THESIS

ENVIRONMENTAL FACTORS ASSOCIATED WITH CHEATGRASS INVASION IN THE GUNNISON BASIN, COLORADO

Submitted by

Shannon Sokolow

Department of Forest, Rangeland, and Watershed Stewardship

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISON BY SHANNON SOKOLOW ENTITLED ENVIRONMENTAL FACTORS ASSOCIATED WITH CHEATGRASS INVASION IN THE GUNNISON BASIN, COLORADO BE ACCEPTED AS FULLFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

Committee on Graduate Work

[redacted]

[redacted]

[redacted]

Adviser

[redacted]

Co-Adviser

[redacted]

Department Head

ABSTRACT OF THESIS

ENVIRONMENTAL FACTORS ASSOCIATED WITH CHEATGRASS INVASION IN THE GUNNISON BASIN, COLORADO

Cheatgrass (*Bromus tectorum* L.) has invaded vast areas of sagebrush (*Artemisia tridentata* Nutt.) dominated rangeland throughout the western U.S. In the high-elevation, semi-desert, sagebrush ecosystem of the Gunnison Basin, cheatgrass infestations are primarily restricted to disturbed sites. I conducted observational and experimental studies to evaluate: 1) the range of a viable seedbank from the edge of cheatgrass patches into the native communities, 2) the differences in soil characteristics under the cheatgrass invaded and uninvaded communities, and 3) the effects of surface soil disturbance, addition of shredded sagebrush litter, and addition of water to simulate above-normal fall precipitation on cheatgrass establishment and productivity. Results of the observational studies suggest that there are viable cheatgrass seeds up to 2 m into the uninvaded areas of the Gunnison Basin, but for some unknown reason, they do not germinate and/or successfully establish. I observed significantly higher nitrate-nitrogen in invaded areas once the cheatgrass senesced, strong trends towards lower soil organic matter, total organic carbon, total carbon and total nitrogen in the invaded areas, and significantly higher phosphorus-to-iron ratios in cheatgrass invaded areas compared to uninvaded areas. Results of the observational studies suggest that there are likely a variety of interacting environmental conditions that could be preventing the germination or establishment of cheatgrass seeds outside of the cheatgrass patches. Results of my experimental study suggest that land management tools that disturb surface soil or add litter may increase the invasibility of cheatgrass into high-elevation, sagebrush habitats in the Gunnison Basin. There was no significant effect of adding additional water on cheatgrass density, biomass, or seed density, which might have been attributed to the above-normal precipitation (about 2.5 times > 30 year average) that naturally occurred in September 2003 (the water treatment application period). Plots under the sagebrush plants had significantly higher cheatgrass density, biomass, and seed density than interspace plots. In both plot locations, disturbance significantly increased cheatgrass density, biomass, and seed density. Similarly, adding sagebrush litter in interspaces significantly increased cheatgrass density, biomass, and seed density compared to the controls. Despite the significant soil treatment effects and the natural, above-normal precipitation that occurred, the small amount of cheatgrass biomass and seed produced during this study indicates that cheatgrass in the Gunnison Basin is kept in check by a variety of environmental factors.

Shannon Sokolow
Department of Forest, Rangeland, and
Watershed Stewardship
Fort Collins, CO 80523
Summer 2005

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CHAPTER I

INTRODUCTION

Invasion by non-native species represents a major part of global change with significant environmental and economic consequences (Vitousek et al. 1996; Pimentel et al. 2000). The rapid invasion of cheatgrass (*Bromus tectorum* L.) in the western U.S. has lead to increased frequency and magnitude of wildfires, altered nutrient cycling patterns, decreased biodiversity, loss of wildlife habitat, and restricted livestock grazing (Mack 1981; Monsen 1994; Knapp 1996; Evans et al. 2001; Booth et al. 2003). Cheatgrass has an amazing ability to out-compete native species by actively exploiting resources earlier in the growing season (Monsen 1994). Until recently, cheatgrass has primarily invaded lower-elevation, arid and semi-arid ecosystems, but it is now becoming more prevalent in higher elevation areas (C.S. Brown, personal communication, 2004). There is a growing concern that cheatgrass will invade the high-elevation, semi-desert sagebrush (*Artemisia tridentata* Nutt.) community in the Gunnison Basin of Colorado, as it has in the Great Basin, since there is some similarity between the sagebrush ecosystems of the two areas (West 1983).

The earliest records of cheatgrass presence in the Gunnison Basin date back to 1957 (B. Green, personal communication, 2005). To date, cheatgrass in the Gunnison

Basin has been primarily associated with roadside disturbances, campgrounds, heavily used wildlife areas, sheep bedding grounds, and a few burned areas (Hayes and Scott 2000). However, some local resource specialists believe that cheatgrass has spread significantly over more land area during the past 10 to 15 years and it will only be a matter of time before it encroaches into large areas of adjacent sagebrush rangeland (A. Hayes, personal communication, 2002). A significant cheatgrass invasion in the Gunnison Basin could lead to many detrimental consequences, including, but not limited to: 1) the forced non-use of grazing permits to curtail spread of cheatgrass seed by livestock on public rangelands, 2) a significant reduction in reliable forage for both wildlife and livestock, 3) an increase in costs associated with wildfire suppression and rehabilitation, and 4) a deterioration or loss of habitat for the Gunnison sage grouse (*Centrocercus minimus*). Therefore, a study is needed to evaluate the potential for cheatgrass to spread into the native plant communities of the Gunnison Basin.

A large challenge is to determine areas that are susceptible to invasions when the factors that facilitate cheatgrass invasions are not well understood. Several studies have correlated nutrient availability, soil texture, surface soil disturbances, litter cover, and precipitation patterns with cheatgrass invasion. For instance, Evans and Young (1984) observed increased cheatgrass germination and production with increased depressions on the soil surface (rough microtopography) that catch wind-dispersed seeds, retain soil moisture, and provide more adequate soil coverage for seeds as the soil settles. In a disturbed sagebrush rangeland in Nevada, Evans and Young (1970) found that a layer of grass litter deposited over cheatgrass seeds provided insulating effects for the surface soil (thereby moderating soil moisture and temperature fluxes), ultimately increasing germination rates.

The timing and pattern of rainfall events can also influence germination rates and successful establishment of seedlings. Anderson (1989) concluded that cheatgrass emergence in a no-till winter wheat production system in Akron, Colorado, was higher in September and October than July and August, even though there was less total rainfall. He suggested that this was possibly a result of average air temperatures cooling from 23°C in July and August to 14°C in September and October. Gunnison's climatic patterns are quite similar to Anderson's study site: high precipitation in July and August, tapering off in September, and significantly cooler temperatures occur by October, bringing an end to the growing season. Allen et al. (1994) found that cheatgrass seeds germinate at higher rates with intermittent hydration than continuous hydration. Therefore, risk of cheatgrass invasion may also be higher in areas that experience natural hydration-dehydration cycles.

In the last 10 to 15 years, attention has been given to understanding the soil properties that tend to be associated with cheatgrass invasion. Some studies focused on soil properties that facilitate cheatgrass invasion, while others focused on the soil properties that change as a result of invasion. Research efforts to date suggest a correlation between cheatgrass invasion and soil pH, salinity levels, decomposition rates, and concentrations of plant available N, P, and K. Yet, there is still conflicting information in the literature as to whether cheatgrass invasion is positively or negatively correlated with these soil parameters. The inconsistencies may be related to differences in such things as: climatic patterns at the study sites, history of disturbance and current disturbance regimes, soil sampling methodologies utilized, neighboring species competitive interactions, time passed since the invasion, and pre-invasion soil characteristics.

In the literature, the most inconsistent of all the observed soil parameters in relation to cheatgrass establishment are correlations between N cycling dynamics and cheatgrass invasion. Some studies have observed a positive correlation between cheatgrass invasion and rates of N mineralization, nitrification, decomposition, or inorganic N uptake and availability (Bolton et al. 1993; Meyer et al. 2001b; Booth et al. 2003; Lowe et al. 2003; Norton et al. 2004). Others were either unable to detect a consistent relationship between nitrogen dynamics and cheatgrass production and establishment (Svejcar and Sheley 2001; Lowe et al. 2002), or detected a negative correlation (Belnap and Phillips 2001; Evans et al. 2001; Ogle et al. 2003). The inconsistent results are most likely due to the fact that N cycling dynamics are difficult to evaluate since N is so mobile, volatile, and variable throughout the year.

The correlations between cheatgrass establishment and soil pH, salinity levels, soil texture, and levels of plant available P and K are more consistent in the literature, but far less studied. Belnap and Phillips (2001) and Miller et al. (2001) found that invaded areas tended to have finer textured soils (thus increased water-holding capacity and fertility) than uninvaded areas. Dakheel et al. (1993), Hanson (1999), and Miller et al. (2001) found higher levels of available P in cheatgrass invaded areas or more successful germination and establishment of cheatgrass under experimental additions of available P. Belnap et al. (2003) conducted lab and greenhouse studies to determine if soil amendments that altered the availability of N, P, and K could be used to inhibit cheatgrass emergence, while not affecting native perennial grasses. In doing so, they observed a positive relationship between pH and cheatgrass emergence, and found that high salt concentrations inhibited cheatgrass germination and emergence. These kinds of analyses still need to be repeated in the variety of environments where cheatgrass has been found.

The patterns of cheatgrass invasion, as well as the altered ecosystem level effects upon cheatgrass invasion, are still not fully understood and seem to be highly dependent on environmental conditions of the study areas used. Since the Gunnison Basin is not yet infested with cheatgrass, it provides a unique opportunity to study the possible causal factors of cheatgrass invasion and spread in higher elevation sagebrush ecosystems. The purpose of this present study was to 1) determine whether viable cheatgrass seeds are dispersed into the native sagebrush community adjacent to existing cheatgrass patches, 2) determine if there are significant differences in soil chemistry and texture under invaded versus uninvaded areas, and 3) evaluate the effects of fall precipitation, surface soil disturbances, and sagebrush litter cover on the establishment and productivity of cheatgrass in the Gunnison Basin.

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CHAPTER II

SEED BANK AND SOIL ANALYSIS OF CHEATGRASS INVADED AREAS

ABSTRACT

Differences in soil characteristics between cheatgrass (*Bromus tectorum* L.) invaded areas and adjacent, uninvaded areas are not completely understood. In the Gunnison Basin of west-central Colorado, a semi-desert sagebrush (*Artemisia tridentata* Nutt.) ecosystem, cheatgrass populations still remain relatively small. They are primarily restricted to disturbed sites and have distinct boundaries between them and the adjacent uninvaded sagebrush communities. This study analyzed 1) the range of a viable seedbank from the edge of these cheatgrass patches into the native communities, and 2) the differences in soil characteristics within the invaded and uninvaded communities. Soil seedbank samples were taken from within and at the edge of the infested areas and at distances of 0.5, 1.0, and 2.0 m from the edge. Seed density decreased exponentially with increasing distance from the cheatgrass patch. As expected, a viable cheatgrass seed bank existed up to at least 2.0 m from the edge of the existing cheatgrass patches (112 seeds/m^2 on average), possibly allowing the population to perpetuate in successive years, assuming the seeds develop into established plants. There was significantly higher nitrate-nitrogen in invaded areas once the cheatgrass senesced. There were also strong trends towards lower soil organic matter, total organic carbon, total carbon and total

nitrogen in invaded areas. Significantly higher soil phosphorus-to-iron ratios in cheatgrass invaded areas were also observed. Results of this study suggest that there are likely a variety of interacting environmental conditions that could be preventing the germination or establishment of the cheatgrass seeds outside of the cheatgrass patches.

INTRODUCTION

An understanding of soil-plnt relationships is important for the successful management of invasive weedy plants. Cheatgrass (*Bromus tectorum* L.), an invasive annual grass, currently dominates at least 20% of the semi-arid sagebrush (*Artemisia tridentata* Nutt.) communities in the Great Basin of the western U.S. (Knapp 1996). However, in a very similar type of sagebrush ecosystem in the Gunnison Basin of west-central Colorado, cheatgrass populations still remain relatively small, and primarily restricted to disturbed sites, indicating that the sagebrush community in Gunnison is rather resistant to invasion. Are there environmental factors that make the Gunnison Basin sagebrush ecosystem more resistant to invasion than similar areas in the Great Basin? Since the cheatgrass patches in the Gunnison Basin have rather defined edges (with adjacent, uninvaded native communities), they provide a unique opportunity to analyze the differences in soil characteristics between invaded and uninvaded areas, while holding most other environmental variables constant.

Ecologists and land managers still do not completely understand what soil characteristics facilitate cheatgrass invasion and whether or not cheatgrass invasions cause changes in soil characteristics (Belnap et al. 2000; Monaco et al. 2003). Correlations between cheatgrass invasion and a variety of soil characteristics, such as inorganic constituents (especially N and P), soil OM, soil texture, salinity and pH, have been analyzed by others through a variety of field and greenhouse studies. However, these types of analyses have not been conducted in all community types where cheatgrass exists, the soil-plant processes involved are still not completely understood, and there have been considerable conflicting results.

Patterns in N cycling dynamics in cheatgrass invaded versus uninvaded areas have varied in the literature. Some studies have observed a positive correlation between cheatgrass invasion and rates of N mineralization, nitrification, decomposition, or inorganic N uptake and availability (Bolton et al. 1993; Meyer et al. 2001a; Booth et al. 2003; Lowe et al. 2003; Norton et al. 2004). Others were either unable to detect a consistent relationship between N dynamics and cheatgrass performance (Svejcar and Sheley 2001; Lowe et al. 2002), or detected a negative correlation (Belnap and Phillips 2001; Evans et al. 2001; Ogle et al. 2003). The inconsistent results are most likely due to the fact that N cycling dynamics are difficult to evaluate since N is so mobile, volatile, and variable throughout the year. Precipitation patterns, plant community composition, timing of soil sampling, and the methods used for the soil analyses could all affect the patterns observed in N cycling dynamics.

There have been very few studies that have looked at other soil characteristics that may be correlated to cheatgrass invasion. A few studies have concluded that cheatgrass growth and establishment are also positively correlated with P levels (Halvorson 1989; Dakheel et al. 1993; Hanson 1999; Miller et al. 2001). The research of Belnap and Phillips (2001) in perennial bunchgrass communities of southeastern Utah has shown significantly higher silt, Fe, Mn, Cu, and K:Mg ratios, and lower sand and exchangeable Ca in cheatgrass invaded areas relative to uninvaded areas. Yet, since there have been so few of these kinds of studies, there is a need for further analysis of soil characteristics that tend to be correlated with cheatgrass invasion.

