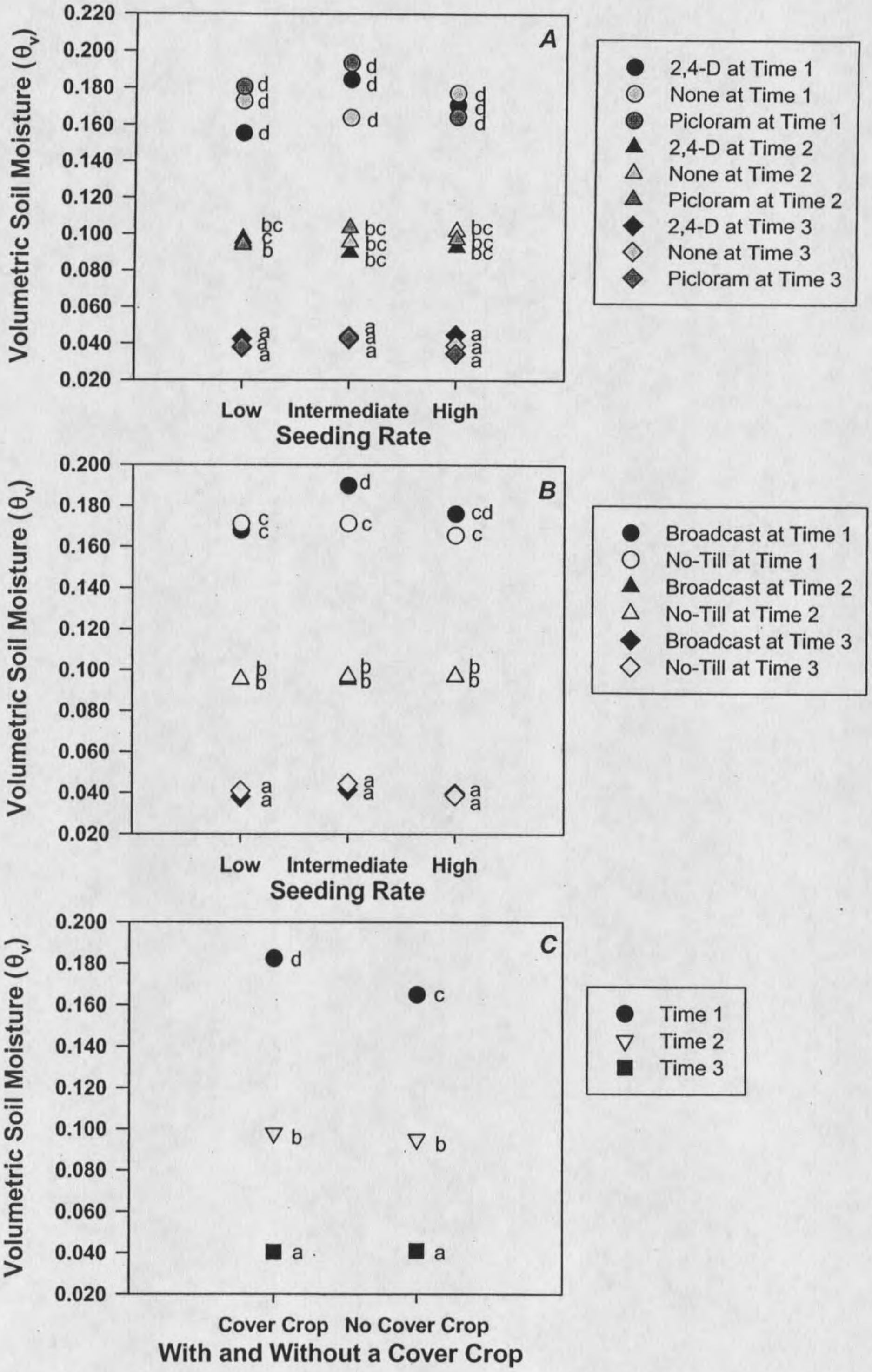

Figure 2.7. Volumetric soil moisture as influenced by A) herbicide, sampling time, and seeding rate, B) seeding method, sampling time, and seeding rate, and C) sampling time and cover crop. Means followed by the same letters represent similarities ($\alpha<0.05$) among treatments.

Seeding method also interacted with seeding rate and time of sampling to influence soil moisture ($p=0.027$). Again, soil moisture was highest at the first sampling period and lowest for the last sampling period for all seeding rate/method combinations (Figure 2.7B). There were no differences among seeding rate/method combinations within the middle and final sampling periods. During the first sampling period, soil moisture in plots broadcast at the intermediate rate was similar to plots broadcast at the highest rate, and higher than plots broadcast at the lowest rate and drill seeded at any rate.

The effect of cover crop on soil moisture depended on time of sampling ($p<0.001$). Soil moisture was highest during the first sampling period and lowest during the final sampling period (Figure 2.7C). Within the first sampling period, soil moisture was higher when a cover crop was seeded than when a cover crop was not seeded. There were no differences between cover crop treatments within the middle and final sampling periods.

Soil Nitrate

Differences in soil nitrate concentrations were not always greater than lab accuracy lending some risk to the interpretations of results. The effect of seeding method on soil nitrate concentrations depended on cover crop treatments. When a cover crop was not seeded, soil nitrate concentrations were higher in plots that were broadcast seeded (0.96 mg $kg^{-1}$ $NO_3$-N) than plots that were drill seeded (0.70 mg $kg^{-1}$ $NO_3$-N) (Figure 2.8). Nitrate concentrations were similar between broadcast and drill seeded plots with a cover crop. Nitrate concentrations were also similar within broadcast and drill seeded plots.

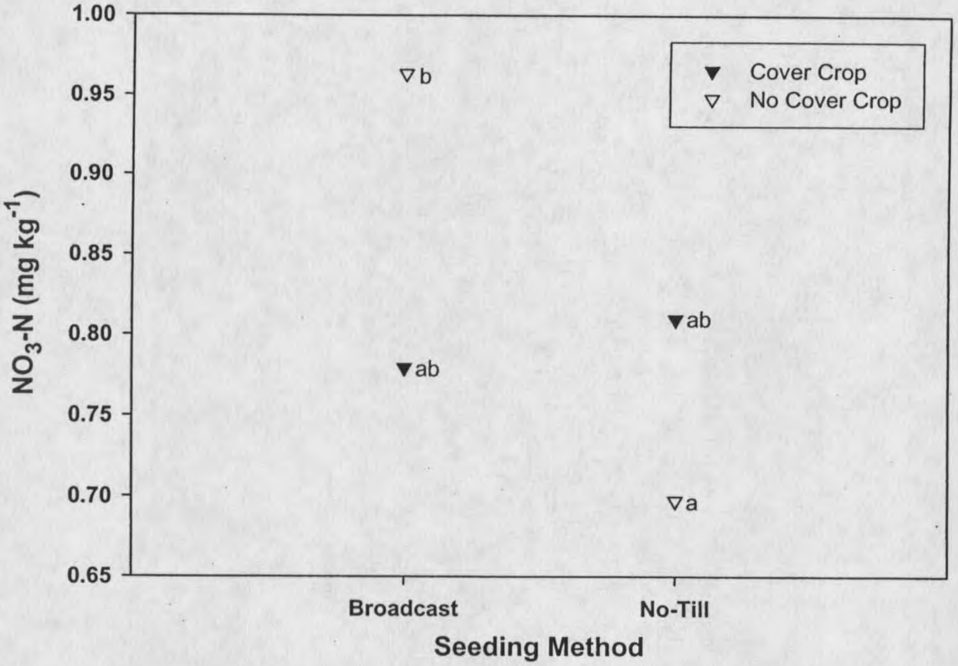

Figure 2.8. The influence of cover crop and seeding method on soil nitrate concentrations. Means followed by the same letters represent similarities ($\alpha<0.05$) among treatments.

Seeding rate, cover crop, and herbicide interacted to influence soil nitrate concentrations. Nitrate concentrations did not differ among herbicide treatments within any given seeding rate/cover crop combination (Figure 2.9). Seeding at the lowest rate without a cover crop and treating with picloram, resulted in higher nitrate concentrations than seeding at the intermediate rate without a cover crop and treating with 2,4-D or nothing, seeding at the highest rate with a cover crop and no herbicide, seeding at the highest rate without a cover crop and applying 2,4-D, and seeding at the intermediate rate with a cover crop and applying 2,4-D. There were no differences in soil nitrate concentrations within herbicide treatments among seeding rate/cover crop combinations.

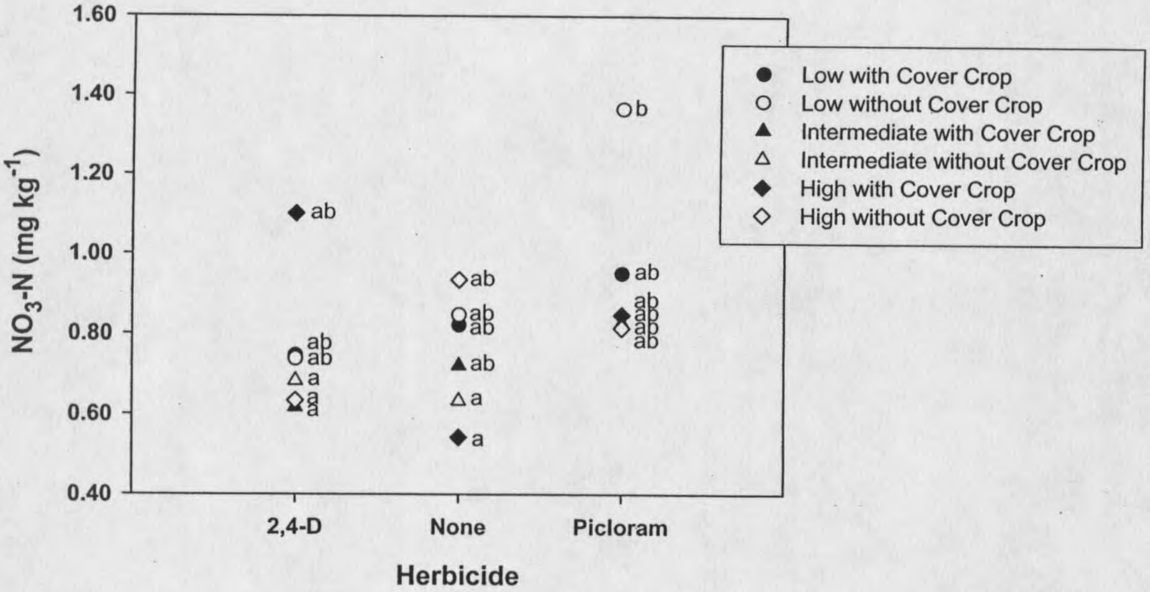

**Figure 2.9**. The influence of seeding rate, cover crop, and herbicide on soil nitrate concentrations. Means followed by the same letters represent similarities ($\alpha<0.05$) among treatments.

## Discussion

Successful invasive plant management must consider the attributes of an invaded system and modify the mechanisms of succession to catalyze a change in species composition rather than focusing solely on controlling invasive species (Sheley et al. 1996, Luken 1997). By modifying the three general causes of succession, site availability, species availability, and species performance (Pickett et al. 1987a, Sheley et al. 1996), three late seral native grasses, *P. spicata*, *F. scabrella*, and *F. idahoensis*, were established. In our study, colonization and disturbance interacted to influence successful establishment of these grass species. Drill seeding increased the likelihood of the seeds finding sites suitable for germination and emergence. As seeding rate increased, more seeds were available to take advantage of suitable safe sites. Doerr and Redente (1983), Jackson (1999), and Montalvo et al. (2002) also found drill seeding to be more effective than broadcast seeding for establishing native grasses.