Understanding the soil characteristics that are typically found in cheatgrass invaded areas in the Gunnison Basin will guide the selection of management tools (such as additions of soil amendments) to reduce or prevent invasion. Furthermore, knowing the range of the cheatgrass seed bank would give land managers an idea of how far into the native community management efforts should be applied. I had two objectives with this study, 1) to conduct a seed bank analysis to evaluate how far into the adjacent, uninvaded, native sagebrush community viable seeds exist, and 2) to compare soil characteristics in cheatgrass invaded areas versus the adjacent, uninvaded, native sagebrush areas.

METHODS

Study Sites

Sampling for this study was conducted in the Gunnison Basin, which is located in the west-central part of Colorado. The Gunnison area has an average frost-free growing season of 71 days and approximately 28 cm of average annual precipitation (Hunter and Spears 1975). Most of the precipitation occurs in July and August (WRCC 2003b), with highest snowfall occurring in January, February, and March (Hunter and Spears 1975). June is typically dry, but monsoon summer rains are frequent in July and August (Hunter and Spears 1975). Elevations range from 2200 m to about 3900 m (Hunter and Spears 1975).

Study sites were selected based on accessibility, elevation (various elevations were sampled in order to represent the range of elevations in the Gunnison Basin), and discreteness of the boundaries between the uninvaded sagebrush and cheatgrass dominated communities. The seed bank samples were collected at 7 sites around the Gunnison Basin: 1) Willow Creek (south of Blue Mesa Reservoir), 2) Soap Creek Road, 3) Red Creek Road, 4) Sapinero Mesa (a small burn area), 5) Taylor Park Road (near Pothole Reservoirs), 6) Willow Creek (northwest of Ohio City), and 7) Woods Gulch. Brief descriptions, approximate locations relative to a major highway, aspects, slopes, elevations, and UTM coordinates of each site are in Table 2.1. Species lists for each site are in Table 2.2. Plant species present were determined in August 2002 by identifying all species in 5 randomly placed 1 m^2 plots (at each site). It should be noted that 2002 was a drought year; therefore drought intolerant species may not have been adequately represented in the sampling because they did not green-up that year. Soil texture and chemistry samples were collected at the same 7 sites in 2002, but only at the Red Creek, Sapinero Mesa, Soap Creek Road, and Woods Gulch sites in 2003.

Each site had an invading cheatgrass patch with defined edges. Elevations ranged from 2317 to 2871 m. At all sites, the cheatgrass patch was along a road, except at the Sapinero Mesa site where the cheatgrass patch was in an upland, previously burned sagebrush area about 30 m away from the road, and the Woods Gulch site where the cheatgrass patch was next to a heavily used cattle trail along the south side of a creek (the road was north of the creek about 200 m up a hill).

Soil Sampling Design

During the first year (2002) of the study, soil sampling occurred in mid August after cheatgrass plants had senesced and dropped most seeds. Seed bank soil cores (3 cm deep, 10 cm in diameter) were collected along 4 transects (2 m long) extending out from the middle of the cheatgrass patch at each site. Transects were spaced somewhat evenly apart along approximately a 100 m stretch of the cheatgrass patch edge. Five locations along each transect were sampled: within the patch, at the edge of the patch, and at distances of 0.5, 1.0, and 2.0 m from the edge of the patch. At each location along each transect, one soil core was collected, making a total of 4 soil cores for each location. The 4 soil cores from each location were composited into one larger sample and placed in cloth soil sample bags. Samples were air-dried and stored under laboratory conditions until late October 2002, which allowed cheatgrass seeds to after-ripen (Allen et al. 1995). They were then thinly spread on trays of sterile soil and watered as needed under greenhouse conditions. As plants germinated, I identified, counted, and discarded the cheatgrass seedlings, as well as all other species' seedlings. After each counting, I stirred the entire contents of the trays to bring the seeds that may have been buried too deep (thereby preventing germination) closer to the surface. This process continued for approximately 7 weeks until no more cheatgrass seedlings emerged. No further soil sieving of the seed bank samples (to find remaining caryopses) was carried out because the literature suggests that as long as time is permitted for seed after-ripening, about 99% of all viable seeds should germinate under ideal greenhouse conditions (Hull and Hansen 1974; Mack and Pyke 1983; Allen et al. 1995).

In August 2002, I also collected soil samples at each site for soil texture and chemistry analyses. At all 7 sites, ten soil cores were randomly collected from each invaded and adjacent univaded area with a 5.7 cm diameter by 10 cm bucket auger. The soil cores taken at each location were composited into a bucket, thoroughly mixed, and a subsample was placed in cloth soil sample bags and transported in a portable cooler to the laboratory. Samples were air-dried, ground, and sieved through a 2 mm screen. They were refrigerated until mid September and then transported to the Colorado State University Soil, Water, and Plant Testing Laboratory (Fort Collins, CO). All soil samples were analyzed for pH, EC, percent soil OM, total percent C, total percent N, TOC, C:N ratio, concentrations of NH_4-N, NO_3-N, P, Zn, Fe, MN, Cu, Ca, Mg, Na, and K, as well as soil texture (composition of sand, silt, and clay).

Soil chemistry samples were collected again the following year, but at multiple times throughout the growing season to include the changes in plant available nutrients depending on the growth stage of the plants. Soils were collected in late May, early July, late July, and late August 2003. Only 4 of the original 7 sites were utilized in this part of the study. The same soil sampling methods used in 2002 were used again for the 2003 samples. Furthermore, the soil analyses were the same as for the 2002 samples, excluding exchangeable Ca, Mg, Na, and K and composition of sand, silt, and clay.

Soil Laboratory Analyses

The Colorado State University Soil, Water, and Plant Testing Laboratory analyzed all soil samples using the following procedures. Soil pH and EC were both determined with a saturated paste (Sparks 1996). The modified Walkely-Black method was used to determine percent OM (Sparks 1996). Total C and N concentrations were analyzed using a CHN furnace (Leco 1000 CHN analyzer, Leco Corp., St. Joseph, MI) (Sparks 1996). Carbonate carbon (CO_3-C) was determined with the gravimetric method described by the Soil Survey Investigation Staff (1991). Calcium carbonate ($CaCO_3$) was determined by dividing CO_3-C by 0.12. Total organic carbon was determined by subtracting the percent CO_3-C equivalent from total C. The ratio of C:N was calculated by dividing TOC by the percent total N. Concentrations of plant available NH_4-N were analyzed with 2M KCL extracts using the sodium salicylate method by flow injection analysis (OI Analytical Flow Solution 3000, OI Analytical, College Station, TX) (Sparks 1996). Plant available NO_3-N, K, P, Zn, Fe, Mn, and Cu were all extracted with ammonium bicarbonate-diethelyenetriaminepentaacetic acid (AB-DTPA) (Sparks 1996). Nitrate-N was analyzed by cadmium reduction using flow injection analysis. Phosphorus was determined colorimetrically using the molybdate-blue method (Sparks 1996). The K, Zn, Fe, Mn, and Cu concentrations were found with inductively coupled plasma atomic emission spectroscopy (ICP-AES) (Sparks 1996). Water and 1N NH_4OAC (ammonium acetate) extractions were performed to determine the $cmol_c/kg$ of exchangeable Ca, Mg, Na, and K in the soil samples. The exchangeable bases of each were determined by subtracting the water extract values from the ammonium acetate values, as described by the Soil Survey Investigation Staff (1996). Soil texture, including composition of sand, silt and clay, were determined by the hydrometer method (Klute 1986).

Data Analyses

All statistical analyses for the soil chemistry samples were performed using SAS® Version 8.2 software (SAS 2001). I used a one-way ANOVA to compare soil characteristics of the 2002 soils samples from inside versus outside of the cheatgrass infested areas. A repeated measures analysis of variance, with collection date as the repeated measure, was performed for the 2003 soil samples using the mixed procedure (ProcMixed) to detect differences in the soil parameters (excluding analyses of the exchangeable bases and soil texture) from inside versus outside infested areas. I also calculated and statistically analyzed differences in P:Fe ratios between invaded and uninvaded areas. Data were log transformed where necessary to meet the assumptions of normality in an analysis of variance. Significant differences were accepted at $p \leq 0.05$.

RESULTS

Seed Bank

Seed density decreased exponentially with increasing distance from the cheatgrass patch (Fig. 2.1). Values ranged from over 4000 seeds m^{-2} to approximately 100 seeds m^{-2} at 2.0 m from the edge of the cheatgrass patch. As expected, there was a viable cheatgrass seed bank up to at least 2.0 m from the edge of the existing cheatgrass patches.

Soil Chemistry and Texture

For all of the 2002 and 2003 soil chemical analyses, data from the Wood's Gulch site (Table 2.3) was dropped because it appeared to be an outlier for several of the soil parameters when compared to all other sites (Table 2.4). Soils under the cheatgrass invaded areas at the Wood's Gulch site had unusually high OM, NH_4-N, Zn, Fe, C, and TOC. I suspect that the high OM, NH_4-N, C, TOC, and Fe were likely due to the heavy use by cattle just prior to soil sampling; however, the reason for the unusually high Zn is unclear. Cattle feces not only provide high inputs of OM, C, and NH_4-N, but they also can lower the soil pH. Availability of Fe drastically increases with each unit of pH increase (K.A. Barbarick, personal communication, 2005). The soil pH at the Wood's Gulch site was the lowest out of all the sites (Table 2.3).

Analyses of the soil samples collected in August 2002 revealed that cheatgrass invaded areas had lower OM ($p = 0.0317$) and higher P:Fe ($p = 0.0141$) than the adjacent uninvaded areas (Table 2.4). The NO_3-N was also higher (by about 2.5 times, $p = 0.0223$) within the cheatgrass areas as compared to the uninvaded areas (Table 2.4).

There were strong trends toward lower TOC ($p = 0.06$), total N ($p = 0.0956$), and Fe ($p = 0.0827$) in the soil within invaded areas as compared to the uninvaded areas (Table 2.4).

In the soil samples collected summer 2003, I observed significantly higher EC ($p = 0.0166$), and P:Fe ($p = 0.0347$) in the cheatgrass invaded areas as compared to the uninvaded areas (Table 2.4). There was a significant soil collection date by invasion status interaction for NO_3-N. Therefore, differences in NO_3-N concentrations between invaded and uninvaded areas were evaluated separately for each month. In the late May soil collection, NO_3-N was lower ($p = 0.0581$) within cheatgrass invaded areas, but in the early July, late July, and late August soil collections, NO_3-N was higher within cheatgrass invaded areas ($p = 0.0015$, 0.0672, and 0.0151, respectively; Fig. 2.2). This trend was also qualitatively observed in the data from the Wood's Gulch site (Table 2.3). Apparently, NO_3-N accumulated in the soil once the cheatgrass senesced at all sites. All other soil parameters tested in the 2003 soil samples showed no statistically significant differences between invaded and uninvaded areas (Table 2.4). However, there were trends toward lower OM ($p = 0.066$), total N ($p = 0.0968$), total C ($p = 0.0762$), and TOC ($p = 0.0938$) in the cheatgrass invaded areas (Table 2.4), which is similar to what I observed in the 2002 soil samples.

DISCUSSION AND CONCLUSIONS

Seed Bank

Annual plant populations are highly reliant on a viable seed bank for their perpetuation (Pyke 1994). Results from this seed bank study indicate that viable cheatgrass seeds are dispersed up to at least 2.0 m from the edge of existing cheatgrass patches into the adjacent native sagebrush vegetation in the Gunnison Basin. The observed exponential decline in seed density with increasing distance from the mother plants is typical of most wind dispersed bromegrass seeds (Hulbert 1955). Since very few mature cheatgrass plants can be found in the adjacent native rangeland at the sites studied, I am led to conclude that there are likely a variety of interacting environmental conditions that could be preventing the germination or establishment of the cheatgrass seeds outside of the cheatgrass patches.

Perhaps in the Gunnison Basin, cheatgrass seeds outside of the invaded areas either: 1) do not germinate because environmental conditions are not adequate, 2) successfully germinate but do not establish into mature plants because seedling survival is prevented by limiting soil conditions or competition by neighboring plants, or 3) do not germinate even if germination conditions are adequate because they have been induced into dormancy. Non-dormant cheatgrass seeds have the potential to be induced into dormancy when exposed to specific patterns of environmental conditions, such as sunlight, soil moisture, and soil temperature (Young and Evans 1975; Pyke 1994; Meyer et al. 1997). Future research could directly test these hypotheses about the germination and establishment dynamics of cheatgrass seeds that are dispersed outside of the established cheatgrass patches.

Soil Chemistry and Texture

Results from the soil chemistry analysis indicate that there are some detectable soil chemistry differences within cheatgrass invaded areas versus adjacent uninvaded areas in the Gunnison Basin. However, out of all the soil parameters analyzed, the only statistically significant pattern I observed in both study years was a higher level of soil NO_3-N within the invaded areas once the cheatgrass senesced (Fig. 2.2). Several other studies have observed an accumulation of NO_3-N under cheatgrass invaded areas in mid summer and early fall (Bolton et al. 1990; Svejcar and Sheley 2001; Booth et al. 2003; Norton et al. 2004).

A few scenarios could explain the observed accumulation of NO_3-N under invaded areas at the time of cheatgrass senescence. First, total root uptake of NO_3-N would be less in the invaded areas since cheatgrass senesces earlier than most of the other native plants. An accumulation of NO_3-N is likely to occur at this point since mid summer soil temperatures and precipitation still permit microbial mineralization and subsequent nitrification. Second, soil microbial activity may be greater within invaded areas (thereby increasing mineralization rates) due to the retained moisture and moderated temperatures under the cheatgrass litter layer that is dropped (Evans and Young 1970; Booth et al. 2003). Third, soil microbial activity may be higher in invaded areas because of the large input of OM from the shallow, very fine roots that senescing cheatgrass can provide. Uninvaded areas probably do not have this large, shallow OM input so early in the growing season. However, since the native species are still active when cheatgrass has senesced, they are probably leaking nutrients via root exudates, which are a more easily accessible nutrient source than the organic material provided by senesced cheatgrass roots (Juma and McGill 1986). A comparison of the amount of N provided by organic inputs of cheatgrass roots versus exudates from the native species should be further analyzed.

Future research is warranted to determine why NO_3-N accumulates within cheatgrass invaded areas in mid summer and early fall. Soil sampling throughout the year, for multiple years, and at several soil depths would provide valuable information.

Other research has shown between year, season, and depth variation in N cycling dynamics within cheatgrass invaded versus uninvaded areas (Bolton et al. 1993; Evans et al. 2001; Svejcar and Sheley 2001; Belnap et al. 2003; Norton et al. 2004). Furthermore, since a few studies have found no correlation or a negative correlation between cheatgrass invasion and inorganic N availability (Evans et al. 2001; Svejcar and Sheley 2001), this present study should be repeated for more years to confirm these results.

There was about 38% less OM within cheatgrass invaded areas as compared to uninvaded areas in the summer 2002 samples, and though not significant, there was a trend toward lower OM in the 2003 samples. The lack of a statistically significant difference in year 2003 may have been due to the small sample size (only 3 sites). There were also strong trends toward lower TOC, total C, and total N in the invaded areas during the time of sampling in both years (none of which had a significant soil collection date effect). Together, these results suggest that there is less accumulation of organic materials in the invaded areas due to either higher rates of decomposition or less organic matter inputs.