In broadcast seeded plots, establishment did not increase as seeding rate increased. This suggests the depressions made on the soil surface prior to broadcasting did not provide the appropriate adequate safe sites to accommodate the establishment of these species. Chambers (2000a) found that small holes, similar in size to those made in this experiment, were effective in trapping wind-blown seed, but quickly filled with topsoil and supported fewer seedlings than larger holes.

Treatments intended to influence species performance did not have the same overwhelming effects on emergence of seeded grasses as those designed to modify colonization and disturbance. The basis for adding a cover crop was to modify species performance by utilizing excess nitrogen that would have otherwise been used by early seral invasive species, providing a competitive advantage to late seral native grasses that tend to have a higher affinity for soil nitrogen (Herron et al. 2001). The only difference in establishment between cover crop treatments was for *P. spicata* seeded at the highest rate and treated with 2,4-D. Soil moisture tended to be higher with a cover crop, but soil $NO_3$-N concentrations did not differ among 2,4-D treated plots. I would have expected *P. spicata* density to be higher, rather than lower, if the difference in soil moisture had influenced this result, because higher soil moisture has been shown to improve establishment (Davis and Pelsor 2001, Abbott and Roundy 2003, Bakker et al. 2003). If I had sampled soil $NO_3$-N in the spring during germination and emergence, I may have detected a difference. During and one month following spring carbon amendment treatments, Reever Morghan and Seastedt (1999) found differences in soil $NO_3$-N concentrations, but two months following application (July), there were no differences between treatments. Similarly, Pokorny (2002) found season to influence $NO_3$-N concentrations in an *F. idahoensis*/*P. spicata* grassland in southwestern Montana.

Herbicide treatments were also intended to modify species performance. The only difference among herbicide treatments was between 2,4-D and picloram in the establishment of *F. idahoensis*, which was due primarily to the sensitivity of *F. idahoensis* seedlings smaller than the 5-leaf stage to 2,4-D (Bussan et al. 2001). Sheley et al. (2001) also reported no differences in establishment of desired grasses among broadleaf herbicide treatments within the first year, even when knapweed density was reduced by 70 to 90%. While the treatments intended to modify species performance did not appear to influence the germination and emergence of the desired grasses, many studies illustrate their importance during the second and third years of establishment (Sheley et al. 2000, Davis and Pelsor 2001, Sheley et al. 2001, Anderson et al. 2002).

Picloram only provided 50% control of *C. maculosa* and *P. recta*, less than that previously reported for fall application at 0.28 kg a.i. $ha^{-1}$ (Sheley et al. 2000a, Sheley et al. 2001). Studies have shown picloram is most effective when applied during moist conditions (Watson et al. 1989, Sterling et al. 1996). Picloram is also degraded by sunlight within the first seven days following application if there is no precipitation to incorperate the chemical into the soil (Rice 1989, Watson et al. 1989). The fall of 2001 was drier than normal. This study site received 10.7 mm of precipitation between 24-31 October 2001. It was not until 18 November 2001, that it rained again, 17 days following the picloram application. While 2,4-D provided about 90% control of both *C. maculosa* and *P. recta*, it does not offer long term control (Lacey 1995) and due to grass sensitivity, it can not be applied early in the season when it would be most effective in reducing competition between emerging desired grasses and exotic forbs.

The exotic grass on the site did not effect the establishment of the desired species, but its density did increase with picloram and drill seeding. *Poa pratensis* and *Poa compressa*, both rhizomatous, were the dominant exotic grasses. The shallow disking by the no-till drill may have severed rhizomes stimulating growth in these grass species (Chandler et al. 1994). Picloram may have released the perennial exotic grasses from competition with *C. maculosa* and *P. recta* (Renney and Hughes 1969). Davis (1990), Sheley and Jacobs (1997), and Sheley et al. (2000) observed similar responses.

It is clear from the ANCOVA and regressions that establishment of *P. spicata*, *F. scabrella*, and *F. idahoensis* were not influenced by pretreatment cover of *C. maculosa* and *P. recta*, or densities of *C. maculosa*, *P. recta*, and exotic grasses. In a greenhouse study, Jacobs and Sheley (1999a) found *C. maculosa* does not compete with *P. spicata* during establishment, perhaps due to niche partitioning. It may also be argued that resources required for plant establishment were not limited during the spring of 2002, facilitating successful germination and survival of seeded grasses (Davis et al. 2000). While soil moisture did not differ consistently among treatment combinations, the spring (2002) following planting was wetter than average. Davis and Pelsor (2001) found native tallgrass prairie forbs seeded into an old field dominated by non native grasses established better under wet conditions than dry conditions, regardless of whether or not exotic grasses were controlled. Chambers (2000a, 2000b, 2001) found in semi-arid and arid environments, seedling establishment and survival improves with higher soil moisture. In a mine reclamation study in Colorado, Doerr and Redente (1983) found soil moisture was more of a limiting factor in grass biomass production than fertilizer.

While there is ample evidence supporting the practice of maximizing native plant diversity to resist weed invasions (Pyke and Archer 1991, Tilman 1997, Stohlgren et al. 1999, Naeem et al. 2000, Dukes 2001, Blumenthal et al. 2003), the true challenge lies in actually reestablishing competitive native species after invasive species have dominated a community ( Velagala et al. 1997, Jacobs et al. 1998). Luken (1997) emphasizes the need for land managers to have a sound understanding of the attributes of the invaded system and the necessity to move away from focusing on invasive species in order to achieve the goal of a diverse, native plant dominated community. By considering and modifying the three general causes of succession during revegetation, rather than simply trying to control *C. maculosa* and *P. recta*, I was able to establish three native grasses, and hopefully redirect the successional pathway of this invasive plant dominated community toward one of diverse native species. To this end, I emphasize that successional management is a dynamic process and requires continued monitoring and possibly repeating species performance or disturbance treatments in order to maintain a desired trajectory (Sheley et al. 1996).

## References Cited

Abbott, L. B. and B. A. Roundy. 2003. Available water influences field germination and recruitment of seeded grasses. Journal of Range Management 56(1):56-64.

Allen-Diaz, B. and J. W. Bartolome. 1998. Sagebrush-grass vegetation dynamics: comparing classical and state-transition models. Ecological Applications 8(3):795-804.

Anderson, J. L., J. S. Jacobs and R. L. Sheley. 2002. Using successional management to restore invasive plant dominated wildlands. *In* The Ecological Society of America 87th Annual Meeting, Tucson, AZ.

Bakker, J. D., S. D. Wilson, J. M. Christian, X. Li, L. G. Ambrose and J. Waddington. 2003. Contingency of grassland resotration on year, site, and competition form introduced grasses. Ecological Applications 13(1):137-153.

Belcher, J. W. and S. D. Wilson. 1989. Leafy spurge and species composition of a mixed-grass prairie. Journal of Range Management 42:172-175.

Berger, J. J. 1993. Ecological restoration and nonindigenous plant species: a review. Restoration Ecology 1:74-82.

Blumenthal, D. M., N. R. Jordan and E. L. Svenson. 2003. Weed control as a rationale for restoration: the example of tallgrass prairie. Conservation Ecology 7(1):Article 6.

Bussan, A. J., S. A. Dewey, T. D. Whitson and M. A. Trainor. 2001. Weed Management Handbook 2001-2002: Montana, Utah, Wyoming, pp. 294. EB 23. Montana State University Extension Service, Bozeman, Montana.

Bussan, A. J. and W. E. Dyer. 1999. Herbicides and Rangeland. *In:* Biology and Management of Noxious Rangeland Weeds (*ed*) R. L. Sheley and J. K. Petroff, pp. 116-132. Oregon State University Press, Corvallis.

Chambers, J. C. 2000a. Seed movements and seedling fates in disturbed sagebrush steppe ecosystems: implications for restoration. Ecological Applications 10(5):1400-1413.

Chambers, J. C. 2000b. Using threshold and alternative state concepts to restore degraded or disturbed ecosystems. *In* High Altitude Revegetation Workshop no. 14. Information series (Colorado Water Resources Research Institute); no. 91, pp. 134-145. Colorado State University, Colorado State University, Fort Collins, Colorado.

Chambers, J. C. and A. R. Linnerooth. 2001. Restoring riparian meadows currently dominated by *Artemisia* using alternative state concepts--the establishment component. Applied Vegetation Science 4:157-166.

Chandler, K., S. D. Murphy and C. J. Swanton. 1994. Effect of tillage and glyphosate on control of quackgrass (*Elytrigia repens*). Weed Technology 8:450-456.

Clements, F. E. 1916. Plant succession: an analysis of the development of vegetation., pp. 512. Carnegie Institution of Washington, Washington, D. C.

Cox, J. E. 1989. Observations, experiments, and suggestions for research on sheep-spotted knapweed reslationship. *In* Knapweed Symposium *ed.* P. K. F. a. J. R. Lacey, pp. 79-82. Montana State University, Bozeman, Montana.

Cuda, J. P., B. W. Sindelar and J. H. Cardellina. 1989. Proposal for an integrated management system for spotted knapweed (*Centaurea maculosa* Lam.). *In* Knapweed Symposium *ed.* P. K. F. a. J. R. Lacey, pp. 197-202. Montana State University, Bozeman, Montana.

Davis, E. S. 1990. Spotted knapweed (*Centaurea maculosa* Lam.) seed longevity, chemical control, and seed morphology. Thesis (M.S.) Montana State University.

Davis, E. S., P. K. Fay, T. K. Chicoine and C. A. Lacey. 1993. Persistence of spotted knapweed. Weed Science 41:57-61.

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

Davis, M. A. and M. Pelsor. 2001. Experimental support for a resource-based mechanistic model of invasibility. Ecology Letters 4:421-428.

Doerr, T. B. and E. F. Redente. 1983. Seeded plant community changes on intensively disturbed soils as affected by cultural practices. Reclamation and Revegetation Research 1983(2):13-24.

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

Grime, J. P., J. G. Hodgson and R. Hunt. 1988. Comparative plant ecology: a functional approach to common British species. Unwin Hyman, London, UK.

Herron, G. J., R. L. Sheley, B. D. Maxwell and J. S. Jacobsen. 2001. Influence of nutrient availability on the interaction between spotted knapweed and bluebunch wheatgrass. Restoration Ecology 9(3):326-331.

Hirsch, S. A. and J. A. Leitch. 1996. The impact of knapweed on Montana's economy. *In* Agriculture Economic Report, pp. 44. North Dakota State Universtiy, Fargo, ND.

Hobbs, R. J. and S. E. Humphries. 1995. An integrated approach to the ecology and management of plant invasions. Conservation Biology 9(4):761-770.

Jackson, L. L. 1999. Establishing tallgrass prairie on grazed permanent pasture in the upper midwest. Restoration Ecology 7(2):127-138.

Jacobs, J. S., M. F. Carpinelli and R. L. Sheley. 1998. Revegetating Weed-Infested Rangeland: What We've Learned. Rangelands 20(6):10-15.