The results of this study support the findings of others that have shown enhanced microbial activity and decomposition rates following cheatgrass invasion (Bolton et al. 1993; Booth et al. 2003; Norton et al. 2004). Norton et al. (2004) and Booth et al. (2003) found that cheatgrass invasion promotes OM decomposition. Norton et al. (2004) mostly attributed this to increased microbial decomposition from the increased porosity and labile organic inputs in the near-surface soil horizons within cheatgrass invaded areas. Booth et al. (2003) found higher gross mineralization rates, gross soil nitrification rates, higher soil nitrification potentials, as well as greater mass and N loss of buried litter bags in cheatgrass invaded areas. However, the results of a few other studies suggested lower rates of decomposition in cheatgrass invaded areas compared to uninvaded areas, possibly due to less microbial activity and diversity (Belnap and Phillips 2001; Evans et al. 2001; Ogle et al. 2003). Further analysis of the quality of litter inputs, soil moisture and temperature patterns, and microbial activity and diversity in the invaded versus uninvaded areas of the Gunnison Basin would help explain these findings.

Several studies have shown a positive correlation between cheatgrass invasion and increased P availability (Halvorson 1989; Dakheel et al. 1993; Hanson 1999; Miller et al. 2001). In both study years, P availability was greater in the invaded areas, but the difference was not statistically significant. Yet, I did find significantly higher P:Fe ratios in invaded areas in both study years. The Fe availability is largely regulated by soil pH; the lower the soil pH, the more Fe becomes available (K.A. Barbarick and E.F. Redente, personal communications, 2005). Since Fe can bind with P to create $FePO_4$ precipitates, the more available Fe in the soil, the more P will bind up in a plant unavailable form (the $FePO_4$ precipitate). Even though my results did not demonstrate a statistically significant difference in pH between invaded and uninvaded areas, the difference could be significant biologically. Averaged across all sites and sampling dates, invaded areas had a higher pH (Table 2.4). The exception was the Wood's Gulch site that I dropped from the statistical analyses, which had lower pH in invaded areas (Table 2.3), probably due to cattle feces. Invaded areas should have less available Fe with the higher pH's (which is somewhat supported by my observed trend toward lower Fe in invaded areas in the summer 2002 samples). With less Fe available to bind with P, less $FePO_4$ would be created, rendering more P available in the invaded areas. Therefore, even though my results did not find significantly higher P in the invaded areas, they do somewhat support the theory that cheatgrass establishment may be positively correlated with plant available P.

The only other statistically significant soil chemistry difference my results demonstrated was higher EC in the invaded areas relative to uninvaded areas, suggesting that cheatgrass may be able to tolerate soils with higher soluble salt concentrations better than the native species in the adjacent community. However, since the EC values in both the invaded and uninvaded areas were always lower than 4.0 ds/m, which is the point at which salt concentrations tend to have adverse effects on plants (K.A. Barbarick and E.F. Redente, personal communications, 2005), there probably is little biological significance to this finding. Furthermore, it should be noted that in the 2003 soil samples, only 3 sites were used for the statistical analyses, and 2 out of the 3 sites were along roadsides that are frequently sprayed with anti-dust materials. Since my results only demonstrated a significant difference in EC values between invaded and uninvaded areas in the 2003 soil samples, I question whether this result only eludes to the fact that the cheatgrass invaded areas at these sites were closer to the road where they received more inputs of these anti-dust materials. Magnesium chloride ($MgCl_2$) is the most common material used to reduce dust on dirt roads in the Gunnison Basin. Both Mg and Cl are soluble salts, therefore, spraying $MgCl_2$ could lead to higher soil soluble salt concentrations. Since some plants are known to be very sensitive to Cl (K.A. Barbarick, personal communication, 2005), a future research study could look at the tolerance of cheatgrass versus some of the more common native species to Cl and other common soluble salts.

Repeated soil sampling should also be carried out at more sites (including more off-road sites) for multiple years to confirm or negate this result.

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Table 2.1. Site descriptions for 7 study sites in the Gunnison Basin, Colorado.

Site name	Location	Aspect/Slope	Elev (m)	UTM Coord (Datum WGS84)	Description
Willow Creek (S. of Blue Mesa Reservoir)	2.09 km from Hwy149	SW - road 0%, down into riparian 13%	2323 m	13 S 0320097 4258491	roadside infestation that becomes more sparse as it moves into riparian community
Soap Creek Road	13.68 km from Hwy92	E - 5%	2369 m	13 S 0298208 4268827	thick infestation in a gravel road turn out, lessens as it moves into sagebrush lupine dominated community; might have been burned in the past (sagebrush skeletons present)
Red Creek Road	2.25 km from Hwy50	W - 4%	2317 m	13 S 0305359 4262907	roadside infestation, upland sagebrush community type next to Red Creek
Sapinero Mesa	11.75 km from Hwy50, 1.93 km from Lake City cut-off	N - 6% E - 10% S - 5% W - 6%	2585 m	13 S 0309884 4249469	old upland sagebrush burn site, infestation thickest in center of the E facing slope
Taylor Park Road	13.67 km from end of paved road (Hwy742)	W - 12%	2871 m	13 S 0360616 4311561	infestation thick for about 100 m along road, scatters a bit downslope from road into sagebrush community, riparian community about 20 m from roadside
Willow Creek (NW of Ohio City)	not documented	SW - 2%	2662 m	13 S 0358065 4271130	infestation mostly next to road, but scattered individuals towards creek; looks like it was previously disturbed by plowing/fire (sagebrush very sparce and rabbitbrush mostly dominates); evidence of lots of gopher activity
Woods Gulch	not documented	NW - 11%	2651 m	13 S 0358843 4264203	infestation starts along road, follows drainage down to creek, also found across creek along heavily used cattle trail next to creek, infestation thins as move up-slope from creek into sagerbrush upland community

Table 2.2. Species lists for 7 study sites in the Gunnison Basin, Colorado.

Species	Site: Willow Creek (S of Blue Mesa Reservoir)	Soap Creek	Red Creek	Sapinero Mesa (small burn area)	Taylor Park Road *	Willow Creek (NW of Ohio City)	Woods Gulch
Achillea millefolium (common yarrow)	x					x	
Achnatherum hymenoides (Indian ricegrass)				x			
Agropyron cristatum (crested wheatgrass)						x	
Artemisia frigida (fringe sagewort)			x				
Artemisia ludoviciana (white sagebrush)						x	
Artemisia tridentata ssp. *wyomingensis* (Wyoming big sagebrush)				x		x	
Artemisia sp.			x			x	
Brassica sp. (mustard)		x					
Bromus inermis (smooth brome)	x						
Bromus marginatus (mountain brome)						x	
Bromus tectorum (cheatgrass)		x	x				
Carex geyeri (Geyer's sedge)	x	x		x	x		x
Castilleja sp. (Indian paint brush)		x				x	
Chenopodium album (lambsquarters)						x	
Chrysothamnus viscidiflorus (green rabbit brush)	x	x	x	x		x	
Elymus elymoides (squirreltail)						x	
Equisetum sp. (horsetail)			x				
Eriogonum umbellatum (sulphur-flower		x	x				
Festuca arizonica (Arizona fescue)		x		x	x		
Hesperostipa comata (needle-and-thread grass)		x	x	x		x	x
Juncus sp. (rush)		x					

* Only two 1m^2 lots were sampled

Table 2.2. (Continued) Species lists for 7 study sites in the Gunnison Basin, Colorado.

	Site						
Species	Willow Creek (S of Blue Mesa Reservoir)	Soap Creek	Red Creek	Sapinero Mesa (small burn area)	Taylor Park Road *	Willow Creek (NW of Ohio City)	Woods Gulch
Koeleria macrantha (prairie junegrass)			x		x		
Leymus cinereus (basin wildrye)						x	
Lupinus sp. (lupine)		x	x		x		
Mahonia repens (Oregon grape)		x					
Mentha sp. (mint)						x	
Oxytropis sp. (loco weed)					x		
Pascopyrum smithii (western wheatgrass)	x	x			x		x
Phlox hoodii (Hood's phlox)				x		x	x
Poa fendleriana (muttongrass)				x			
Poa sp. (bluegrass)	x	x	x			x	x
Purshia tridentata (antelope bitterbrush)							x
Rosa woodsii (Wood's rose)	x	x					
Senecio spp. (groundsel)		x					
Symphoricarpos occidentalis (western snowberry)	x			x		x	x
Taraxacum officinale (common dandelion)						x	
Unknown Forb #1		x	x			x	x
Unknown Forb #2	x	x		x			
Unknown Forb #3					x		
Unknown Forb #4		x					
Unknown Forb #5		x					

* Only two 1m^2 lots were sampled

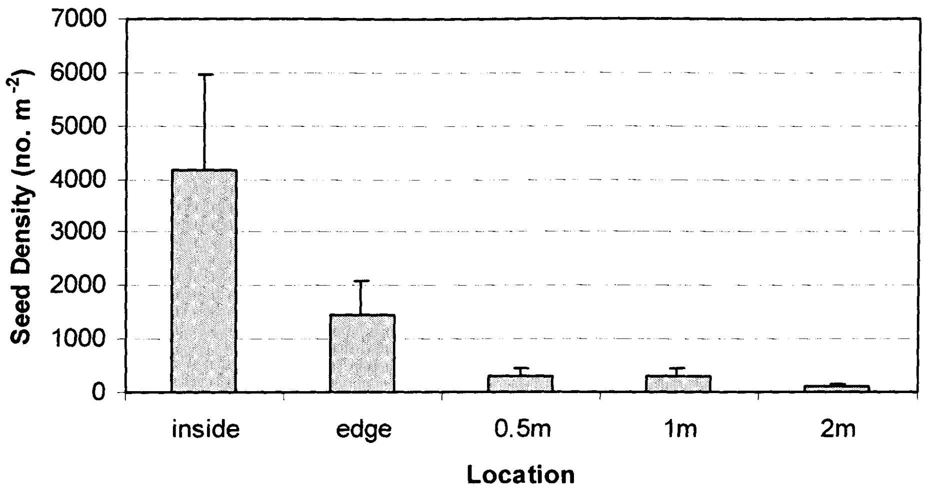

Figure 2.1. Average viable seed density (± 1 standard error) in the soil at 5 sampling locations (averaged across 7 sites).

Table 2.3. Soil parameters for the Wood's Gulch site, Gunnison Basin, Colorado.

	2002		2003							
	Invaded	*Uninvaded*	*Invaded*				*Uninvaded*			
Parameters	(mid Aug)	(mid Aug)	mid May	early July	late July	late Aug	mid May	early July	late July	late Aug
pH	5.8	6.2	5.8	5.9	5.9	5.9	6.4	6.2	6.3	6.2
EC[1] (ds/m)	0.6	0.4	0.3	0.4	0.3	0.4	0.3	0.5	0.4	0.6
OM (%)	7.9	5.9	6.5	10.3	12.5	11.3	7.8	6.4	6.0	7.2
NH_4-N (mg/kg)	23.0	5.6	4	5.1	4.5	2.8	4.4	5.0	4.2	3.2
NO_3-N (mg/kg)	11.2	4.0	7.6	3.4	9.7	8.9	7.6	2.9	5.6	4.9
P (mg/kg)	18.2	17.0	14.5	18	16.6	16.2	13.6	12.2	8.7	10.8
K (mg/kg)	498.0	492.0	203	218	277	208	253	251	249	285
Zn (mg/kg)	16.40	5.48	11.6	12.3	12.2	15.1	5.56	4.70	3.81	5.48
Fe (mg/kg)	113.0	58.8	78	101	93.9	118	53.5	49.7	45.1	58.8
Mn (mg/kg)	13.9	5.9	19.1	19.8	12.7	13.2	9.67	16.3	5.69	11.4
Cu (mg/kg)	0.86	1.50	2.23	1.09	2.14	1.37	2.95	1.76	1.55	1.36
CEC	25.9	17.1	18.6	17.8	22.4	23.7	21.2	19.3	23.9	22.1
Total N (%)	0.393	0.331	0.257	0.362	0.423	0.42	0.328	0.272	0.250	0.305
Total C (%)	4.56	3.81	3.814	4.445	5.398	5.033	4.359	3.71	3.195	3.926
TOC (%)	4.36	3.27	3.772	4.422	5.278	5.008	4.234	3.652	3.062	3.894
C:N	11.10	9.89	14.68	12.22	12.48	11.92	12.91	13.43	12.25	12.77
Sand (%)	50	48	-	-	-	-	-	-	-	-
Silt (%)	40	40	-	-	-	-	-	-	-	-
Clay (%)	10	12	-	-	-	-	-	-	-	-
Ca exchangeable ($cmol_c$/kg)	5.2	4.9	-	-	-	-	-	-	-	-
Mg exchangeable ($cmol_c$/kg)	1.7	1.6	-	-	-	-	-	-	-	-
Na exchangeable ($cmol_c$/kg)	0.2	0.1	-	-	-	-	-	-	-	-
K exchangeable ($cmol_c$/kg)	0.5	0.5	-	-	-	-	-	-	-	-

[1] EC = electrical conductivity; OM = organic matter; CEC = cation exchange capacity;
- Laboratory analysis wasn't performed on the soil samples

Table 2.4. Comparison of soil parameters in cheatgrass invaded and uninvaded areas in the Gunnison Basin, Colorado, 2002 and 2003.