Jacobs, J. S. and R. L. Sheley. 1999a. Competition and niche partitioning among *Pseudoroegneria spicata*, *Hedysarum boreale*, and *Centaurea maculosa*. Great Basin Naturalist 59(2):175-181.

Jacobs, J. S. and R. L. Sheley. 1999b. Spotted knapweed, forb, and grass response to 2,4-D and N-fertilizer. Journal of Range Management 52:482-488.

James, D. 1992. Some principles and practices of desert revegetation seeding. Arid Lands Newsletter 32:22-27.

Lacey, C. A., J. R. Lacey, P. K. Fay, J. M. Story and D. L. Zamora. 1999. Controlling Knapweed on Montana Rangeland, pp. 1-17. Montana State University Extension Service, Bozeman.

Lacey, J. R., C. B. Marlow and J. R. Lane. 1989. Influence of spotted knapweed (*Centaurea maculosa*) on surface runoff and sediment yield. Weed Technology 3:627-631.

Luken, J. O. 1997. Management of Plant Inavasions: Implicating Ecological Succession. *In:* Assessment and Management fo Plant Invasions (*ed*) J. O. Luken, pp. 133-144. Springer-Verlag, New York.

Masters, R. A. and S. J. Nissen. 1998. Revegetating Leafy Spurge (*Euphorbia esula*)-Infested Rangeland with Native Tallgrasses. Weed Technology 12:381-390.

McKone, M. B., C. A. Lacey and D. Bedunah. 1989. Evaluation of clopyralid rate and time of application on spotted knapweed (*Centaurea maculosa*). *In* Knapweed Symposium *ed*. P. K. Fay and J. R. Lacey, pp. 83-94. Plant and Soil Science Department and Extension Service, Montana State University, Bozeman, Montana.

Miller, R. F., T. J. Svejcar and N. E. West. 1994. Implications of livestock grazing in the Intermounain sagebrush region: plant composition. *In:* Ecological implications of livestock herbivory in the west (*ed*) M. Vavra, W. A. Laycock and R. D. Pieper. Society of Range Management, Denver, CO.

Montalvo, A. M., P. A. McMillan and E. B. Allen. 2002. The relative importance of seeding method, soil ripping, and soil variables on seeding success. Restoration Ecology 10(1):52-67.

Mueggler, W. F. and W. L. Stewart. 1980. Grassland and shrubland habitat types of Western Montana, pp. 154. USDA Forest Service, Ogden, Utah.

Mulvaney, R. L. 1996. Nitrogen-Inorganic Forms. *In:* Soil Testing and Plant Analysis. SSSA Book Series (*ed*) R. Westerman. Soil Science Society of America, Madison, Wisconsin.

Naeem, S., J. M. H. Knops, D. Tilman, K. M. Howe, T. Kennedy and S. Gale. 2000. Plant diversity increases resistance to invasion in the absence of covarying extrinsic factors. Oikos 91:97-108.

Noble, I. R. and R. O. Slatyer. 1980. The use of vital attributes to predict successional changes in plant communities subject to recurrent disturbances. Vegetatio 43:5-21.

Olson, B. E. 1999. Impacts of Noxious Weeds on Ecological and Economic Systems. *In:* Biology and Management of Noxious Rangeland Weeds (*ed*) R. L. S. a. J. K. Petroff, pp. 4-18. Oregon State University Press, Corvallis, OR.

Olson, B. E., R. T. Wallander and J. R. Lacey. 1997. Effects of sheep grazing on a spotted knapweed-infested Idaho fescue community. Journal of Range Management 50:386-390.

Or, D., J. R. VanShaar, B. Fisher, R. A. Hubscher and J. Wraith. 2002. WinTDR Users Guide. Utah State University Plants, Soils, and Biometeorology, Logan, Utah.

Packard, S. and C. F. Mutel. 1997. The Tallgrass Restoration Handbook, pp. 463. Island Press, Washington D. C.

Pickett, S. T. A., S. L. Collins and J. J. Armesto. 1987a. A hierarchical consideration of causes and mechanisms of succession. Vegetatio 69:109-114.

Pickett, S. T. A., S. L. Collins and J. J. Armesto. 1987b. Models, mechanisms and pathways of succession. The Botanical Review 53(3):335-371.

Pimentel, D. 2002. Introduction: non-native species in the world. *In:* Biological Invasions; Economic and Environmental Costs of Alien Plant, Animal, and Microbe Species (*ed*) D. Pimentel, pp. 3-8. Cornell University, Ithaca.

Pokorny, M. L. 2002. Plant Functional Group Diversity as a Mechanism for Invasion Resistance. Thesis (Masters of Science) Montana State University.

Pyke, D. A. and S. Archer. 1991. Plant-plant interactions affecting plant establishment and persistence on revegetated rangeland. Journal of Range Management 44(2):550-557.

Randall, J. M. 1996. Weed control for the preservation of biological diversity. Weed Technology 10:370-383.

Reever Morghan, K. J. and T. R. Seastedt. 1999. Effects of soil nitrogen reduction on nonnative plants in restored grasslands. Restoration Ecology 7(1):51-55.

Renney, A. J. and E. C. Hughes. 1969. Control of knapweed, Centaurea species in British Columbia with Tordon herbicides. Down to Earth 24:6-8.

Rice, P. M. 1989. Degredation of Tordon 22K herbicide by sunlight. *In* Knapweed Symposium *ed.* P. K. Fay and J. R. Lacey, pp. 88-94. Plant and Soil Science Department and Extension Service, Montana State University, Bozeman, Montana.

Rice, P. M. 1991. Sulfur Cinquefoil: a new thrreat to biological diversity. Western Wildlands 17:34-40.

Rice, P. M. 1999. Sulfur Cinquefoil. *In:* Biology and Management of Noxious Rangeland Weeds (*ed*) R. L. Sheley and J. K. Petroff, pp. 382-388. Oregon State University Press, Corvallis, Oregon.

SAS. 2001. SAS. SAS Institute Inc., Cary, NC.

Sheley, R. L., C. A. Duncan, M. B. Halstvedt and J. S. Jacobs. 2000a. Spotted knapweed and grass response to herbicide treatments. Journal of Range Management 53(2):176-182.

Sheley, R. L. and J. S. Jacobs. 1997. Response of spotted knapweed and grass to picloram and fertilizer combinations. Journal of Range Management 50:263-267.

Sheley, R. L., J. S. Jacobs and M. F. Carpinelli. 1998. Distribution, biology, and management of diffuse knapweed (*Centaurea diffusa*) and spotted knapweed (*Centaurea maculosa*). Weed Technology 12:353-362.

Sheley, R. L., J. S. Jacobs and D. E. Lucas. 2001. Revegetating spotted knapweed infested rangeland in a single entry. Journal of Range Management 54:144-151.

Sheley, R. L., B. E. Olson and C. Hoopes. 2000b. Impacts of noxious weeds on the ecology and economy of Montana. EB 152. Montana State University Extension, Bozeman, Montana.

Sheley, R. L. and J. K. Petroff. 1999. Biology and Management of Noxious Rangeland Weeds, pp. 438. Oregon State University Press, Corvallis.

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.

Sterling, T. M., N. K. Lownds and L. W. Murray. 1996. Environmental effects on picloram uptake and ethylene production by broom snakeweed. Journal of Range Management 49(3):245-250.

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(1):25-46.

Story, J. M., K. W. Boggs, W. R. Good, P. Harris and R. W. Nowierski. 1991. *Metzneria paucipunctella* Zeller (Lepidoptera: Gelechiidae). A moth introduced against spotted knapweed: its feeding strategy and impact on two introduced *Urophora* spp. (Diptera: Tephritidae). Canadian Entomology 123:1001-1007.

Tilman, D. 1997. Community invasibility, recruitment limitation, and grassland biodiversity. Ecology 78(1):81-92.

Velagala, R. P. 1996. Using seed rate and plant densities to enhance intermediate wheatgrass establishment in spotted knapweed dominated rangeland. Thesis (M. S.) Montana State University.

Velagala, R. P., R. L. Sheley and J. S. Jacobs. 1997. Influence of density on intermediate wheatgrass and spotted knapweed interference. Journal of Range Management 50:523-529.

Vitousek, P. M., C. M. D'Antonio, L. L. Loope and R. Westbrooks. 1996. Biological invasions as global environment change. American Scientist 84(5):468-479.

Wali, M. K. 1999. Ecological succession and the rehabilitation of disturbed terrestrial ecosystems. Plant and Soil 213:195-220.

Watson, V. J., P. M. Rice and E. C. Monnig. 1989. Environmental fate of picloram used for roadside weed control. Journal of Environmental Quality 18:198-205.

Whisenant, S. G. 1999. Repairing Damaged Wildlands: A Process-Orientated, Landscape-Scale Approach. Cambridge University Press, Cambridge, United Kingdom.

Willson, G. D. and J. Stubbendieck. 2000. A provisional model for smooth brome management in degraded tallgrass prairie. Ecological Restoration 18(1):34-44.

## CHAPTER 3

# USING SUCCESSIONAL THEORY TO GUIDE RESTORATION OF INVASIVE PLANT DOMINATED RANGELAND: IMPACTS ON EXISTING NATIVE SPECIES

### Introduction

Millions of hectares of rangeland throughout the western United States are dominated by non-indigenous plants (Sheley and Petroff 1999). In Montana alone, it is estimated that *Centaurea maculosa* Lam. costs the livestock industry $11 million a year, and if allowed to spread to its potential range could cost as much as $155 million annually (Hirsch and Leitch 1996). Managing invasive plants on rangeland generally focuses on increasing forage production by controlling native and non-native forbs (Sheley and Petroff 1999). This may, however, exacerbate the weed problem, by creating plant communities that lack functional diversity thereby increasing their susceptibility to invasion ( Levine and D'Antonio 1999, Naeem et al. 2000, Dukes 2001, Pokorny 2002).

Ecologists emphasize the importance of species richness and diversity in maintaining ecosystem function, productivity, and sustainability ( McNaughton 1977, Chapin et al. 1997, Hooper and Vitousek 1997, Tilman and Knops 1997, Naeem 1998). Working in a Minnesota grassland, Tilman et al. (1996) found plant productivity and resource utilization to improve as species richness increased. When manipulating microbial communities, Naeem and Li (1997) observed higher stability in biomass and density measures when more than one species per functional group was present. Frank and McNaughton (1991) compared the response to drought of eight grasslands in

Yellowstone National Park and found greater stability in communities with higher plant diversity.

There is substantial evidence suggesting plant communities possessing high species richness and diversity are better able to resist invasion. Tilman (1997) seeded up to 54 species into an existing oak savanna and found establishment of the seeded species to be negatively correlated with initial species richness. In small grassland plots, Kennedy et al. (2002) found establishment of exotic plant species was reduced by increasing species richness. In a California grassland, invasion by the annual *Centaurea solstitialis* L. was reduced by increasing functional diversity which reduced resource availability (Dukes 2001).

Increasingly, restoring invasive plant dominated communities to functionally diverse systems is proposed as a means of controlling weeds (Berger 1993, Jacobs and Sheley 1999a). Research by Pokorny (2002) found grassland communities with a diverse forb component were better able to resist invasion by *C. maculosa* than communities composed of grasses alone. Carpinelli (2000) was able to create a relatively weed resistant community by increasing niche occupation using grasses and forbs. Blumenthal et al. (2003) found weed biomass and stem number to be significantly reduced seven years after reseeding a weed infested prairie with 18 native species. Despite the evidence that forbs are critical in developing a weed resistant plant community, most restoration of weed infested rangeland focuses on the successful establishment of grasses (Sheley et al. 2001, Bakker et al. 2003). Where desirable forbs are present, seeding grasses using techniques that minimize negative impacts on forbs would improve our ability to restore these systems.

Successional management provides land managers an ecological framework to base restoration efforts (Sheley et al. 1996). Successional management uses Pickett et al.'s (1987) three general causes of succession—site availability, species availability, species performance—as a framework for developing management strategies to direct an invasive plant dominated community toward one that is functionally diverse (Sheley et al. 1996). This theory uses current technology to manipulate the processes driving the three general causes of succession in order to predictably direct succession (Sheley et al. 1996).

In a companion study (Chapter 2), I tested the potential for using successional management to guide the restoration of native grasses on rangeland dominated by *C. maculosa* and *Potentilla recta* L. I hypothesized as the three general causes of succession were increasingly addressed, establishment of the seeded grasses would increase. Treatments intended to influence site availability, no-till drill seeding and broadcast seeding over small holes, and species availability, seeding at three different rates, interacted to influence grass establishment. These data indicated grass establishment was greatest when species were drill seeded at the highest rate. Treatments intended to manipulate species performance, herbicides and the addition of cover crop, did not influence grass establishment, but the broadleaf selective herbicides significantly reduced the density of *C. maculosa* and *P. recta* below that of the control. I anticipate the control of the invasive species provided by picloram and 2,4-D will influence grass establishment in subsequent years. I concluded that by considering and modifying the three general causes of succession during revegetation, rather than simply trying to control *C. maculosa* and *P. recta*, I was able to establish three native grasses, and possibly redirect the successional pathway of this invasive plant dominated community toward one of diverse native species.

The overall objective of this study was to quantify the response of the pre-existing native plant community to successsionally based restoration of invasive plant dominated rangeland. My underlying hypothesis was that as integrated weed management strategies increasingly modify the three general causes of succession in a complimentary manner, the successional trajectory toward a desired plant community would be initiated (Sheley et al. 1996). My first specific objective was to determine the influence of no-till drilling and broadcast seeding over small holes on the density of native plants and the Simpson's diversity and richness of the plant community. I hypothesized that the disturbance associated with the seeding methods would not negatively impact the plant community. This objective attempted to manipulate site availability by disturbing the soil surface in a manner that would maximize grass establishment without disrupting existing vegetation. The second objective was to determine the influence of three seeding rates of native grasses on the density of native plants and diversity and richness of the plant community. Three rates were used based on research by Velegala (1996) that suggests the rate of grass establishment, when seeding into existing vegetation, is improved by increasing seeding rate. I hypothesized that the plant community would not be influenced by the differences in seeding rates. The third objective was to determine the effect picloram (4-amino-3,5,6 trichloropicolinic acid) and 2,4-D amine (2,4-dichlorophenoxyacetic acid, dimethylamine salt) on the density of native species and the diversity and richness of the plant community. These treatments attempted to manipulate species performance by controlling the invasive species *C. maculosa* and *P. recta* and reducing competition with the seeded grasses. I hypothesized that both picloram and 2,4-D would reduce forb density, species richness, and diversity. Finally, I determined the influence of a cover crop on the density of native species and the diversity and richness of the plant community. This treatment also attempted to manipulate species performance by seeding an early seral species that would preemptively use available soil nitrogen. I hypothesized the cover crop would have no effect on the plant community.

## Methods

### Study Site

This study was conducted on the Kicking Horse Wildlife Mitigation Area south of Ronan, Montana (47° 29' N, 114° 5' W). The site was a *Festuca scabrella/Pseudoroegneria spicata* habitat type interspersed with ephemeral prairie pothole wetlands (Mueggler and Stewart 1980). It was dominated by various non-native plant species including *Centaurea maculosa* Lam. and *Potentilla recta* L. The most common exotic grasses were *Poa compressa* L., *Poa pratensis* L., *Bromus tectorum* L., and *Dactylis glomerata* L. There were remnant stands of native plant species, including *Achillea millifolium* (L.), *Anemone cylindrica* Gray, *Antennaria* spp., *Arnica sororia* Greene, *Castilleja pallescens* (Gray) Greene, *Danthonia intermedia* Vasey, *Festuca idahoensis* Elmer., *Geum triflorum* Pursh, *Koeleria cristata* Pers., *Lomatium triternatum*

(Pursh) Coult. & Rose, and *Poa sandbergii* Vasey. Historical disturbances associated with this site were grazing by cattle, those associated with limited agricultural practices, and intense meadow vole (*Microtis pennsylvanicus*) activity. The more palatable species of this habitat type, *F. scabrella* and *P. spicata*, were far less common than the less palatable species, *F. idahoensis*, *P. sanbergii*, and *Danthonia intermedia* Vasey.

The soil is a Post-Ronan-Water complex. It is a deep, well drained silt loam and silty clay loam (glaciolacustrine deposits) with sodic properties within the top 76 cm. The slope varies from 2 to 15 percent and the elevation is 940 m. The average annual precipitation ranges from 350-450 mm per year and the average temperature is 7.6° C.

### Experimental Design

The study was conducted as a factorially (3 herbicides x 2 cover crops x 3 seeding rates x 2 seeding methods=36) arranged randomized complete block. Replications were located in three locations across the landscape, with one location containing two blocks. I established 144, 11.0 x 36.6 m plots, 36 in each of four blocks. The 36 treatment combinations were randomly assigned and applied as whole plot treatments. The three herbicide treatments were picloram at 0.28 kg a.i. $ha^{-1}$, 2,4-D at 2.2 kg a.i. $ha^{-1}$, and a control with no herbicide. Cover crop treatments included seeding with and without a cover crop of winter wheat (*Triticum aestivum* L.). I seeded a mix of three native grasses (bluebunch wheatgrass [*Pseudoroegneria spicata* (Pursh) Scribn. and Smith], Idaho fescue [*Festuca idahoensis* Elmer], rough fescue [*Festuca scabrella* Torrey ex Hook.]) at three rates; low (977 pure live seed (PLS) $m^{-2}$), intermediate (1322 PLS $m^{-2}$), and high

(1557 PLS $m^{-2}$). The two different seeding methods utilized were no-till drill seeding and broadcast seeding following soil surface disturbance.

## Procedures

In August 2001, plots were established in areas dominated by *C. maculosa* and/or *P. recta*. Replications were distributed within 152 ha, encompassing three pastures and blocked by pasture. The largest pasture was divided into two blocks.

During the first week of November 2001, picloram was applied using a pick-up truck mounted with a chemical injection sprayer having a boom width of 12.0 m. Approximately 241 L $ha^{-1}$ of solution was applied with a single pass over the plot. Conditions were overcast, wind <8 km $hr^{-1}$, 70% humidity, and a temperature of 6.4 °C. Because of the lack of precipitation during August and September (Figure 2.1), very few adult *C. maculosa* or *P. recta* plants initiated fall regrowth. Since these were target weed species, the 2,4-D treatment was postponed until the following summer. When the seeded grass species reached the 3- to 6-leaf growth stage in the second week of July 2003, 2,4-D amine was applied using an ATV mounted pressurized sprayer with a spray width of 3.6 m. The unit delivered approximately 210 L $ha^{-1}$ of solution. Conditions were clear, wind <8 km $hr^{-1}$, 52% humidity, and a temperature of 26 °C.

Plots were seeded immediately following the application of picloram in November 2001. The native seed mix was blended to ensure the same number of live seeds of each species, *P. spicata*, *F. idahoensis*, and *F. scabrella*, per kilogram of the seed mix. A Truax® native seed no-till range drill was used for all seeding. The drill was calibrated to dispense roughly 977, 1322, and 1557 PLS $m^{-2}$ for the seeding rates. The cover crop was placed in a separate box of the seed drill designed specifically for smaller hard seeds. This box was calibrated to dispense the cover crop at a rate of roughly 54 seeds m$^{-2}$.

To disturb the soil, an AerWay® was pulled behind a tractor making approximately 18-9x9x10 cm holes per square meter of soil to collect moisture during spring rains. Seeds were then broadcast over the plots. The drill was modified to broadcast seeds by disconnecting the feed tubes between the seed box and discs just above the discs. Using hose clamps, 15 cm lengths of metal pipe were attached to the hose ends. The weight of the pipe prevented the tubes from bouncing and directed seeds toward the ground. The no-till drill planted seeds to a depth of 6 to 12 mm by opening a furrow, dropping seeds into the furrow, then rolling it closed. Within a seeding method, plots without the cover crop were seeded first, followed by plots receiving the cover crop.

### Sampling

For sampling purposes, plots were divided into three equal subplots in an attempt to capture variation within the plot. Density of all species was sampled two times, each time progressing block by block to minimize the influence of the time required to sample these larger plots. The first sampling period was 2-26 June 2002. We started when *Balsamorhiza sagittata* (Push) Nutt. and *Camassia quamash* (Pursh) Greene were flowering in an effort to capture early season forbs. The second sampling period was 15-27 July 2002, during peak standing crop of native grasses. Density was determined by randomly placing two 0.2 m x 0.5 m Daubenmire frames in each subplot. All species within each frame were counted. Grass density was determined by counting each tiller.

Analysis

Species richness is defined as the number of species found in each plot, not including the three seeded grasses, *P. spicata*, *F. scabrella*, and *F. idahoensis*, and *C. maculosa* and *P. recta*. Density and equitability were calculated using Simpson's diversity index;

Simpson's index, $D = \dfrac{1}{\sum_{i=1}^{R} P_i^2}$, Equitability, $E = \dfrac{1}{\sum_{i=1}^{R} P_i^2} \times \dfrac{1}{R}$, where $R$ is richness and $P_i$ is the proportion, for each species, of individuals that contribute to the entire sample. (Begon et al. 1996)

A five-way analysis of variance was used to determine the effects of block, seeding method, seeding rate, herbicide, and cover crop on spring and summer density of the existing native grasses, native forbs, richness, Simpson's diversity and equitability. Since plots were divided into subplots for sampling and plots were randomly located on the landscape, subplots were treated as random effects and all treatments were nested within subplots. The complete ANOVA model included all main effects, two- and three-way interactions. To meet the assumptions of homogeneity of variance and normality, square root transformations were performed on spring and summer native forb density and spring native grass density. We were not able to normalize summer residuals for native grass density due to a high number of zeroes within the data set. The response variables were divided into two groups for analysis, native grasses and native forbs were analyzed by one model, and richness, diversity and equitability by another. After analyzing the complete model for each group, three-way interactions that were not significant for any response variables within a group were removed. The Bonferroni multiple comparison test for pairwise comparisons was used to compare means associated with main effects and interactions using $\alpha=0.05$. All statistical analyses were performed using SAS (SAS 2001). Non-transformed means will be presented with statistical comparisons based on transformed data.

## Results

### Native Forbs

Spring. The effect of herbicide on spring native forb density was dependent on seeding rate and method (p=0.041). When picloram was applied in combination with drill seeding at the highest rate (58.4 forb $m^{-2}$), native forb density was lower than in treatment combinations involving 2,4-D or no herbicide and was similar to all other picloram treatments (Figure 3.1). Forb density in plots treated with picloram was lower than in plots drill seeded at the lowest rate without an herbicide (166.7 plants $m^{-2}$) and broadcast seeded at the intermediate rate with a summer 2,4-D herbicide application (174.2 forb $m^{-2}$).