	2002			2003		
Parameters	Invaded	Uninvaded	p-value	Invaded	Uninvaded	p-value
pH	6.80	6.50	0.1946	7.05	6.68	0.2182
EC[1] (ds/m)	0.50	0.43	0.3276	0.61	0.47	0.0166
OM (%)	2.30	3.70	0.0317	2.47	3.63	0.0666
NH_4-N (mg/kg)	5.60	5.13	0.5484	4.11	4.83	0.2558
NO_3-N (mg/kg)	5.50	2.10	0.0223 §	‡	‡	‡
P (mg/kg)	13.10	11.60	0.6146	14.83	11.48	0.1462
K (mg/kg)	427.60	429.90	0.9812	419.60	380.71	0.683
Zn (mg/kg)	1.40	1.90	0.1394	1.33	1.61	0.6489 §
Fe (mg/kg)	24.40	32.30	0.0827 §	15.77	21.92	0.2793 §
Mn (mg/kg)	6.70	6.40	0.8143	10.67	8.27	0.1026
Cu (mg/kg)	1.20	1.30	0.5359	1.53	1.72	0.4542
P:Fe	0.81	0.49	0.0141 §	1.13	0.62	0.0347
CEC	14.60	14.80	0.9284	18.03	19.87	0.262
Total N (%)	0.14	0.17	0.0956 §	0.10	0.15	0.0968 §
Total C (%)	1.50	1.80	0.1598	1.49	2.00	0.0762 §
TOC (%)	1.03	1.40	0.0658 §	0.11	0.27	0.0938 §
C:N	6.80	7.90	0.1042	13.11	13.16	0.9417 §
Sand (%)	63.70	63.50	0.939	-	-	-
Silt (%)	21.50	24.00	0.1852	-	-	-
Clay (%)	14.80	12.50	0.2682	-	-	-
Ca exchangeable ($cmol_c$/kg)	4.00	4.00	1.0000	-	-	-
Mg exchangeable ($cmol_c$/kg)	1.60	1.30	0.4601	-	-	-
Na exchangeable ($cmol_c$/kg)	0.12	0.10	0.3632	-	-	-
K exchangeable ($cmol_c$/kg)	0.40	0.40	1.0000	-	-	-

[1] EC = electrical conductivity; OM = organic matter; CEC = cation exchange capacity;
‡ Average across the 4 soil collection dates was not appropriate because of a significant soil collection date by invasion status interaction, see Figure 2.2.;
§ Data were log transformed to meet assumptions of normality in an ANOVA
- Laboratory analysis wasn't performed on soil samples

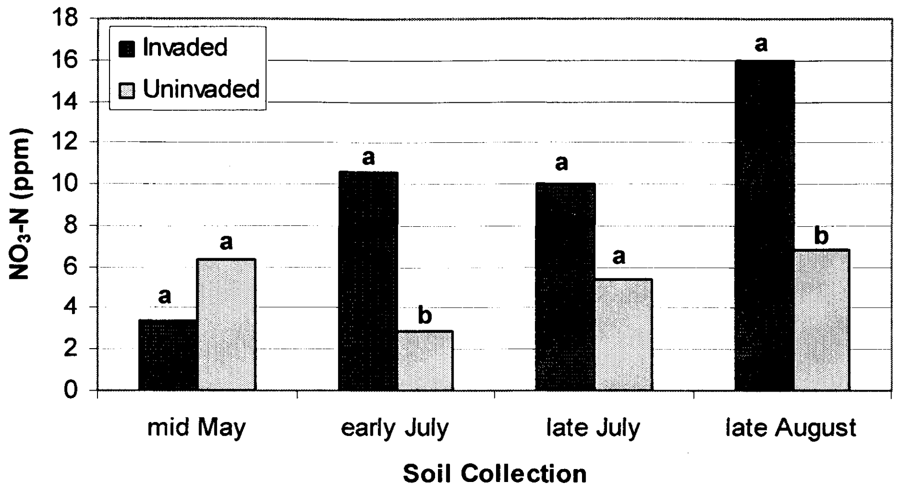

Fig. 2.2. Mean soil NO_3-N concentrations (across sites) for each soil collection in 2003. Within each soil collection period, different letters above bars indicate significant differences between NO_3-N concentrations in invaded and uninvaded areas.

CHAPTER III

EFFECT OF ADDED WATER AND SURFACE SOIL MANIPULATIONS ON CHEATGRASS

ABSTRACT

Cheatgrass (*Bromus tectorum* L.) has invaded vast areas of sagebrush (*Artemisia tridentata* Nutt.) dominated rangeland throughout the western U.S. In the high-elevation, semi-desert, sagebrush ecosystem of the Gunnison Basin, cheatgrass infestations are primarily restricted to disturbed sites. The objective of this study was to determine the effect of surface soil disturbance, addition of sagebrush litter, and addition of water to simulate above-normal fall precipitation on cheatgrass establishment and productivity. Thirty-two whole-plots were treated with simulated rain events in late August, middle September, and early October 2003. Five subplots in each whole-plot (total 160 subplots) were treated by either hand raking the top 5 cm of soil or adding sagebrush litter to simulate brush mowing litter deposition (only applied in the sagebrush interspaces). Data were collected in the fall of 2003 and spring of 2004. There was no significant effect ($p > 0.5$) of adding additional water on cheatgrass density, biomass, or seed density, which might have been attributed to the above-normal precipitation (about 2.5 times > 30 year average) that naturally occurred in September 2003. Plots under sagebrush plants had higher ($p < 0.0011$) cheatgrass density, biomass, and seed density

than interspace plots (excluding litter plots) by 1.5, 1.8, and 2.2 times, respectively. In both locations, disturbance increased ($p < 0.0001$) cheatgrass density, biomass, and seed density by approximately 4, 7, and 6.5 times, respectively. Similarly, adding sagebrush litter in interspaces increased ($p \leq 0.0026$) cheatgrass density, biomass, and seed density by 5.2, 5.9, and 6.1 times, respectively. My results suggest that land management tools that disturb surface soil or add litter may increase the invasibility of high-elevation sagebrush habitats in the Gunnison Basin. However, despite the significant soil treatment effects and the natural, above-normal precipitation that occurred, the small amount of cheatgrass biomass and seed produced indicates that the remaining native vegetation can successfully compete with cheatgrass, thereby keeping it in check.

INTRODUCTION

The invasion of cheatgrass (*Bromus tectorum* L.) throughout most of the sagebrush (*Artemisia tridentata* Nutt.) dominated rangelands of the western United States is of concern to land managers, ranchers, wildlife managers and natural resource researchers. As a result of cheatgrass invasions, millions of hectares of perennial shrub-steppe communities have been converted into annual grasslands characterized by minimal biodiversity, increased wildfire frequency, and reduced perennial forage for wildlife and livestock (Klemmedson and Smith 1964; Mack 1981; Hunter 1990; Young and Tipton 1990). Cheatgrass has invaded approximately 20% of the Great Basin sagebrush zone, making it difficult for native species to successfully compete (Knapp 1996). There is a growing concern among some resource specialists that cheatgrass will invade in the Gunnison Basin of Colorado, as it has in the Great Basin, since there are similarities between the sagebrush ecosystems of the two areas (West 1983).

The Gunnison Basin provides a unique opportunity to determine some possible driving forces behind cheatgrass invasions, since cheatgrass is present in the Basin but has not yet dominated the native sagebrush rangeland in as it has in the Great Basin. The Gunnison Basin differs from the Great Basin in terms of elevation, precipitation patterns and timing, and length of the growing season. The Gunnison Basin semidesert sagebrush areas are at higher elevations, ranging from about 2,000–3,000 m (Hunter and Spears 1975), compared to only about 1,000-2,000 m for the Great Basin (West 1983). This difference results in shorter spring and fall growing seasons, wetter summers, and slightly higher annual precipitation than most of the Great Basin (see climatic diagrams in Fig. 2.1). These differences may be inhibiting a major invasion of cheatgrass in the Gunnison Basin.

Precipitation patterns are extremely influential in determining plant species composition in sagebrush steppe systems (Bates et al. 1998; Anderson and Inouye 2001; Maier et al. 2001). Cheatgrass, unlike most of the native perennial grasses, germinates in the fall, overwinters in a semidormant state, and then resumes growth when temperatures warm up in the spring (Hulbert 1955). Cheatgrass has a competitive advantage over perennial native grasses for water and nutrients by becoming active early in the spring growing season before most perennial species have even initiated growth (Hulbert 1955). Some studies have suggested that fall precipitation timing and amounts, as well as patterns of soil moisture (wet-dry cycles), can influence germination rates, production, and establishment of cheatgrass (Frasier et al. 1987; Anderson 1989; Allen et al. 1994; Frasier 1994; Morris 2001).

Some studies have correlated surface soil disturbances and litter cover with cheatgrass invasion (Evans and Young 1972; Young and Evans 1973; Evans and Young 1984; Meyer et al. 2001a). Depressions on the soil surface, commonly resulting from surface soil disturbances, catch wind-dispersed seeds, retain soil moisture, and provide more adequate soil coverage for seeds as the soil settles (Evans and Young 1972; Boudell et al. 2002). Some litter types have been found to moderate soil moisture and temperature fluxes, providing less extreme microsite conditions (Evans and Young 1970), while other litter types have been found to suspend seeds, thereby exposing them to more extreme periods of drying (Young et al. 1971) .

This present study examined whether increased fall precipitation in the Gunnison Basin would expedite cheatgrass invasion by increasing plant density, total standing biomass, and seed production. I also evaluated the effect of surface soil disturbance and a sagebrush litter layer on cheatgrass establishment. I tested three hypotheses: 1) a watering treatment consisting of three rainfall events distributed around September will increase cheatgrass density, biomass, and seed density more than the treatments with one or two rainfall events, 2) addition of sagebrush litter on the bare soil of the interspaces between mature sagebrush plants will increase cheatgrass density, biomass, and seed density when compared to the control plots, and 3) disturbing the surface soil of the interspaces and mixing the litter with mineral soil under the sagebrush plants will increase cheatgrass density, biomass, and seed density when compared to the control plots.

METHODS

Study Area

This study was conducted in the Gunnison Basin, which is located in the west-central part of Colorado. The Gunnison area has an average frost-free growing season of 71 days and approximately 28 cm of average annual precipitation (Hunter and Spears 1975). Most of the precipitation occurs in July and August (WRCC 2003b), with highest snowfall occurring in January, February, and March (Hunter and Spears 1975). June is typically dry, but monsoon summer rains are frequent in July and August (Hunter and Spears 1975). Elevations range from 2,200 m to about 3,900 m (Hunter and Spears 1975). The study site is at 2,587 m elevation on a fairly level (0.5 to 1-percent), north-west facing slope, about 48 km south west of the town of Gunnison. The chosen site was representative of the dominant sagebrush community and range sites present throughout the Gunnison Basin.

The area is classified as a dry mountain loam range site (Hunter and Spears 1975). Soils at the site are sandy loams belonging to the Parlin-Hopkins series. The Parlin soils are clayey over loamy-skeletal, montmorillonitic, Aridic Argiborolls, and the Hopkins soils are fine-loamy over fragmental, mixed, Torriorthentic Haploborolls (Hunter and Spears 1975). Wyoming big sagebrush (*Artemisia tridentata* Nutt. ssp. *wyomingensis* Beetle & Young) is the predominant shrub species of the community, with a small percentage of green rabbitbrush (*Chrysothamnus viscidiflorus* [Hooker] Nutt.) present. The predominant grass and grass-like species are elk sedge (*Carex garberi* Fern.), Sandberg bluegrass (*Poa secunda* J. Presl), prairie junegrass (*Koeleria macrantha* [Ledeb.] J.A. Schultes), squirreltail (*Elymus elymoides* [Raf.] Swezey), muttongrass (*Poa* *fendleriana* [Steud.] Vasey), Arizona fescue (*Festuca arizonica* Vasey), and pine needlegrass (*Achnatherum pinetorum* [M.E. Jones] Barkworth). Scattered throughout the site are Hood's phlox (*Phlox hoodii* Richards), Indian paintbrush (*Castilleja* sp.), sulphur buckwheat (*Eriogonum umbellatem* Torr.), hairy golden aster (*Heterotheca villosa* [Pursh] Shinners), and Oregon grape (*Mahonia repens* [Lindl.] G. Don).

Experimental Design

The effects of additional fall precipitation, surface soil disturbances, and litter cover on cheatgrass density, biomass, and seed production were evaluated using a randomized complete block design with a split-plot treatment structure. Whole-plot treatments consisted of simulated rain events on three dates. Each plot ultimately received the same amount of water; however, plots differed in the number and distribution of the rainfall events across the three dates. Part of each whole-plot was in the interspaces between sagebrush plants and part was under an adjacent sagebrush plant. Eight whole-plots within each block received one of eight watering treatments (including an unwatered plot which served as a control). To prevent run-off from one whole-plot impacting another, all whole-plots were separated within the study area.

Subplot treatments consisted of three surface soil manipulations: no manipulation, disturbance of the top 5 cm of surface soil using a hand rake, or addition of a sagebrush litter layer to simulate the litter deposition of a brush mowing treatment. Subplots in interspaces consisted of a litter treatment, surface soil disturbance treatment, or no treatment (Fig. 2.2). Subplots under the sagebrush received either a surface soil disturbance or no treatment (Fig. 2.2). There were four blocks for a total of 32 whole-plots and 160, 20 x 50 cm subplots.

The plots were placed approximately 30 m away from an already existing cheatgrass infestation along a roadside. Seeds were collected from the nearby infestation in July 2003, tested for viability (94% germination, 3% dormant seeds), and allowed to after-ripen under laboratory conditions until they were planted in the field at the end of August 2003. One hundred seeds per each 20 x 50 cm subplot were broadcast seeded by hand without any covering treatment after the surface soil manipulations were implemented. The surface soil disturbance in each subplot consisted of mixing the top 5 cm of soil using a hand rake. The additional litter treatment (in the interspaces only) consisted of spreading 65 g of sagebrush litter per subplot.

The litter was prepared from freshly collected sagebrush plants that were run through a chipper to simulate the size of litter left behind by a brush mowing treatment. The amount of litter spread in each subplot was determined by averaging the weight of 10 litter samples deposited from a recent brush mowing treatment in Kezar Basin, Gunnison, Colorado. A sample consisted of the surface layer of litter from a 20 x 50 cm area.

To evaluate the effect of precipitation timing on cheatgrass establishment, all of the subplots (except control plots) were supplemented with a total of 3.36 cm (3360 ml) of water in different timing patterns over the study period. The 3.36 cm was approximately two times the standard deviation of the 30 year precipitation average for September. Eight watering treatments were applied (including an unwatered control), where some plots received all of the water on each date, while other plots only received one-half or one-third of the water on each date. However, all of the plots (except controls) received the total 3360 mL by the end of the treatment applications.

The tap water used for watering the plots was left out in buckets for a few days prior to watering to allow for chlorine evaporation. The water was measured with a graduated cylinder and applied to the subplots by slowly pouring it into a 20 x 50 cm sheet metal pan with 23 holes drilled in the bottom that were 0.16 cm in diameter. Watering treatment dates were: 30 August, 15 September, and 4 October, 2003. An electric fence, approximately 0.5 m high, was constructed around the study area to exclude sheep grazing within the experimental plots.

The naturally occurring surface soil moisture and temperature under sagebrush plants and in interspaces, within each block, were recorded on data loggers (HOBO micro stations; Onset Computer Corporation, Bourne, MA) with soil moisture sensors (20-cm EC-20 ECHO Dielectric Aquameter; Decagon Devices Inc, Pullman, WA) and soil temperature sensors (12-Bit Temperature Sensors, Onset Computer Corporation). The sensors were buried (horizontally) at a depth of 3 cm.

Cheatgrass plants in each subplot were counted in early November 2003 and mid April, May, and June 2004. To determine total cheatgrass biomass in each subplot, plants were clipped in June at peak biomass, oven dried at 55°C for 48 hours, and weighed. Seeds on the plants collected from each subplot were also counted, oven dried, and weighed.

Data Analyses

All statistical analyses were performed using SAS® Version 8.2 software (SAS 2001). A repeated measures analysis of variance, with month as the repeated measure, was performed using the mixed procedure (ProcMixed) to detect differences in cheatgrass density among watering treatments and surface soil manipulations. A one-way ANOVA was used to compare cheatgrass biomass, seed density, and seed biomass for all treatments. For each analysis, an orthogonal contrast was used to compare under sagebrush plots to interspace plots. Cheatgrass plant density data were square root transformed, and plant biomass data were log transformed to meet the assumptions of normality in an analysis of variance. Significant differences were accepted at $p \leq 0.05$.

Soil temperature and soil moisture sensor data were averaged from all 4 blocks. However, soil temperature data were missing from 18 September 2003 to 23 September 2003 in blocks 3 and 4 and from 27 October 2003 to 31 October 2003 in block 4 due to malfunction of the sensors from rodent damage. Soil water content data were missing from 18 September 2003 to 23 September 2003 in the blocks 3 and 4 under the sagebrush, from 5 August 2003 to 23 September 2003 in block 3 interspace, from 27 October 2003 to 31 October 2003 in block 4 under the sagebrush, and for the whole time period in block 4 interspace, due to malfunction of the sensors from rodent damage.

RESULTS

Simulating additional fall rain had no effect on cheatgrass plant density (p=0.6081, Table 2.1) or biomass (p=0.5674, Table 2.1), as well as seed density (p=0.5305, Table 2.1) or biomass (p=0.5150, Table 2.1). The soil manipulation by month was significant for cheatgrass plant density. Therefore, the soil manipulation effects were analyzed separately for each month (Table 2.2). However, in every month, the same patterns emerged, except cheatgrass density was only significantly different between the disturbed and added litter plots in the November 2003 count (Table 2.2). The disturbed plots had about 1.4 times greater density than the litter plots in the November count. By the spring of 2004, there were no detectable differences between the disturbance and litter treatments. Plant density was always significantly higher in the disturbance plots (regardless of location), and in the interspace litter plots relative to the controls. The disturbance treatment in both locations, and the litter additions in the interspaces, significantly increased cheatgrass biomass (Fig. 2.3) when compared to the control plots.

There was a significant ($p<0.0001$) soil manipulation effect on seed density and biomass. Disturbance of the top 5 cm of soil increased seed density by about 6.5 times in the interspace ($p=0.0022$) and under the sagebrush ($p<0.001$) compared to the undisturbed control (Table 2.2). Addition of sagebrush litter in the interspaces also increased ($p=0.0027$, Table 2.2) seed density by about 6 times when compared to the undisturbed control. There was no difference ($p=0.9468$) in seed density between the disturbed and added litter plots. Similar effects were observed for seed biomass (Table 2.2).

The orthogonal contrast run in each analysis revealed that plots under the canopy of sagebrush individuals had higher cheatgrass plant density and biomass, as well as seed density and biomass, than the interspace plots. By the end of the growing season in the June observation, the disturbed plots under the sagebrush had greater plant density ($p=0.0008$, Table 2.2) and biomass ($p=0.0001$, Table 2.2), as well as seed density ($p<0.0001$, Table 2.2) and biomass ($p<0.0001$, Table 2.2), than the disturbed plots in the interspaces. The plots with no surface soil manipulation under the sagebrush also had significantly higher plant density ($p=0.001$, Table 2.2) and biomass ($p=0.0134$, Fig.2.3) than in the interspaces. However, seed density and biomass were not different ($p=0.4983$, $p=0.5372$, Table 2.2) between the undisturbed plots in the interspaces versus under the sagebrush.

Sensor data showed that the naturally occurring soil temperatures were generally higher in the interspace locations than under the shrubs (Fig. 2.4). The naturally occurring soil moisture was greater in the interspaces than under shrubs for a few days after a rainfall event, however, the interspaces dried out faster than the under shrub locations (Fig. 2.4).

DISCUSSION

Watering Treatment Effects

I expected to see increased cheatgrass density, biomass and seed production from the addition of simulated fall precipitation on cheatgrass seeded plots within the high elevation, semidesert sagebrush habitat of the Gunnison Basin. Unlike the native cool-season perennial grasses found in the area, cheatgrass can germinate in the fall when temperatures are still cool and overwinter in a semidormant, vegetative state (Hulbert 1955). This gives it a head start in the spring on developing root systems such that, by the time native species are actively growing, cheatgrass can more effectively exploit surface soil moisture and nutrients (Cline et al. 1977). Since the Gunnison Basin has distinctly different climatic patterns than the cheatgrass invaded areas in the Great Basin, I hypothesized that an increase in fall precipitation might facilitate cheatgrass invasion. Morrow and Stahlman (1984) stated that cheatgrass growth and seed production are significantly reduced if seeds do not germinate in the fall, but that enough seed is produced by the spring cycle for the species to perpetuate. However, I thought that an increase in fall germination might facilitate cheatgrass invasion, not just cheatgrass perpetuation.

Results of my study suggest that increased September rain in the high elevation semidesert, sagebrush-bunchgrass community of the Gunnison Basin will have no significant effect on cheatgrass density, biomass, or seed production. I found no significant differences in cheatgrass plant density and biomass, and seed density and biomass, as a result of the timing and amount of water added. These results are inconsistent with the findings of the few other studies that have looked at the effect of fall rain on cheatgrass germination and establishment (Mack and Pyke 1983; Anderson 1989; Meyer et al. 2001a; Morris 2001). Meyer et al. (2001a) observed an increase in cheatgrass biomass per plant resulting from 25 mm of extra rainfall in mid-October and mid-March under shrub clumps within a shadscale (*Atriplex confertifolia*)/gray molly (*Kochia americana*) community in Utah. Anderson (1989) found 6 times the rate of cheatgrass emergence in a no-till winter wheat production system near Akron, Colorado in September and October than July and August from the same amount of precipitation, suggesting that moisture regimes in late-fall may be critical for cheatgrass establishment. Mack and Pyke (1983) observed an increase in cheatgrass emergence from 1.8 cm of precipitation over a 2 week period in late-August. However, when no precipitation fell during the following 3 weeks, a good portion of the cheatgrass plants that germinated from the August rains died. They found a smaller death rate with later emerging seedlings since there was less chance for low soil moisture conditions. Morris (2001) added 200 mm of water in 50 to 100-mm amendments over a 2 week period during October to a sagebrush steppe area in Idaho where cheatgrass was present. She found an exponential increase in cheatgrass cover in the treated plots with increased moisture availability. The few published studies indicated a significant correlation between cheatgrass emergence and fall precipitation (Mack and Pyke 1983; Anderson 1989; Meyer et al. 2001a; Morris 2001).

Although my results are inconsistent with the findings in the aforementioned studies, my inability to demonstrate a significant relationship between fall precipitation and cheatgrass establishment is supported by the literature. Meyer et al. (2001a) simulated 25 mm of extra rainfall in mid-October and mid-March in shrub interspaces within a shadscale (*Atriplex confertifolia*)/gray molly (*Kochia americana*) community in Utah and observed no change in cheatgrass biomass per plant. Uresk et al. (1979) found a weak relationship between spring soil moisture and cheatgrass growth rates in an abandoned agricultural field in south-central Washington. They concluded that since cheatgrass growth is generally complete by the time soil moisture becomes limiting, soil temperature is the more influential factor in determining growth rates. The same may hold true for fall soil moisture and cheatgrass establishment. Cheatgrass seeds have the highest germination success at air temperatures of 10°C (Hulbert 1955). September and October temperatures in Gunnison may be too low for maximum germination rates, even though plenty of soil moisture is available. Young and Tipton (1990) looked at the relationship between climate change and cheatgrass invasion in arid areas of the Lahontan Basin, Nevada. They explained that from their experience living in the region, higher cheatgrass production seemed to occur during years when effective rains came early enough in the fall that temperatures were still favorable for germination. However, after reviewing historical climate data and evidence of cheatgrass spread, they actually found that the decade when cheatgrass apparently invaded new arid areas in the Lahontan Basin was a period of drought. They concluded that if climate change plays an important role in the spread of cheatgrass, then the change must be subtle and there must be other conditions already present that are correlated with cheatgrass invasion at the time of the climatic change. Increased fall precipitation may not be as influential on cheatgrass invasion as other plant dynamics can be, such as community resource competition, human and natural disturbances regimes, and genetic adaptations.

The non-significant effects of the watering treatments in this present study may also be attributed to the naturally occurring above average precipitation during September 2003 (about 2.5 times > 30 year average) when the water treatments were applied. Since the amount of water to be applied was based on the 30 year average of precipitation for September, it is likely that the effects of the watering treatments were overshadowed by the naturally occurring September precipitation. Richardson et al. (1989) found the same overshadowing effect of a wet year when attempting to detect effects of moisture deficits on cheatgrass seed production. The soil moisture sensor data in this present study (from the data loggers buried within each block) showed that relatively large rain events, which nearly saturated the soil, occurred a few days prior to two out of the three water treatment dates (Fig. 2.4). Fluctuations in soil moisture (wet-dry cycles) can trigger seed germination (Frasier et al. 1987; Allen et al. 1994; Allen et al. 1995). Allen et al. (1994) found that intermittent hydration-dehydration episodes may increase cheatgrass germination rates. Furthermore, Fisher et al. (1987) found that N loses (per unit of precipitation) are greater after large infrequent rainfall events than after several small frequent events. In this present study, dehydration events prior to the supplemental watering never occurred because there were so many natural rain events between treatment dates.

Surface Soil Manipulation Effects

My results suggest that surface soil disturbances and additions of sagebrush litter will likely increase the invasibility of high elevation, semidesert sagebrush ecosystems. I found that surface soil disturbances significantly increased cheatgrass density and biomass, as well as seed density and biomass, under sagebrush individuals and in interspaces.

My results support the general agreement in the literature that surface soil disturbances and litter cover can facilitate weed invasion in a native plant community (Crawley 1987; Hobbs 1991). Surface soil disturbances create microtopographic pits where seeds are sheltered from wind, water, and animal dispersal, and where changes in soil nutrient cycling, moisture content, and temperature regimes occur. Cheatgrass seeds germinate at higher rates when slightly covered with soil compared to seeds laying on the surface (Wicks et al. 1971; Evans and Young 1972,1984). Depressions on the soil surface catch wind and water dispersed seeds, retain soil moisture, and allow for more soil coverage of seeds (Evans and Young 1984). Litter cover can moderate soil temperatures by acting as an insulating mulch layer (it can increase soil temperatures under cool conditions and decrease soil temperatures under warm conditions, thereby narrowing the range of the soil temperature fluxes). It also can act like surface soil disturbances in catching and containing dispersed seeds and increasing soil moisture availability (Evans and Young 1970).

Several authors have observed increases in cheatgrass from surface soil disturbances. Meyer et al. (2001a) observed significant increases in cheatgrass recruitment and production, in a wet year, from cryptobiotic crust trampling in a shadscale-gray molly community in Utah. However, in a dry year, the surface soil disturbances reduced cheatgrass recruitment and production. Their results support the theory that there are multiple environmental factors occurring simultaneously that promote significant increases in cheatgrass emergence and survival. Evans and Young (1972) found greater cheatgrass seedling emergence from soil pits compared to a smooth soil surface, and from seeds buried under 1 cm of soil compared to seed broadcast on the surface. By monitoring soil temperatures and moisture conditions, they determined that the rough soil surface helps retain soil moisture and moderate soil temperatures, thereby creating a more ideal microclimate for cheatgrass germination.

Various other studies have documented a correlation between increased cheatgrass establishment and a litter layer (Evans and Young 1970; Pierson and Mack 1990; Kelrick 1991). A litter layer can reduce germination of annual grasses when the seeds get suspended in the litter which limits contact with the mineral soil (Young et al. 1971). However, the shredded sagebrush litter that was used in this present study probably allowed seeds to reach the mineral soil (since the litter consisted of larger chunks of sagebrush rather than fine fibers of grass stems), and kept them in place while moderating soil temperature and increasing soil moisture. Evans and Young (1970) found that almost three times as many cheatgrass plants emerged under a litter layer composed of medusahead (*Taeniatherum asperum* [Sim.] Nevski), cheatgrass, and tumble mustard (*Sisymbrium altissimum* L.) when compared to bare soil. My results suggest that habitat management tools that leave behind a layer of sagebrush litter, such as a brush mower, should be used with caution, and treated sites should be monitored for increases in cheatgrass emergence.

Interspace Versus Under Sagebrush Canopy

I expected to see higher cheatgrass production under the canopy of sagebrush individuals. Much of the literature suggests that shrub canopies can provide resource islands of improved germination conditions for grasses and forbs, including greater resource availability (Smith et al. 1997; Meyer et al. 2001a). A qualitative assessment of preexisting cheatgrass populations in the Gunnison Basin, both under sagebrush canopies and in interspaces, revealed that cheatgrass plants under sagebrush canopies were more numerous and larger than plants in the interspaces. The results of this study confirmed our observations of higher cheatgrass production under sagebrush canopies than in shrub interspaces.

Shrub canopies can moderate surface soil temperatures by providing thermal cover, and improve moisture retention by providing shade. Hence, drought stress and temperature extremes are minimized, making the area more suitable for seed germination compared to shrub interspaces. The moderated temperatures and increased soil moisture can increase nutrient cycling rates, in turn providing increased resources critical for plant growth (Robertson 1982; Bolton et al. 1993; Steinberger and Sarig 1993; Smith et al. 1994; Alon and Steinberger 1999). Furthermore, the increased litter deposition under a sagebrush canopy provides increased soil organic matter pools which can be directly related to nutrient cycling rates (Burke 1989). Data from the soil temperature sensors buried at the site (about 3 cm below the surface, Fig. 2.4) showed that soil temperatures were higher in the interspaces than under the shrubs, which is supported by the findings of other studies in the literature (Pierson and Wight 1991). However, interspaces actually contained more soil moisture than the under shrub locations for a few days after rainfall events (Fig. 2.4), but the trend reversed as time progressed until another rainfall event. This was probably because the shrubs intercepted rain water, allowing much of it to evaporate or be diverted from under the shrub (Rundel and Jarrell 1989). However, the under shrub location is shaded and has a large layer of litter, which helps to minimize evaporative losses.

CONCLUSIONS

The results from this study suggest that fall precipitation may have less of an effect on cheatgrass production and establishment in the Gunnison Basin than previous literature has suggested (Mack and Pyke 1983; Anderson 1989; Meyer et al. 2001a; Morris 2001). However, I may have observed no significant effects of the watering treatments because they were overshadowed by the unusually high fall precipitation during treatment applications. It also should be noted that even with the naturally occurring above average fall precipitation, overall very little cheatgrass biomass and seed were produced compared to areas in the Great Basin where cheatgrass has established itself. The significant surface soil treatment effects detected in this study suggest that the chances of cheatgrass becoming established in the Gunnison Basin may increase when there is a cheatgrass seed source present in the area and sagebrush habitat management tools are used that either disturb the surface soil or deposit a layer of litter. However, the small amount of cheatgrass biomass and seed produced in this study compared to heavily invaded areas in the Great Basin indicates that the remaining native vegetation was able to compete with the introduced cheatgrass for available resources. For example, within the first growing season after a burn in a big sagebrush (*Artemisia tridentate* Nutt.)/Thurber needlegrass (*Achnatherum thurberianum* [Piper] Barkworth) community in north Reno, Nevada, Young and Evans (1978) found at least 960 seeds per plant. In contrast, an average of only 6 seeds per plant were observed in this present study.