Summer. The effect of herbicide on summer forb density depended on seeding rate (p=0.001). Forb density was reduced the most by 2,4-D (3.1 to 22.1 plants $m^{-2}$) (Figure 3.2A). In herbicide control plots, forb density was lower in plots seeded at the highest rate (46.7 plants $m^{-2}$) than plots seeded at the lowest rate (74.2 plants $m^{-2}$) and was similar to plots seeded at the intermediate rate (65.8 plants $m^{-2}$). Within picloram treatments, seeding at the lowest and highest rates reduced native forb density more than seeding at

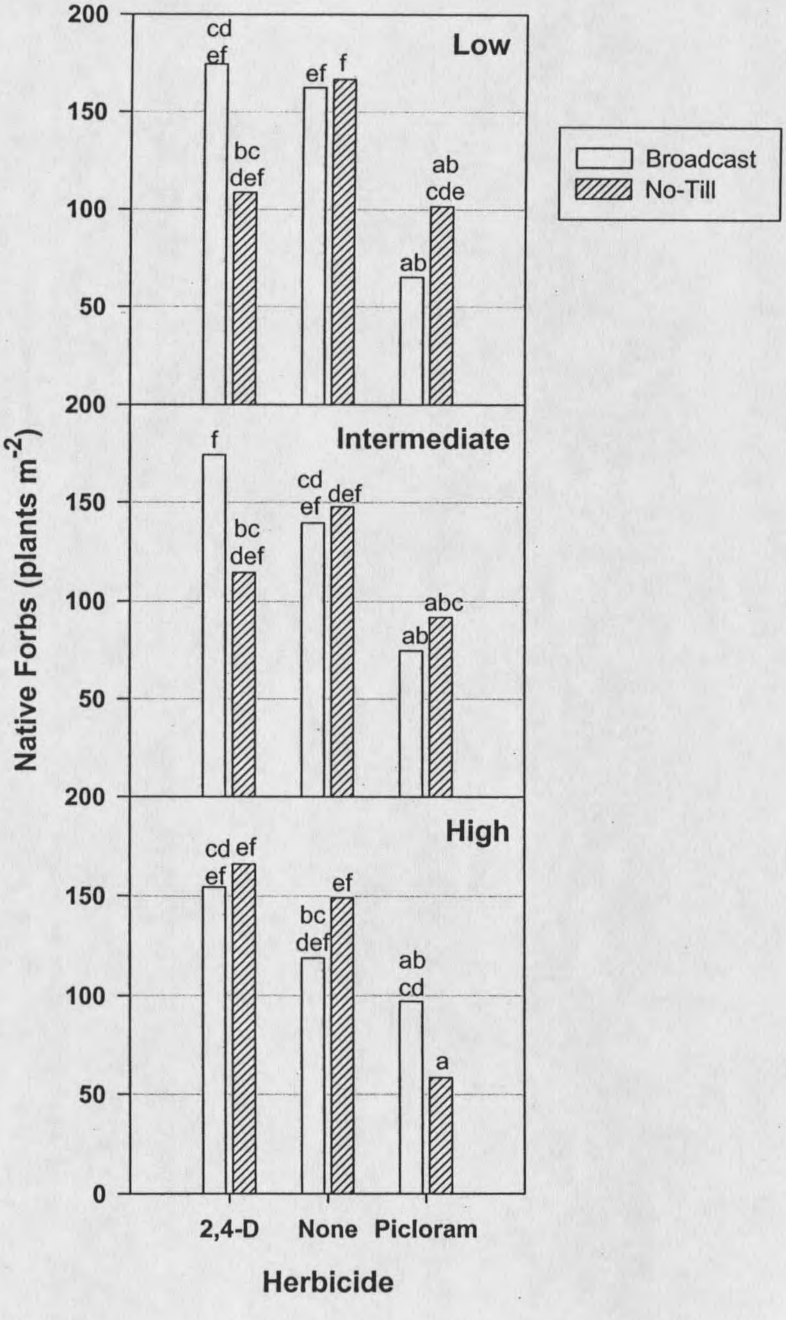

Figure 3.1. The influence of seeding method, seeding rate, and herbicide on spring native forb density. Means followed by the same letters represent similarities ($\alpha$<0.05) among treatments.

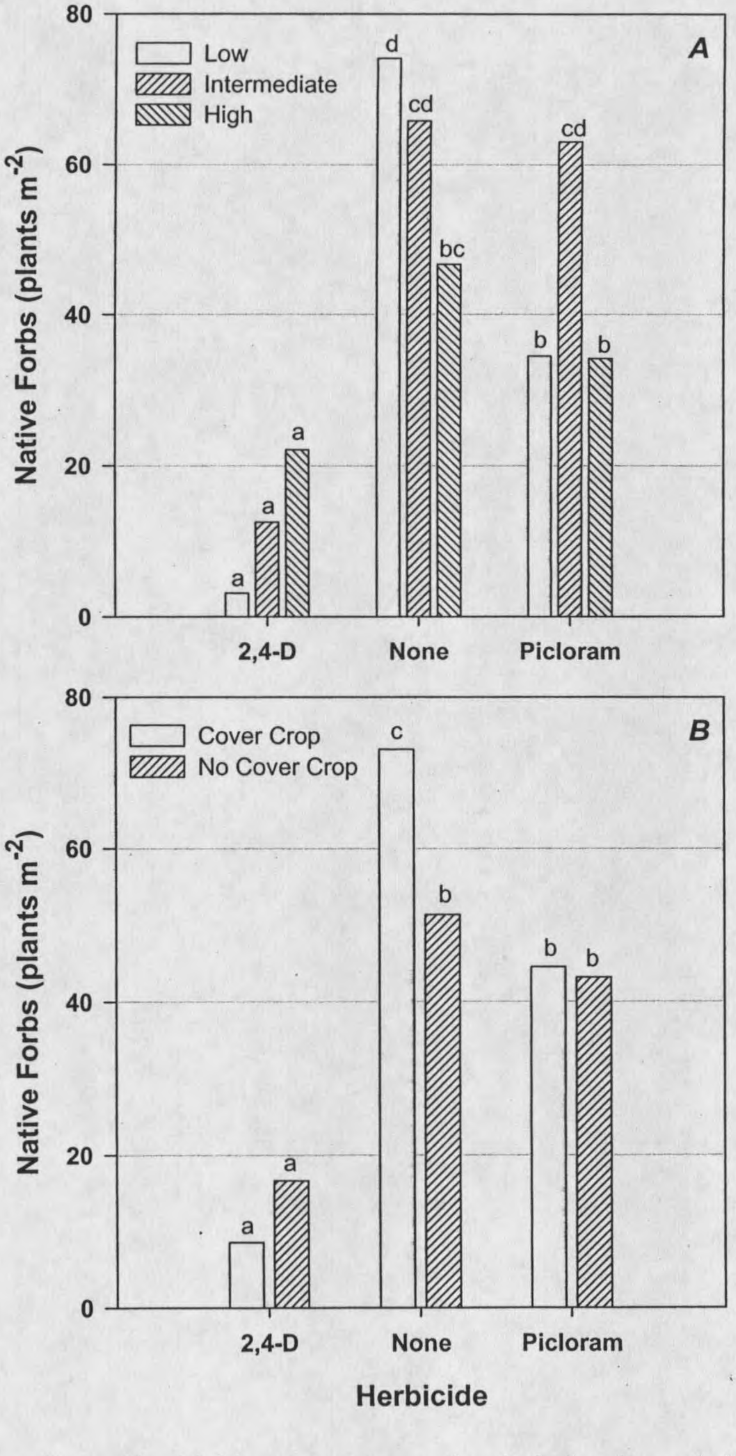

Figure 3.2. The effect of herbicide on summer native forb density as influenced by A) seeding rate and B) cover crop. Means followed by the same letters represent similarities ($\alpha<0.05$) among treatments.

the intermediate rate. Forb densities were similar among plots seeded at the low and intermediate rates with no herbicide and at the intermediate rate with picloram. Seeding at the highest rate without an herbicide yielded similar forb densities to all seeding rate/picloram combinations.

Cover crop and herbicide interacted to influence native forb density (p=0.010). The 2,4-D treatment reduced forb density more than the other herbicide treatments (Figure 3.2B). Summer forb density increased from 51.3 to 73.1 plants m$^{-2}$ with the presence of a cover crop in non herbicide treated plots. The density of forbs in picloram treated plots was similar to the density in non treated plots without a cover crop.

### Native Perennial Grasses

Spring. Spring density of perennial native grasses was influenced by the interaction of cover crop, seeding method, and herbicide (p=0.033). Drill seeding with a cover crop and no herbicide (42.4 tillers m$^{-2}$) yielded more perennial native grasses than broadcast seeding without a cover crop and treating with 2,4-D (4.3 tillers m$^{-2}$) (Figure 3.3). All other treatment combinations resulted in similar spring density of native grasses.

### Species Richness

Spring. Spring species richness was affected by seeding rate and herbicide (p=0.009). Picloram reduced richness more than either of the other herbicide treatments (Figure 3.4A). Within 2,4-D plots (summer treatment), the higher seeding rate (10.4 species m$^{-2}$) increased species richness over the lowest seeding rate (9.0 species m$^{-2}$). Richness was

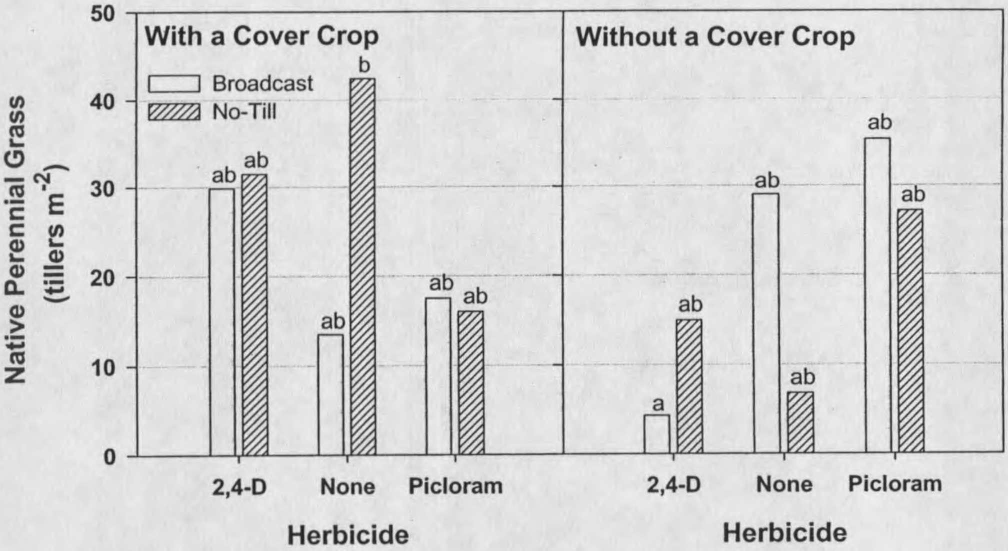

Figure 3.3. The influence of cover crop, seeding method, and herbicide on spring native perennial grass density. Means followed by the same letters represent similarities ($\alpha<0.05$) among treatments.

similar among seeding rates in non herbicide treated plots, but the highest seeding rate increased richness over the lowest seeding rate in the 2,4-D plots.