Further research to determine if additional fall precipitation will facilitate cheatgrass invasion in high elevation sagebrush ecosystems would contribute to the literature. Future studies could also include: 1) nutrient cycling changes as a result of increased precipitation, 2) high elevation temperature restrictions on cheatgrass production and establishment, and 3) interactions with native species (such as whether or not there are certain native species that facilitate or inhibit cheatgrass establishment).

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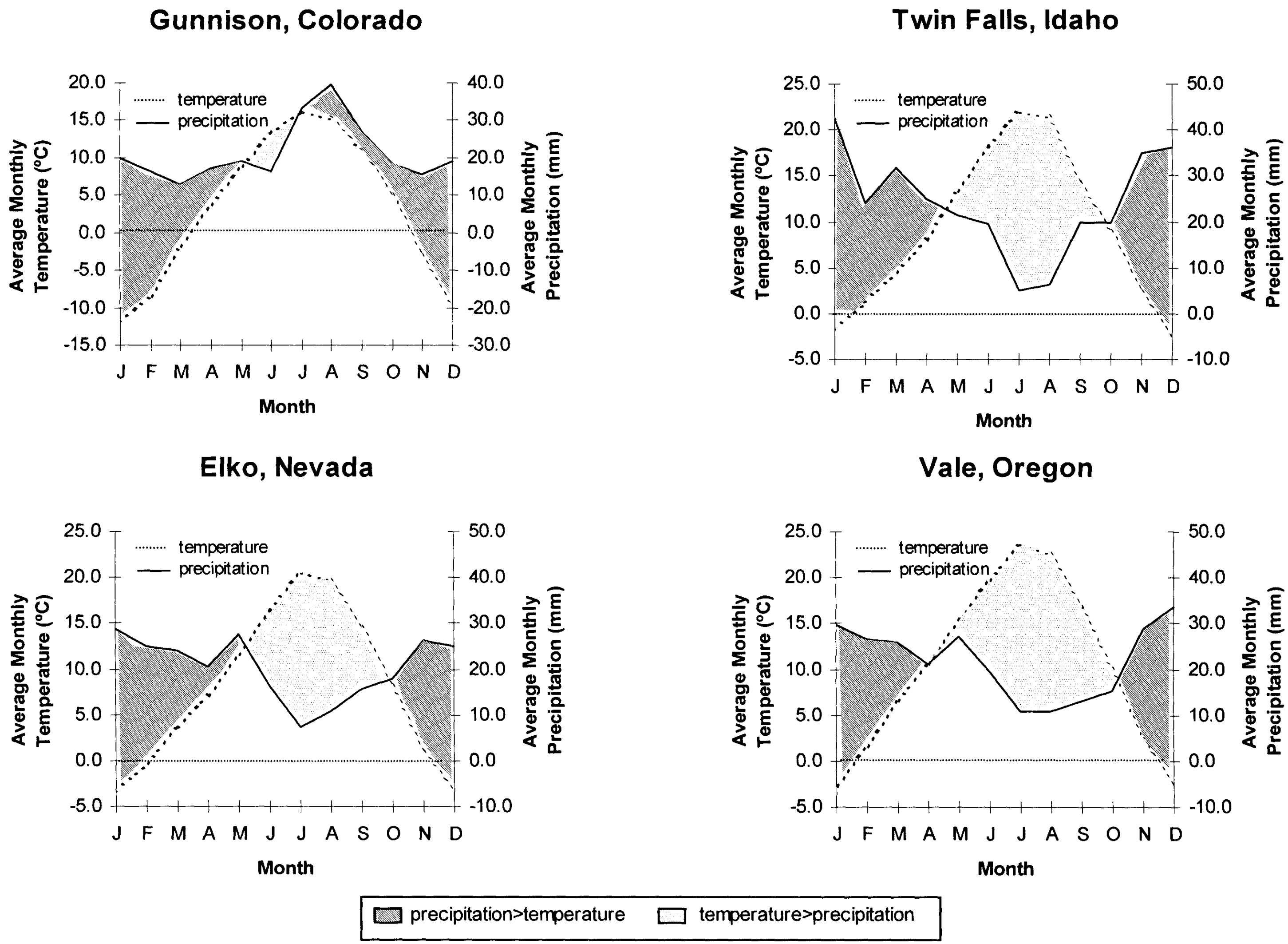

Figure 2.1. Walter diagrams of climatic conditions for Gunnison, CO and three other Wyoming sagebrush communities within the Great Basin region that are currently heavily infested with cheatgrass: Twin Falls ID, Elko NV, and Vale OR (David Pyke, personal communication, June 2004). Graphs include available data from 1971 to 2000 (WRCC 2003a,b,c,d).

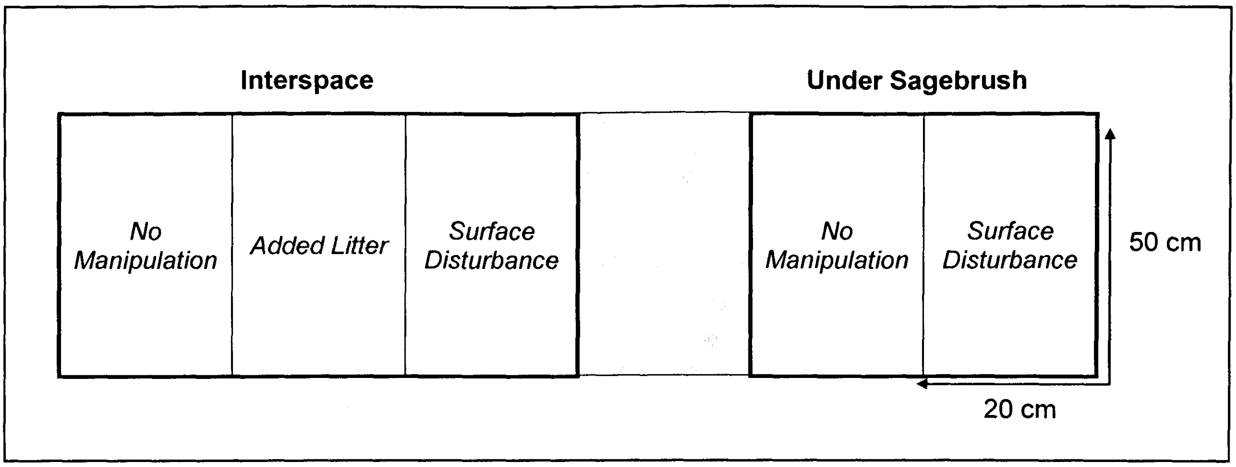

Figure 2.2. Example whole-plot.

Table 2.1. Watering treatment effects on plant density (averaged across month and location), plant biomass (averaged across location), and seed density and biomass (averaged across location).

	Cheatgrass Response Variable			
Treatment	Plant Density (no. m^{-2})	Plant Biomass (g m^{-2})	Seed Density (no. m^{-2})	Seed Biomass (g m^{-2})
30-Aug	114 a	2.24 ab	343 a	0.46 a
15-Sep	114 a	2.32 b	295 a	0.34 a
4-Oct	117 a	2.56 ab	281 a	0.35 a
1/2 30-Aug & 1/2 15-Sep	99 a	2.25 ab	297 a	0.38 a
1/2 30-Aug & 1/2 4-Oct	109 a	3.17 ab	414 a	0.54 a
1/2 15-Sep & 1/2 4-Oct	142 a	5.58 a	793 a	1.0 a
1/3 on each date	91 a	2.56 ab	262 a	0.38 a
No added water	101 a	3.14 ab	405 a	0.48 a

Note: Non-transformed means are provided. For each response variable, the means within a column followed by the same letter are not significant at the $p \leq 0.05$ level. Statistical comparisons were conducted on square root transformed data for plant density and on log transformed data and for plant biomass, but on non-transformed data for seed density and biomass.

Table. 2.2. Surface soil treatment effects on plant density (for each month), plant biomass, and seed density and biomass.

		Cheatgrass Response Variable						
		Plant Density (no. m^{-2})				Plant Biomass	Seed Density	Seed Biomass
Location	Treatment	Nov. '03	Apr. '04	May '04	Jun. '04	(g m^{-2})	(no. m^{-2})	(g m^{-2})
Interspace	Raked	160 a	158 a	148 a	148 b	3.64 b	429 b	0.54 b
	Added Litter	116 b	147 a	164 a	165 b	3.07 b	411 b	0.53 b
	No Manip	25 c	28 c	28 c	33 d	0.52 d	67 c	0.09 c
Under Sage	Raked	151 a	161 a	178 a	212 a	6.77 a	944 a	1.16 a
	No Manip	41 d	44 b	51 b	62 c	0.89 c	143 c	0.17 c

Note: Non-transformed means are provided. For each response variable, the means within a column followed by the same letter are not significant at the $p \leq 0.05$ level. Statistical comparisons were conducted on square root transformed data for plant density, and on log transformed data for plant biomass, but on non-transformed data for seed density and seed biomass.

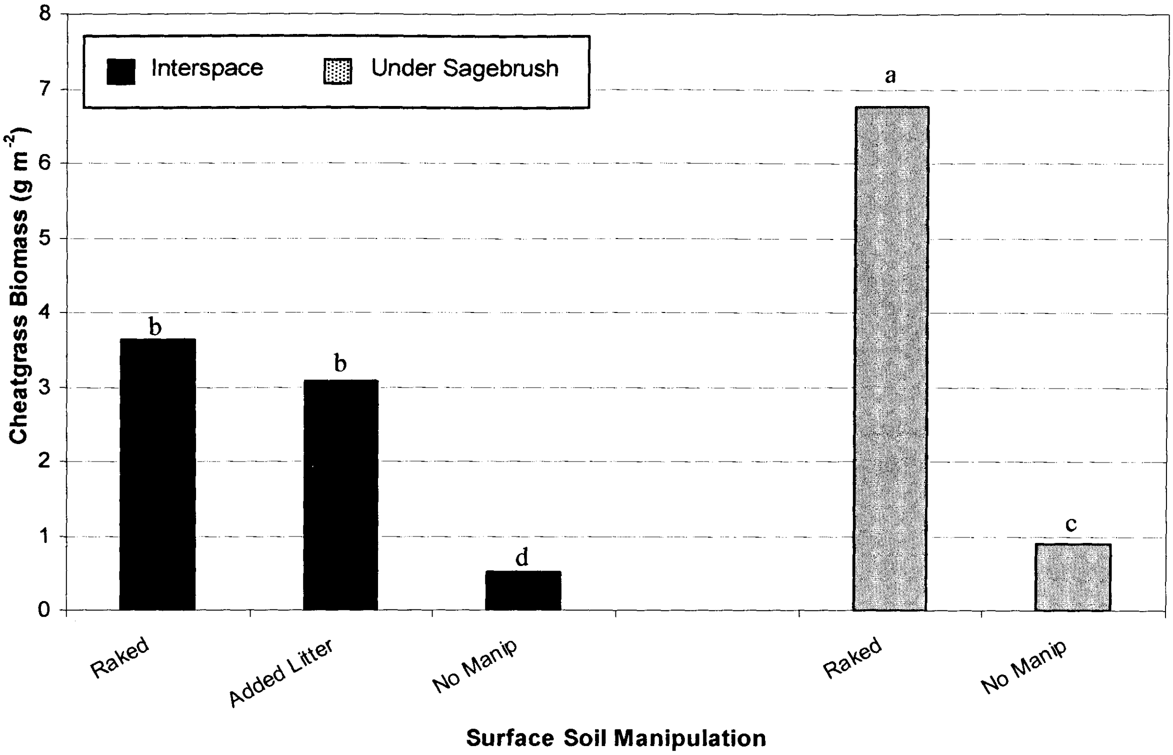

Figure 2.3. Surface soil treatment effects on average cheatgrass biomass (in the interspaces and under sagebrush plants). Letters above bars indicate significant differences ($p<0.05$) among treatments. Statistical comparisons were conducted on log transformed data, but values are graphed as non-transformed for ease of interpretation.

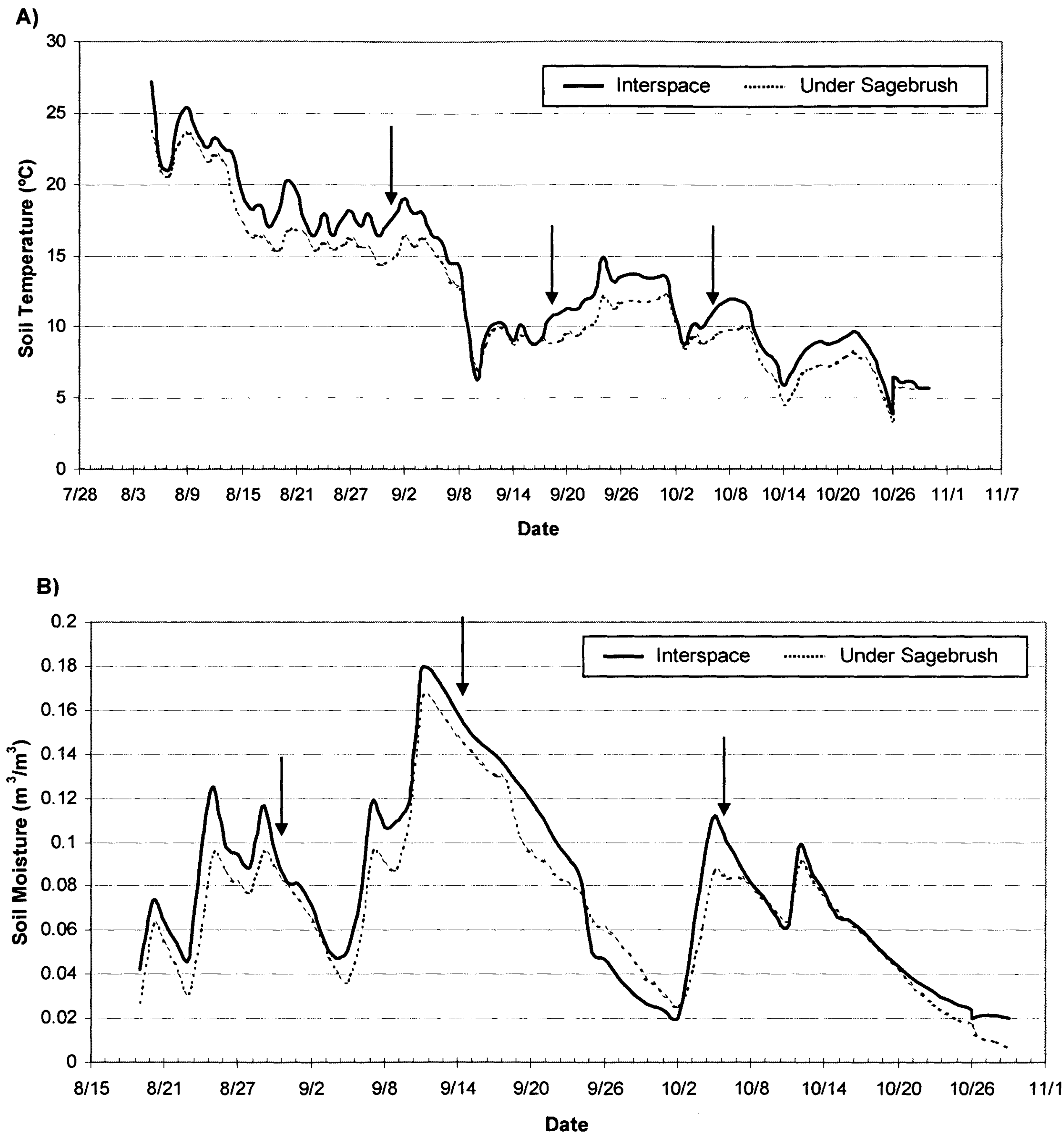

Figure 2.4. Naturally occurring **A)** soil temperature and **B)** soil moisture levels over time at the site. Arrows signify approximate watering treatment application dates (30 Aug., 15 Sept., and 4 Oct. 2003). Soil moisture and temperature sensors were buried (horizontally) at 3 cm depth.