The effect of seeding method and cover crop on spring species richness was influenced by herbicide (p=0.026). Richness was reduced more by picloram than by the other herbicide treatments, except when applied in combination with drill seeding with a cover crop which yielded species richness similar to broadcast seeding without a cover crop for both the control and 2,4-D treated plots (Figure 3.4B). All seeding method/cover crop combinations within and between 2,4-D and control plots had similar effects on species richness.

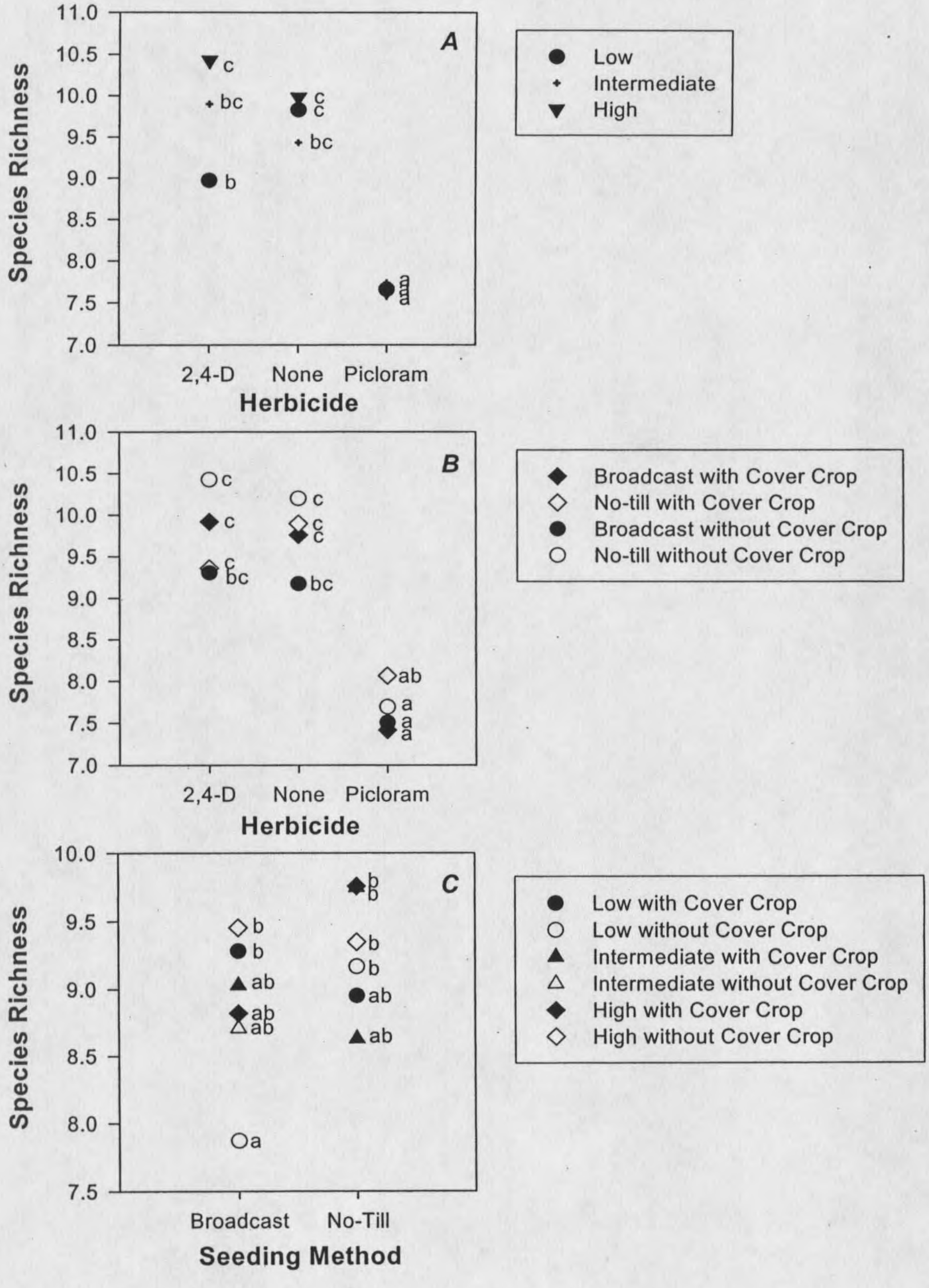

Figure 3.4. Spring species richness as affected by A) seeding rate and herbicide, B) seeding method, cover crop and herbicide, and C) seeding rate, cover crop, and seeding method. Means followed by the same letters represent similarities ($\alpha<0.05$) among treatments.

Seeding rate, method, and cover crop interacted to have an effect on species richness (p=0.001). Broadcast seeding at the lowest rate with a cover crop and at the highest rate without a cover crop increased species richness over broadcast seeding at the lowest rate without a cover crop (Figure 3.4C). Species richness in plots that were broadcast at the lowest rate without a cover crop was also lower than in plots drill seeded at the lowest rate without a cover crop, at the intermediate rate without a cover crop, and at the highest rate with and without a cover crop. Species richness was similar among all seeding rate/cover crop combinations within drill seeded plots.

Summer. Summer species richness was affected by the interaction of cover crop, seeding method, and herbicide (p=0.010). Richness was reduced the most by 2,4-D (Figure 3.5A). Within the 2,4-D treatment, drill seeding without a cover crop increased species richness over broadcast seeding without a cover crop. Drill seeding without a cover crop also increased richness over broadcast seeding without a cover crop within the herbicide control plots. Species richness was similar among all seeding method/cover crop combinations within the picloram treatment. Richness was lower in picloram plots than in non treated plots when drill seeded with a cover crop. Richness was reduced from 6.8 species m$^{-2}$ in plots without an herbicide, to 6.1 species m$^{-2}$ in picloram plots, when broadcast seeded with a cover crop.

The effect of seeding method and herbicide on summer richness was also dependant on seeding rate (p=0.021). The application of 2,4-D reduced richness more than picloram

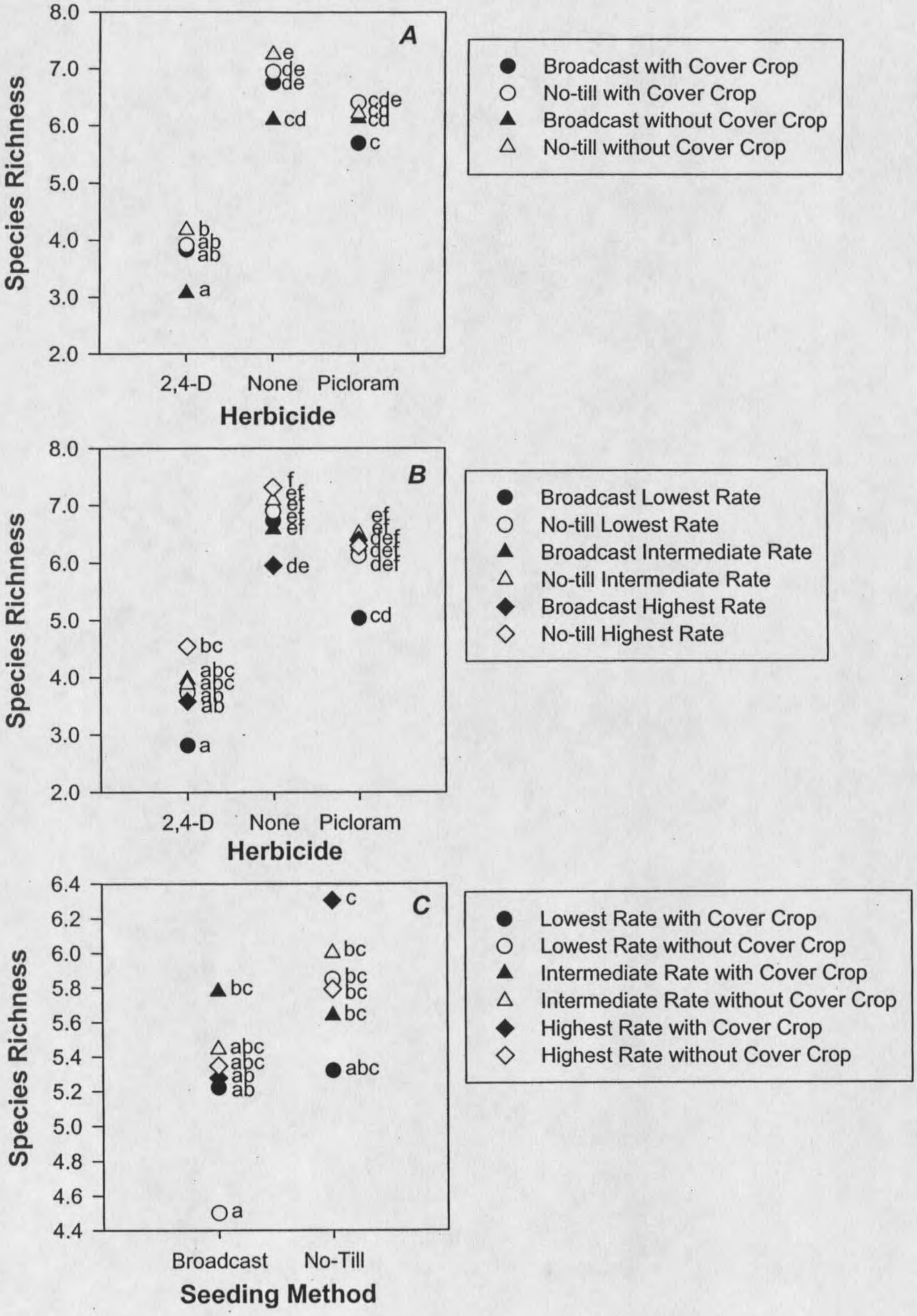

Figure 3.5. Summer species richness as affected by A) seeding method, cover crop, and herbicide, B) seeding method, seeding rate, and herbicide, and C) seeding rate, cover crop, and seeding method. Means followed by the same letters represent similarities ($\alpha<0.05$) among treatments.

or no herbicide (Figure 3.5B). The one exception was drill seeding at the highest rate in combination with 2,4-D, which was similar to broadcast seeding at the lowest rate in combination with picloram. Within non herbicide treated plots, richness was higher when drill seeded at the highest rate than when broadcast at the highest rate. Within the picloram treatment, richness was higher in plots drill seeded at the intermediate rate and broadcast at the highest rate than in plots broadcast at the lowest rate. Other than broadcast seeding at the lowest rate, all seeding rate/method combinations with picloram were similar to all seeding rate/method combinations without an herbicide.

Seeding rate, cover crop, and seeding method interacted to affect summer species richness (p=0.010). Richness in plots broadcast at the lowest rate without a cover crop was lower than in plots broadcast at the intermediate rate with a cover crop and lower than in all drill seeded plots other than those seeded at the lowest rate with a cover crop (Figure 3.5C). Drill seeding yielded similar richness values among all seeding rate/cover crop combinations. Species richness increased from broadcast to drill seeding in plots seeded at the highest rate with a cover crop.

### Simpson's Diversity and Equitability

Spring. The effect of seeding rate on spring diversity was influenced by cover crop (p=0.035). Diversity did not differ among seeding rates when a cover crop was included (Figure 3.6A). However, without the addition of a cover crop, diversity was higher at the intermediate seeding rate (3.2 species) than at the lowest seeding rate (2.8 species).