CHAPTER IV

CONCLUSIONS

SUMMARY

Cheatgrass (*Bromus tectorum* L.) has invaded vast areas of native sagebrush (*Artemisia tridentata* Nutt.) rangeland in the Western U.S. resulting in displaced native species, deteriorated wildlife habitat, altered nutrient cycles, and reduced amounts of perennial forage for livestock (Roberts 1990). According to some local resource specialists in the Gunnison Basin of Colorado, cheatgrass has spread significantly during the past 10 to 15 years and it will only be a matter of time before it encroaches into large areas of adjacent sagebrush rangeland (A. Hayes, personal communication, 2002). However, since the populations of cheatgrass in the Basin remain relatively small with defined boundaries between them and adjacent native communities, they provide a unique opportunity for studying factors that may be correlated with cheatgrass invasion. I conducted observational and experimental studies to: 1) determine whether viable cheatgrass seeds are dispersed into the native sagebrush community adjacent to existing cheatgrass patches, 2) determine if there are significant differences in soil chemistry and texture under invaded versus uninvaded areas, and 3) evaluate the effects of added fall precipitation, surface soil disturbances, and sagebrush litter cover on the potential spread of cheatgrass in the Gunnison Basin.

Results from my observational studies indicated that there is a viable cheatgrass seed bank up to 2.0 m away from the edge of invaded patches into the uninvaded areas of the Gunnison Basin, with approximately 112 seeds/m^2 on average at this distance. Soil chemistry samples collected from within and outside of cheatgrass invaded areas revealed significantly higher NO_3-N in invaded areas once the cheatgrass senesced. There were strong trends towards lower soil OM, total organic C, total C, and total N in the invaded areas. Significantly higher P:Fe ratios in cheatgrass invaded areas were also observed. Since Fe can bind with P to create $FePO_4$ precipitates, the more available Fe in the soil, the more P will bind up in a plant unavailable form (the $FePO_4$ precipitate). Results of the observational studies suggest that there are likely a variety of interacting environmental conditions that could be preventing the germination or establishment of cheatgrass outside of the existing cheatgrass patches.

In my experimental study, there was no significant effect of adding additional water on cheatgrass density, biomass, or seed density, which might have been attributed to the above-normal precipitation (about 2.5 times > 30 year average) that naturally occurred in September 2003 (the water treatment application period). Plots under the sagebrush plants had significantly higher cheatgrass density, biomass, and seed density than interspace plots. In both plot locations, surface soil disturbance also increased these cheatgrass production variables compared to the controls. Similarly, adding sagebrush litter in interspaces significantly increased cheatgrass production compared to the controls. Despite the significant soil treatment effects and the natural, above-normal precipitation that occurred during this study, there was only a small amount of cheatgrass biomass and seed produced.

The results of my observational and experimental studies together suggest that, at this point in time, competition from the native plant community coupled with a set of other environmental variables (such as surface soil moisture and soil chemistry) are keeping cheatgrass from detrimentally spreading in the Gunnison Basin. However, cheatgrass in the Gunnison Basin may be an ideal example of an exotic species in a lag phase of adaptation (Mack et al. 2000; Young and Clements 2005). The lag phase refers to the period of time between the introduction of an immigrant species to a new area and the expansion of its population to "invader" status. The lag phase is partly related to the time it takes for an immigrant species to undergo natural selection for environmental conditions of the new area (Mack et al. 2000; Young and Clements 2005). Since it may just be a matter of time for cheatgrass to adapt to the environmental conditions in the Gunnison area, efforts to control cheatgrass invasion in the Gunnison Basin should include monitoring the expansion of existing populations. Furthermore, land managers should use caution when implementing habitat management tools that leave behind a layer of sagebrush litter, such as a brush mower, or disturb the surface soil, such as a Dixie harrow. Treated sites should also be monitored for increases in cheatgrass. Further research into the effects an increase in fall precipitation may have on cheatgrass establishment and the soil characteristics that promote cheatgrass invasion are needed.

STUDY LIMITATIONS AND SUGGESTIONS FOR FUTURE RESEARCH

The observational studies presented in this thesis did not address whether the differences in soil conditions in cheatgrass invaded versus uninvaded areas were present prior to or after the invasion by cheatgrass. The question remains whether these soil differences facilitated the cheatgrass invasion, or rather the observed differences in soil conditions were a result of the cheatgrass invasion. Furthermore, the amount of time since the initial invasion of the sites used in this study was undetermined. Plant species can have an effect on nutrient cycling, and several studies have found eveidence in which invasive plant species have altered nutrient cycling enough that they could promote their own existence and/or change the structure of the native community (Hobbie 1992). There is also considerable evidence suggesting that cheatgrass tends to invade in areas with certain soil characteristics, and using management tools to alter those characteristics may prevent or reduce the magnitude of a cheatgrass invasion (McLendon and Redente 1992; Paschke et al. 2000; Belnap et al. 2003). Regardless of whether the cheatgrass causes the observed changes in soil conditions or whether it tends to invade in areas with such soil conditions, knowing which soil characteristics differ between already existing cheatgrass patches and their adjacent uninvaded areas could help land managers prevent further invasions (such as by applying soil amendments). In any case, more research on the causes of cheatgrass invasion and the time course of soil changes associated with cheatgrass invasion are warranted.

In this present study, seeds were planted in early September, the day of the first watering treatment. However, at the time of the first observation in November, cheatgrass seedlings in the nearby naturally occurring population (about 30 m north-west of the experimental plots, alongside the road) were larger than the seedlings in the experimental plots. This indicated that seeds in the nearby population might have germinated a few weeks earlier than the seeds in the experimental plots. However, this slight variability in seedling emergence may have been insignificant since precipitation patterns are so variable from year-to-year. Anderson (1996) found drastic differences in fall cheatgrass seedling emergence from year-to-year in a winter wheat crop in Akron, CO, where one year emergence occurred from August through October and the next year from October through December. He attributed emergence variability to erratic seasonal precipitation. The seedlings alongside the road may have also been larger than the seedlings in my experimental plots because germination and growing conditions are better along the road than further out into the native sagebrush rangeland (Greenberg et al. 1997; Geer 2002; Gelbard and Belnap 2003). Frequent soil disturbances along roadsides may alter nutrient cycling, and higher soil moisture content from increased water run-off can improve germination and establishment conditions for plants (Greenberg et al. 1997; Geer 2002; Gelbard and Belnap 2003). Consideration of the most appropriate time to seed would be a crucial step to repeating this experiment.

Based on my observations, the microtopography at the field sites in this study might have caused some minor amounts of water and seed to be transported from one subplot to another. There was little to no chance of water or seed transport between whole-plots (the watering treatments) since they were separated in space. Future studies of this type should consider using a boundary between each subplot during watering treatment applications to avoid water runoff from one subplot to another, possibly carrying cheatgrass seeds with it.

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APPENDICES

APPENDIX A

SEED BANK STUDY RAW DATA AND SOIL CHEMISTRY STATISTICAL SUMMARY AND RAW DATA

Key to Symbols in Appendix A Tables

Site = location of soil collections

- **OhioWillowCrk** = Willow Creek NW of Ohio City
- **RedCrk** = Red Creek Road
- **SapMesa** = Sapinero Mesa
- **Taylor** = Taylor Park Road
- **WillowCrk** = Willow Creek S of Blue Mesa Reservoir

Pop = population

- **Invaded** = invaded by cheatgrass
- **Uninvaded** = uninvaded by cheatgrass

Month = data collection date

- **1** = November 2003
- **2** = April 2004
- **3** = May 2004
- **4** = June 2004

Table A-1. Seed bank study raw data. Number of cheatgrass seedlings emerged in soil seed bank samples from each site.

DATE COUNTED		Willow Crk (Blue Mesa)	Soap Crk	Red Crk	SM (Middle)	SM (Left)	SM (Top)	SM (Right)	SM (Bottom)	Taylor Park	Willow Crk (Ohio City)	Woods Gulch
11/19/2002	inside	212	120	620	317	35	18	106	51	105	44	37
	edge	44	28	218	-	35	25	30	52	18	71	16
	0.5m	10	1	49	-	19	13	25	16	3	11	0
	1m	5	0	50	-	19	11	11	16	2	8	11
	2m	8	2	6	-	0	27	11	9	0	4	0
12/10/2002	inside	3	1	6	3	0	0	3	0	5	0	0
	edge	0	0	2	-	0	1	3	2	0	0	3
	0.5m	0	0	0	-	1	0	0	0	0	0	0
	1m	0	0	0	-	0	0	0	2	0	1	0
	2m	0	0	0	-	0	0	0	0	0	0	2
Total	inside	215	121	626	320	35	18	109	51	110	44	37
	edge	44	28	220	-	35	26	33	54	18	71	19
	0.5m	10	1	49	-	20	13	25	16	3	11	0
	1m	5	0	50	-	19	11	11	18	2	9	11
	2m	8	2	6	-	0	27	11	9	0	4	2
Total ($\#/m^2$)	Inside	4988	2807	14522	7423	812	418	2529	1183	2552	1021	858
	Edge	1021	650	5104	-	812	603	766	1253	418	1647	441
	0.5m	232	23	1137	-	464	302	580	371	70	255	0
	1m	116	0	1160	-	441	255	255	418	46	209	255
	2m	186	46	139	-	0	626	255	209	0	93	46

Notes:
Crk = Creek; SM = Sapinero Mesa

Table A-2. ANOVA for pH in invaded vs. uninvaded areas.

2002 Data

The Mixed Procedure

Class Level Information

Class	Levels	Values
Site	6	OhioWillowCrk RedCrk SapMesa SoapCrk Taylor WillowCrk
Pop	2	Invaded Uninvaded

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	5	2.24	0.1946

2003 Data

The Mixed Procedure

Class Level Information

Class	Levels	Values
Site	3	RedCrk SapMesa SoapCreek
Pop	2	Invaded Uninvaded
Month	4	1 2 3 4

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	1.97	3.19	0.2182
Month	3	10.3	0.46	0.7171
Pop*Month	3	10.3	0.44	0.7304

Table A-3. ANOVA for EC in invaded vs. uninvaded areas.

2002 Data

The Mixed Procedure

Class Level Information

Class	Levels	Values
Site	6	OhioWillowCrk RedCrk SapMesa SoapCrk Taylor WillowCrk
Pop	2	Invaded Uninvaded

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	5	1.18	0.3276

2003 Data

The Mixed Procedure

Class Level Information

Class	Levels	Values
Site	3	RedCrk SapMesa SoapCreek
Pop	2	Invaded Uninvaded
Month	4	1 2 3 4

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	6.59	10.16	0.0166
Month	3	11.5	1.59	0.2458
Pop*Month	3	11.5	0.90	0.4693

Table A-4. ANOVA for %OM in invaded vs. uninvaded areas.

2002 Data

The Mixed Procedure

Class Level Information

Class	Levels	Values
Site	6	OhioWillowCrk RedCrk SapMesa SoapCrk Taylor WillowCrk
Pop	2	Invaded Uninvaded

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	5	8.74	0.0317

2003 Data

The Mixed Procedure

Class Level Information

Class	Levels	Values
Site	3	RedCrk SapMesa SoapCreek
Pop	2	Invaded Uninvaded
Month	4	1 2 3 4

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	3.63	6.73	0.0666
Month	3	11.3	1.44	0.2837
Pop*Month	3	11.3	1.91	0.1852

Table A-5. ANOVA for NH_4-N in invaded vs. uninvaded areas.

2002 Data

The Mixed Procedure

Class Level Information

Class	Levels	Values
Site	6	OhioWillowCrk RedCrk SapMesa SoapCrk Taylor WillowCrk
Pop	2	Invaded Uninvaded

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	5	0.41	0.5484

2003 Data

The Mixed Procedure

Class Level Information

Class	Levels	Values
Site	3	RedCrk SapMesa SoapCreek
Pop	2	Invaded Uninvaded
Month	4	1 2 3 4

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	5	1.65	0.2558
Month	3	11.4	8.45	0.0031
Pop*Month	3	11.4	0.28	0.8378

Table A-6. ANOVA for NO_3-N in invaded vs. uninvaded areas.

2002 Data

The Mixed Procedure (on log transformed data)

Class Level Information

Class	Levels	Values
Site	6	OhioWillowCrk RedCrk SapMesa SoapCrk Taylor WillowCrk
Pop	2	Invaded Uninvaded

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	5	10.66	0.0223

2003 Data

The Mixed Procedure (on log transformed data)

Class Level Information

Class	Levels	Values
Site	3	RedCrk SapMesa SoapCreek
Pop	2	Invaded Uninvaded
Month	4	1 2 3 4

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	3.89	5.79	0.0756
Month	3	10.8	7.78	0.0048
Pop*Month	3	10.8	25.49	<.0001

Differences of Least Squares Means

Effect	Pop	Month	Pop	Month	Estimate	Standard Error	DF	t Value	Pr>|t|
Pop*Month	In	1	Out	1	-0.2612	0.1183	8.06	-2.21	0.0581
Pop*Month	In	2	Out	2	0.5588	0.1183	8.06	4.72	0.0015
Pop*Month	In	3	Out	3	0.2501	0.1183	8.06	2.11	0.0672
Pop*Month	In	4	Out	4	0.3637	0.1183	8.06	3.07	0.0151

Table A-7. ANOVA for P in invaded vs. uninvaded areas.