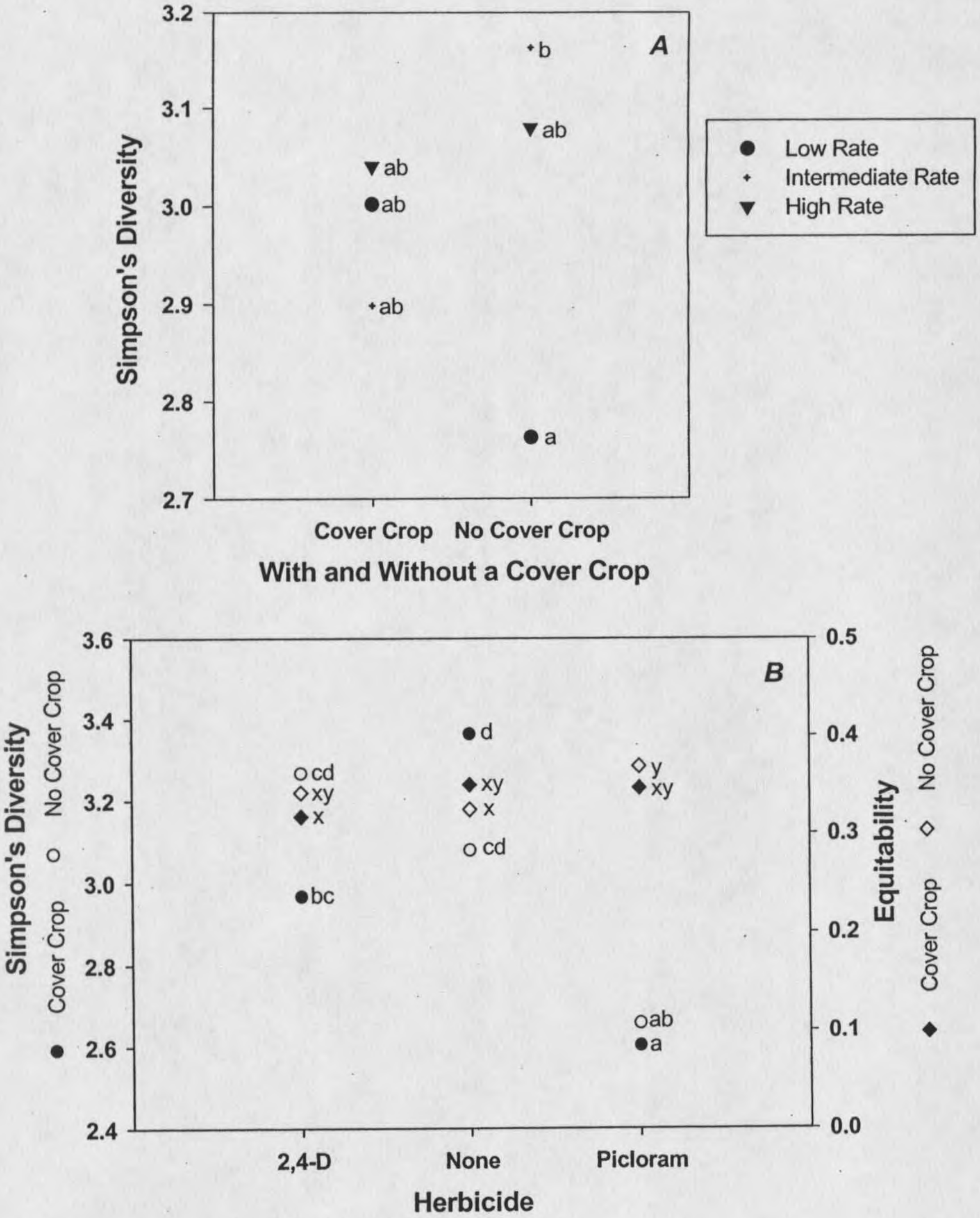

Figure 3.6. A) The effect of seeding rate and cover crop on spring Simpson's diversity. B) The effect of cover crop and herbicide on spring Simpson's diversity and spring equitability. Means followed by the same letters represent similarities ($\alpha<0.05$) among treatments.

Diversity was similar between cover crop and no cover crop treatments for all seeding rates.

Spring diversity and equitability were both influenced by the interaction of cover crop and herbicide (p=0.020 diversity; p=0.026 equitability). Diversity and equitability values were similar between cover crop and no cover crop within all herbicide treatments (Figure 3.6B). With or without a cover crop, diversity was lower when picloram was applied than when no herbicide was applied. Diversity was also higher in the 2,4-D plots than in the picloram plots, with the exception of 2,4-D with a cover crop and picloram without a cover crop, which yielded similar diversity values. In addition, the diversity of plots treated with 2,4-D and a cover crop was less than the diversity of non herbicide treated plots with a cover crop. Equitability did not differ among herbicide treatments with the addition of a cover crop. However, equitability was higher in picloram treated plots without a cover crop (0.37) than in non herbicide treated plots without a cover crop (0.32) and 2,4-D treated plots with a cover crop (0.34).

Summer. Cover crop, seeding method, and herbicide interacted to influence summer diversity (p=0.018). Diversity was lower when treated with 2,4-D than either of the other two herbicide treatments, with the exception of plots treated with picloram and drilled without a cover crop and broadcast with a cover crop, which had density values similar to plots drill seeded without a cover crop and treated with 2,4-D (Figure 3.7). The diversity in plots drill seeded without a cover crop and no herbicide was similar to the diversity in picloram treated plots that had been broadcast seeded without a cover crop, but was higher than all other seeding method/cover crop combinations within the picloram

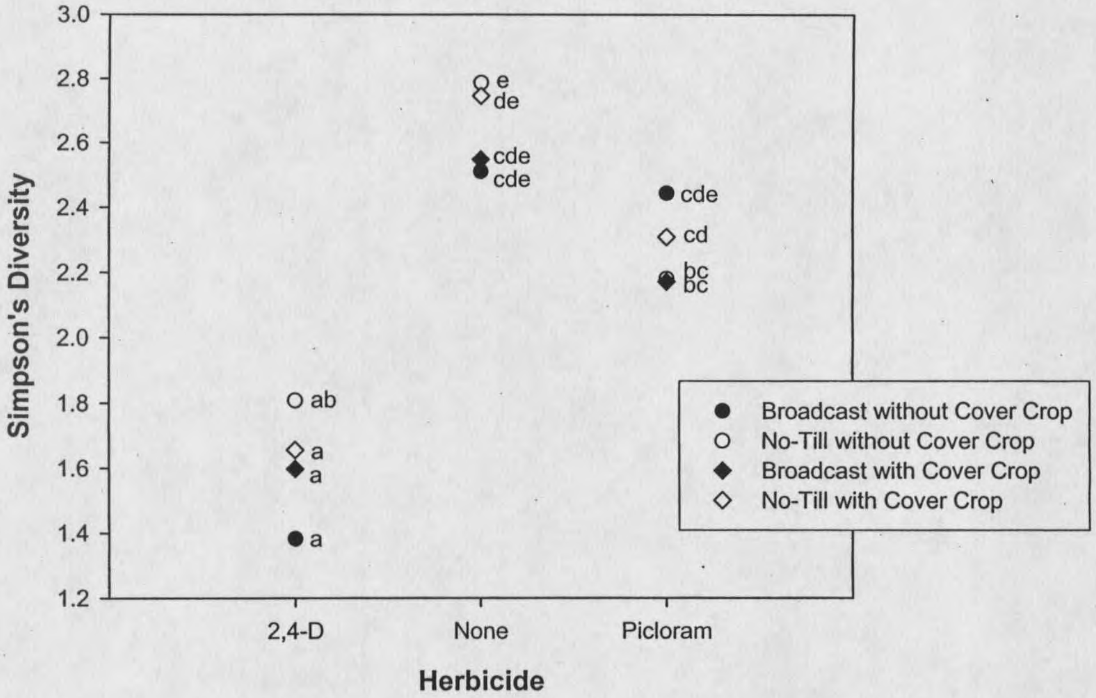

Figure 3.7. Summer Simpson's diversity as affected by seeding method, cover crop, and herbicide. Means followed by the same letters represent similarities ($\alpha<0.05$) among treatments.

treatment. Picloram treatments including broadcast seeding without a cover crop and drill seeding with a cover crop yielded density values comparable to drill seeding with a cover crop and no herbicide. Density was similar among seeding method/cover crop combinations within herbicide treatments.

Diversity was affected by seeding rate (p=0.021). Seeding at the highest rate yielded higher diversity (2.25) than seeding at the lowest rate (2.07), but diversity when seeding at the intermediate rate (2.21) was no different than the diversity at either the lowest or highest rates.

Summer equitability was influenced only by herbicide ($p<0.001$). Equitability was highest when plots were treated with 2,4-D (0.46). Picloram (0.40) and the control (0.41) yielded similar equitability values.

## Discussion

The goal of successional management is to set an invasive plant dominated plant community on a trajectory toward one that is composed of desirable species and functionally diverse (Sheley et al. 1996). Existing native forbs and grasses play an essential role in developing a diverse system, so it is important to understand how successional management strategies impact these species (Pokorny 2002). Species performance practices like broadleaf selective herbicides can negatively impact forbs, while enhancing native grasses. In this study, density of native perennial grasses was not improved by the herbicide treatments, but density of native forbs, species richness, and Simpson's diversity were reduced by picloram applied in the spring or 2,4-D in the summer. Previous studies have found decreases in non-target forb density and cover following an application of picloram (Denny 2003, Rice et al. 1997), but picloram has also been found to have little effect on non-target forb density (Bedunah and Carpenter 1989). In my study, the early season forbs appeared to be more sensitive to picloram than the summer forbs, while 2,4-D dramatically reduced the density of summer forbs. On the contrary, one year following treatment, Jacobs and Sheley (1999b) and Denny (2003) found native forb density to be unaffected by a summer 2,4-D application. Because 2,4-D does not remain active in the soil for an extended period of time, it is possible that I would have observed results similar to those of Jacobs and Sheley (1999b) and Denny (2003) had sampling occurred one year following application.

Several studies reported increased density, cover, and biomass of perennial grasses 1 to 3 years following herbicide application (Rice and Toney 1998, Jacobs and Sheley 1999b, Sheley et al. 2000, Denny 2003). I speculate the limited effect herbicides had on native perennial grass density was a result of there being very few grasses on the site prior to treatment.

The effect of picloram and 2,4-D on richness and Simpson's diversity was similar to the forb density observations, suggesting that some of the early spring forbs were more sensitive to picloram than were the summer forbs. In the first year following herbicide application, Rice et al. (1997) found a decrease in species richness and Shannon diversity with picloram, while Denny (2003) did not find a decline in richness or Shannon-Weiner diversity with either 2,4-D or picloram. Species diversity and richness have been documented to recover to pretreatment levels 3 years following herbicide application, but the target invasive species also recovered (Rice et al. 1997). Continued monitoring will be required to determine the longevity of herbicide effects on diversity and richness of both native and invasive forbs.

The other successional management practices employed in this study did not affect the existing native plant community as strongly as the herbicide treatments. The addition of the cover crop, also a species performance treatment, increased summer forb density in the absence of an herbicide application, but did not consistently influence richness or Simpson's diversity. It is possible that the cover crop served as a nurse crop as winter wheat has been shown to act as a nurse crop for strawberries (Newenhouse and Dana 1989). In a companion study, I found soil moisture tended to be higher, especially in early spring, when a cover crop was present. Davis et al. (2000) found soil moisture improved forb establishment and growth. Disturbance treatments, no-till drill seeding and broadcast seeding over depressions in the soil had only subtle influences on the plant community. Species richness during the summer tended to be higher with drilling than broadcasting, but there were not always significant differences. The disks of the drill could have stimulated the growth of some rhizomatous species that otherwise remained undisturbed with the broadcast treatment (Chandler et al. 1994). Seeding rate, or colonization, also had limited influence on the existing plant community. At the lowest seeding rate, summer Simpson's diversity was less than at the higher seeding rates, which is interesting considering the seeded species were not included in the calculation of richness and diversity. This could also be a nurse crop response (Newenhouse and Dana 1989).

Adopting techniques that minimize negative impacts on existing native communities will improve our ability to restore degraded rangeland. The successional management practices employed in this study had varying effects on the existing native plant community. As expected, herbicides most dramatically affected the forbs, but whether or not this can be considered a long term negative impact requires continued sampling. There is the possibility that niches opened by weed control procedures will simply be reoccupied by invaders, especially without continued management (Levine and D'Antonio 1999; Dukes 2001, Pokorny 2002). Enhancing and preserving species diversity is a significant part of creating a weed resistant plant community through successional management. Continued monitoring and possibly repeating species performance or disturbance practices will play an important role in maintaining diversity and the desired successional trajectory (Sheley et al. 1996).

# References Cited

Bakker, J. D., S. D. Wilson, J. M. Christian, X. Li, L. G. Ambrose and J. Waddington. 2003. Contingency of grassland resotration on year, site, and competition form introduced grasses. Ecological Applications 13(1):137-153.

Bedunah, D. and J. Carpenter. 1989. Plant community response following spotted knapweed (*Centaurea maculosa*) control on three elk winter ranges in western Montana. *In* Knapweed Symposium. EB 45 *ed.* P. K. Fay and J. R. Lacey, pp. 205-212. Plant and Soil Science Department and Extension Service, Montana State University, Bozeman, Montana.

Begon, M., J. L. Harper and C. R. Townsend. 1996. Ecology: Individuals, populations and communities, Third edition. Blackwell Science Ltd, Cambridge.

Berger, J. J. 1993. Ecological restoration and nonindigenous plant species: a review. Restoration Ecology 1:74-82.

Blumenthal, D. M., N. R. Jordan and E. L. Svenson. 2003. Weed control as a rationale for restoration: the example of tallgrass prairie. Conservation Ecology 7(1):Article 6.

Carpinelli, M. F. 2000. Designing weed-resistant plant communities by maximizing niche occupation and resource capture. Thesis (Doctor of Philososhy) Montana State University.

Chandler, K., S. D. Murphy and C. J. Swanton. 1994. Effect of tillage and glyphosate on control of quackgrass (*Elytrigia repens*). Weed Technology 8:450-456.

Chapin, F. S., III, , B. H. Walker, R. J. Hobbs, D. U. Hooper, J. H. Lawton, O. E. Sala and T. Tilman. 1997. Biotic control over the functioning of ecosystems. Science 277(25 July):500-504.

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

Denny, M. K. 2003. Maintaining and establishing culturally important plants after landscape scale disturbance. Thesis (Master of Science) Montana State University.

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

Frank, D. A. and S. J. McNaughton. 1991. Stability increases with diversity in plant communities: empirical evidence from the Yellowstone drought. Oikos 62(360-362).

Hirsch, S. A. and J. A. Leitch. 1996. The impact of knapweed on Montana's economy. *In* Agriculture Economic Report, pp. 44. North Dakota State Universtiy, Fargo, ND.

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

Jacobs, J. S. and R. L. Sheley. 1999a. Competition and niche partitioning among *Pseudoroegneria spicata*, *Hedysarum boreale*, and *Centaurea maculosa*. Great Basin Naturalist 59(2):175-181.

Jacobs, J. S. and R. L. Sheley. 1999b. Spotted knapweed, forb, and grass response to 2,4-D and N-fertilizer. Journal of Range Management 52:482-488.

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

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

McNaughton, S. J. 1977. Diversity and stabilility of ecological communities: a commment on the role of empiricism in ecology. The American Naturalist 111:515-525.

Mueggler, W. F. and W. L. Stewart. 1980. Grassland and shrubland habitat types of Western Montana, pp. 154. USDA Forest Service, Ogden, Utah.

Naeem, S. 1998. Species redundancy and ecosystem reliability. Conservation Biology 12(1):39-45.

Naeem, S., J. M. H. Knops, D. Tilman, K. M. Howe, T. Kennedy and S. Gale. 2000. Plant diversity increases resistance to invasion in the absence of covarying extrinsic factors. Oikos 91:97-108.

Naeem, S. and S. Li. 1997. Biodiversity enhances ecosystem reliability. Nature 390:507-509.

Newenhouse, A. C. and M. N. Dana. 1989. Grass living mulch for strawberries. Journal of the American Horticultural Society 114(6):859-862.

Pickett, S. T. A., S. L. Collins and J. J. Armesto. 1987. A hierarchical consideration of causes and mechanisms of succession. Vegetatio 69:109-114.

Pokorny, M. L. 2002. Plant Functional Group Diversity as a Mechanism for Invasion Resistance. Thesis (Masters of Science) Montana State University.

Rice, P. M., C. Toney, D. J. Bedunah and C. E. Carlson. 1997. Plant community diversity and growth form responses to herbicide applications for control of *Centaurea maculosa*. Journal of Applied Ecology 34:1397-1412.

Rice, P. M. and J. C. Toney. 1998. Exotic weed control treatments for conservation of fescue grassland in Montana. Biological Conservation 85:83-95.

SAS. 2001. SAS. SAS Institute Inc., Cary, NC.

Sheley, R. L., C. A. Duncan, M. B. Halstvedt and J. S. Jacobs. 2000. Spotted knapweed and grass response to herbicide treatments. Journal of Range Management 53(2):176-182.

Sheley, R. L., J. S. Jacobs and D. E. Lucas. 2001. Revegetating spotted knapweed infested rangeland in a single entry. Journal of Range Management 54:144-151.

Sheley, R. L. and J. K. Petroff. 1999. Biology and Management of Noxious Rangeland Weeds, pp. 438. Oregon State University Press, Corvallis.

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.

Tilman, D. 1997. Community invasibility, recruitment limitation, and grassland biodiversity. Ecology 78(1):81-92.

Tilman, D. and J. Knops. 1997. The influence of functional diversity and composition on ecosystem processes. Science 277(5330):1300-1303.

Tilman, D., D. Wedin and J. Knops. 1996. Productivity and sustainability influenced by biodiversity in grassland ecosystems. Nature 379(February 22):718-720.

Velagala, R. P. 1996. Using seed rate and plant densities to enhance intermediate wheatgrass establishment in spotted knapweed dominated rangeland. Thesis (M. S.) Montana State University.

# CHAPTER 4

## SUMMARY

This study investigated the potential for using successional management strategies on invasive plant dominated rangeland. The underlying hypothesis was that as weed management strategies increasingly address the three general causes of succession—site availability, species availability, species performance—in a complementary manner, the successional trajectory will be accelerated toward a desired plant community (Pickett et al. 1987, Sheley et al. 1996). The four overall objectives of the research were to: 1) use two different seeding methods to manipulate site availability and test their effects on seeded grass establishment and existing species density, diversity, and richness; 2) use three different seeding rates to manipulate species availability and test their effects on seeded grass establishment and existing species density, diversity, and richness; 3) use three different herbicide treatments to manipulate species performance and test their influence on seeded grass establishment and existing native species density, diversity, and richness; and 4) manipulate species performance by including a cover crop and testing its effect on seeded grass establishment and existing species density, diversity, and richness.

In Chapter 2, I investigated the effects of seeding method, seeding rate, herbicide, and cover crop on the establishment of three seeded native grasses. I hypothesized that no-till drill seeding at the highest rate, including a cover crop and following a fall picloram application, would yield the highest density of seeded native grasses. The highest rate of establishment for each species occurred when seeds were drilled at the highest rate, however, the herbicide and cover crop treatments did not influence establishment.

It was speculated establishment would improve by reducing the competition between the invasive species and the seeded grasses, but this first year of data suggests that competition was not a factor. Herbicide treatments reduced the density of the two target invasive species, *Centaurea maculosa* Lam. and *Potentilla recta* L. The greatest reduction in density for both species resulted from the summer 2,4-D application, with the fall picloram application providing about 50 % control. It may take more time to determine the differences among herbicide treatments. I had also speculated that a cover crop would reduce soil nitrogen, thereby giving the competitive advantage to the late seral seeded grasses. There was no difference in soil nitrate concentrations between cover crop treatments at the time we sampled, but this does not mean that earlier in the season nitrate concentrations did not differ, or that it may take more time to observe differences between the treatments.

The goal of successional management is to develop a functionally diverse, relatively weed resistant, plant community. My study site had a relatively diverse native forb community, although suppressed in areas heavily dominated by *C. maculosa* and *P. recta*, that was important in developing a diverse plant community. So, Chapter 3 addressed the effect of the management techniques used to establish seeded grasses, on the density, diversity, and richness of the existing native forbs and grasses. I hypothesized that seeding method, seeding rate, and cover crop treatments would not affect the existing plant community, but the herbicide treatments would reduce native forb density, as well as overall species richness and diversity. For the most part, these data supported this hypothesis. However, density, diversity, and richness tended to be higher with drill seeding, but there were not always differences, and in the absence of a herbicide application, summer forb density was higher when a cover crop was included. These treatments did not consistently affect the plant community so generalizations about their influence could not be made from these data.

As expected, the herbicide treatments had significant effects on the existing plant community. Spring forb density, diversity, and richness were all reduced by the fall picloram application, while summer forb density, diversity, and richness were reduced the greatest by the summer 2,4-D application. Summer forb density, diversity, and richness did not always differ between the untreated control and picloram treatments, suggesting early spring forbs may have been more sensitive to picloram than later season forbs. Since the herbicide treatments appeared to affect different forb species, and the herbicides themselves differ considerably in longevity of effectiveness, picloram having a 2 to 3 year soil residual and 2,4-D having a short soil residual, continued monitoring would provide more information about the long term effects of these techniques on existing species.

This research suggests that establishment of seeded native grasses improves as management techniques increasingly address Picket et al.'s (1987) three general causes of succession—site availability, species availability, and species performance. However, the variation in species' response to management techniques, especially the existing plant community, emphasizes the importance of monitoring invasive plant dominated rangeland throughout the restoration process. It takes time for plant communities to equilibrate to the removal or reduction of invasive species which may not be captured after one growing season. Successional management recognizes plant communities as dynamic systems and relies on continued monitoring to maintain a desired trajectory, keeping in mind that it may be necessary to repeat species performance or site availability treatments.

# References Cited

Pickett, S. T. A., Collins, S. L. and Armesto, J. J. 1987. A hierarchical consideration of causes and mechanisms of succession. Vegetatio 69:109-114.

Sheley, R. L., Svejcar, T. J. and Maxwell, B. D. 1996. A Theoretical Framework for Developing Successional Weed Management Strategies on Rangeland. Weed Technology 10:766-773.