2002 Data

The Mixed Procedure

Class Level Information

Class	Levels	Values
Site	6	OhioWillowCrk RedCrk SapMesa SoapCrk Taylor WillowCrk
Pop	2	Invaded Uninvaded

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	5	0.29	0.6146

2003 Data

The Mixed Procedure

Class Level Information

Class	Levels	Values
Site	3	RedCrk SapMesa SoapCreek
Pop	2	Invaded Uninvaded
Month	4	1 2 3 4

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	2.95	3.85	0.1462
Month	3	11.2	1.85	0.1956
Pop*Month	3	11.2	1.33	0.3132

Table A-8. ANOVA for K in invaded vs. uninvaded areas.

<u>2002 Data</u>

The Mixed Procedure

Class Level Information

Class	Levels	Values
Site	6	OhioWillowCrk RedCrk SapMesa SoapCrk Taylor WillowCrk
Pop	2	Invaded Uninvaded

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	5	0.00	0.9812

<u>2003 Data</u>

The Mixed Procedure

Class Level Information

Class	Levels	Values
Site	3	RedCrk SapMesa SoapCreek
Pop	2	Invaded Uninvaded
Month	4	1 2 3 4

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	2.28	0.22	0.6830
Month	3	11.1	1.84	0.1975
Pop*Month	3	11.1	0.29	0.8310

Table A-9. ANOVA for Zn in invaded vs. uninvaded areas.

2002 Data

The Mixed Procedure

Class Level Information

Class	Levels	Values
Site	6	OhioWillowCrk RedCrk SapMesa SoapCrk Taylor WillowCrk
Pop	2	Invaded Uninvaded

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	5	3.08	0.1394

2003 Data

The Mixed Procedure (on log transformed data)

Class Level Information

Class	Levels	Values
Site	3	RedCrk SapMesa SoapCreek
Pop	2	Invaded Uninvaded
Month	4	1 2 3 4

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	4.11	0.24	0.6489
Month	3	11.4	0.88	0.4795
Pop*Month	3	11.4	0.44	0.7315

Table A-10. ANOVA for Fe in invaded vs. uninvaded areas.

2002 Data

The Mixed Procedure (on log transformed data)

Class Level Information

Class	Levels	Values
Site	6	OhioWillowCrk RedCrk SapMesa SoapCrk Taylor WillowCrk
Pop	2	Invaded Uninvaded

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	5	4.69	0.0827

2003 Data

The Mixed Procedure (on log transformed data)

Class Level Information

Class	Levels	Values
Site	3	RedCrk SapMesa SoapCreek
Pop	2	Invaded Uninvaded
Month	4	1 2 3 4

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	2.73	1.81	0.2793
Month	3	10.8	2.29	0.1366
Pop*Month	3	10.8	0.14	0.9358

Table A-11. ANOVA for Mn in invaded vs. uninvaded areas.

2002 Data

The Mixed Procedure

Class Level Information

Class	Levels	Values
Site	6	OhioWillowCrk RedCrk SapMesa SoapCrk Taylor WillowCrk
Pop	2	Invaded Uninvaded

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	5	0.06	0.8143

2003 Data

The Mixed Procedure

Class Level Information

Class	Levels	Values
Site	3	RedCrk SapMesa SoapCreek
Pop	2	Invaded Uninvaded
Month	4	1 2 3 4

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	3.16	5.19	0.1026
Month	3	10.1	6.51	0.0101
Pop*Month	3	10.1	1.20	0.3597

Table A-12. ANOVA for Cu in invaded vs. uninvaded areas.

2002 Data

The Mixed Procedure

Class Level Information

Class	Levels	Values
Site	6	OhioWillowCrk RedCrk SapMesa SoapCrk Taylor WillowCrk
Pop	2	Invaded Uninvaded

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	5	0.44	0.5359

2003 Data

The Mixed Procedure

Class Level Information

Class	Levels	Values
Site	3	RedCrk SapMesa SoapCreek
Pop	2	Invaded Uninvaded
Month	4	1 2 3 4

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	1.84	0.88	0.4542
Month	3	6.16	3.61	0.0825
Pop*Month	3	6.16	0.28	0.8392

Table A-13. ANOVA for CEC in invaded vs. uninvaded areas.

2002 Data

The Mixed Procedure

Class Level Information

Class	Levels	Values
Site	6	OhioWillowCrk RedCrk SapMesa SoapCrk Taylor WillowCrk
Pop	2	Invaded Uninvaded

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	5	0.01	0.9284

2003 Data

The Mixed Procedure

Class Level Information

Class	Levels	Values
Site	3	RedCrk SapMesa SoapCreek
Pop	2	Invaded Uninvaded
Month	4	1 2 3 4

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	1.66	2.78	0.2620
Month	3	7.13	3.32	0.0854
Pop*Month	3	7.13	0.69	0.5869

Table A-14. ANOVA for Total N in invaded vs. uninvaded areas.

2002 Data

The Mixed Procedure (on log transformed data)

Class Level Information

Class	Levels	Values
Site	6	OhioWillowCrk RedCrk SapMesa SoapCrk Taylor WillowCrk
Pop	2	Invaded Uninvaded

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	5	4.20	0.0956

2003 Data

The Mixed Procedure (on log transformed data)

Class Level Information

Class	Levels	Values
Site	3	RedCrk SapMesa SoapCreek
Pop	2	Invaded Uninvaded
Month	4	1 2 3 4

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	6.32	3.80	0.0968
Month	3	12.3	0.66	0.5919
Pop*Month	3	12.3	0.53	0.6705

Table A-15. ANOVA for Total C in invaded vs. uninvaded areas.

2002 Data

The Mixed Procedure

Class Level Information

Class	Levels	Values
Site	6	OhioWillowCrk RedCrk SapMesa SoapCrk Taylor WillowCrk
Pop	2	Invaded Uninvaded

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	5	2.72	0.1598

2003 Data

The Mixed Procedure (on log transformed data)

Class Level Information

Class	Levels	Values
Site	3	RedCrk SapMesa SoapCreek
Pop	2	Invaded Uninvaded
Month	4	1 2 3 4

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	3.29	6.53	0.0762
Month	3	11.2	1.40	0.2947
Pop*Month	3	11.2	0.47	0.7082

Table A-16. ANOVA for TOC in invaded vs. uninvaded areas.

2002 Data

The Mixed Procedure (on log transformed data)

Class Level Information

Class	Levels	Values
Site	6	OhioWillowCrk RedCrk SapMesa SoapCrk Taylor WillowCrk
Pop	2	Invaded Uninvaded

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	5	5.51	0.0658

2003 Data

The Mixed Procedure (on log transformed data)

Class Level Information

Class	Levels	Values
Site	3	RedCrk SapMesa SoapCreek
Pop	2	Invaded Uninvaded
Month	4	1 2 3 4

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	2.87	6.11	0.0938
Month	3	11.6	1.76	0.2102
Pop*Month	3	11.6	0.40	0.7571

Table A-17. ANOVA for C:N in invaded vs. uninvaded areas.

<u>2002 Data</u>

The Mixed Procedure

Class Level Information

Class	Levels	Values
Site	6	OhioWillowCrk RedCrk SapMesa SoapCrk Taylor WillowCrk
Pop	2	Invaded Uninvaded

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	5	3.93	0.1042

<u>2003 Data</u>

The Mixed Procedure (on log transformed data)

Class Level Information

Class	Levels	Values
Site	3	RedCrk SapMesa SoapCreek
Pop	2	Invaded Uninvaded
Month	4	1 2 3 4

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	8.11	0.01	0.9417
Month	3	11.6	1.24	0.3396
Pop*Month	3	11.6	0.61	0.6204

Table A-18. ANOVA for Sand (%) in invaded vs. uninvaded areas.

2002 Data

The Mixed Procedure

Class Level Information

Class	Levels	Values
Site	6	OhioWillowCrk RedCrk SapMesa SoapCrk Taylor WillowCrk
Pop	2	Invaded Uninvaded

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	5	0.01	0.9390

Table A-19. ANOVA for Silt (%) in invaded vs. uninvaded areas.

2002 Data

The Mixed Procedure

Class Level Information

Class	Levels	Values
Site	6	OhioWillowCrk RedCrk SapMesa SoapCrk Taylor WillowCrk
Pop	2	Invaded Uninvaded

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	5	2.36	0.1852

Table A-20. ANOVA for Clay (%) in invaded vs. uninvaded areas.

2002 Data

The Mixed Procedure

Class Level Information

Class	Levels	Values
Site	6	OhioWillowCrk RedCrk SapMesa SoapCrk Taylor WillowCrk
Pop	2	Invaded Uninvaded

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	5	1.55	0.2682

Table A-21. ANOVA for Ca (exchangeable) in invaded vs. uninvaded areas.

2002 Data

The Mixed Procedure

Class Level Information

Class	Levels	Values
Site	6	OhioWillowCrk RedCrk SapMesa SoapCrk Taylor WillowCrk
Pop	2	Invaded Uninvaded

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	5	0.00	1.0000

Table A-22. ANOVA for Mg (exchangeable) in invaded vs. uninvaded areas.

2002 Data

The Mixed Procedure

Class Level Information

Class	Levels	Values
Site	6	OhioWillowCrk RedCrk SapMesa SoapCrk Taylor WillowCrk
Pop	2	Invaded Uninvaded

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	5	0.64	0.4601

Table A-23. ANOVA for Na (exchangeable) in invaded vs. uninvaded areas.

2002 Data

The Mixed Procedure

Class Level Information

Class	Levels	Values
Site	6	OhioWillowCrk RedCrk SapMesa SoapCrk Taylor WillowCrk
Pop	2	Invaded Uninvaded

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	5	1.00	0.3632

Table A-24. ANOVA for K (exchangeable) in invaded vs. uninvaded areas.

2002 Data

The Mixed Procedure

Class Level Information

Class	Levels	Values
Site	6	OhioWillowCrk RedCrk SapMesa SoapCrk Taylor WillowCrk
Pop	2	Invaded Uninvaded

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Pop	1	5	0.00	1.0000

Table A-25. Soils raw data from 2002.

						Total % ($cmol_c$/kg)			NaHCO3	
Site	Population	pH	EC (ds/m)	%OM	C:N	N	C	TOC	P (mg/kg)	CEC
Ohio Willow Creek	Invaded	5.8	0.4	2.9	8.43	0.135	1.35	1.14	20.9	10.4
Red Creek	Invaded	7.4	0.6	2.9	8.98	0.165	1.63	1.48	34.4	18.0
Sapinero Mesa	Invaded	6.2	0.7	2.5	4.99	0.189	1.75	0.94	21.6	18.1
Soap Creek	Invaded	7.5	0.5	2.6	6.65	0.153	1.71	1.02	20.2	14.2
Taylor Park	Invaded	6.2	0.3	0.8	1.86	0.072	0.49	0.13	5.1	3.7
Willow Creek	Invaded	7.5	0.5	2.1	10.10	0.148	2.31	1.49	13.5	23.4
Woods Gulch	Invaded	5.8	0.6	7.9	11.10	0.393	4.56	4.36	40.0	25.9
Ohio Willow Creek	Uninvaded	5.7	0.4	4.2	8.72	0.185	1.92	1.61	21.4	12.0
Red Creek	Uninvaded	6.6	0.4	3.4	8.27	0.188	1.79	1.56	26.5	18.5
Sapinero Mesa	Uninvaded	6.3	0.4	2.7	7.36	0.148	1.31	1.09	13.9	14.0
Soap Creek	Uninvaded	7.0	0.5	4.8	8.14	0.220	2.10	1.79	25.2	18.5
Taylor Park	Uninvaded	6.2	0.3	1.8	4.25	0.118	0.90	0.50	4.8	4.7
Willow Creek	Uninvaded	7.5	0.6	5.5	10.40	0.186	2.67	1.93	28.2	20.8
Woods Gulch	Uninvaded	6.2	0.4	5.9	9.89	0.331	3.81	3.27	33.4	17.1

Table A-25. (Continued). Soils raw data from 2002.

		AB-DTPA Extract (mg/kg)							
Site	Population	NH4-N	NO3-N	P	K	Zn	Fe	Mn	Cu
Ohio Willow Creek	Invaded	4.8	5.5	15.0	219.0	3.51	71.1	5.7	1.51
Red Creek	Invaded	9.7	10.2	18.6	654.0	1.29	12.4	11.0	0.77
Sapinero Mesa	Invaded	5.3	7.6	18.0	813.0	1.27	16.7	9.9	1.20
Soap Creek	Invaded	4.0	6.4	14.0	353.0	1.01	20.4	5.4	1.31
Taylor Park	Invaded	4.2	0.6	3.6	65.6	0.76	18.1	1.8	0.78
Willow Creek	Invaded	5.3	2.8	9.2	461.0	0.66	7.7	6.3	1.51
Woods Gulch	Invaded	23.0	11.2	18.2	498.0	16.40	113.0	13.9	0.86
Ohio Willow Creek	Uninvaded	5.3	5.1	15.0	384.0	4.35	75.7	6.8	1.48
Red Creek	Uninvaded	6.3	2.2	14.0	675.0	1.64	17.4	6.0	0.91
Sapinero Mesa	Uninvaded	5.6	1.4	7.8	376.0	0.65	13.8	9.8	1.04
Soap Creek	Uninvaded	5.1	2.3	10.6	528.0	2.59	42.1	3.4	1.07
Taylor Park	Uninvaded	3.8	0.5	3.0	62.4	1.13	25.1	1.5	0.86
Willow Creek	Uninvaded	4.7	1.2	19.2	554.0	1.23	19.6	10.7	2.35
Woods Gulch	Uninvaded	5.6	4.0	17.0	492.0	5.48	58.8	5.9	1.50

Table A-25. (Continued). Soils raw data from 2002.

		(%)			Water Extract ($cmol_c$/kg)			
Site	Population	Sand	Silt	Clay	Ca	Mg	Na	K
Ohio Willow Creek	Invaded	72	21	7	0.29	0.31	0.03	0.19
Red Creek	Invaded	60	24	16	0.67	0.57	0.03	0.35
Sapinero Mesa	Invaded	66	20	14	0.54	1.31	0.12	0.67
Soap Creek	Invaded	51	28	21	0.77	0.22	0.04	0.10
Taylor Park	Invaded	82	13	5	0.18	0.21	0.03	0.10
Willow Creek	Invaded	51	23	26	1.28	0.27	0.03	0.16
Woods Gulch	Invaded	50	40	10	0.45	0.24	0.02	0.24
Ohio Willow Creek	Uninvaded	74	19	7	0.26	0.30	0.02	0.28
Red Creek	Uninvaded	54	28	18	0.50	0.81	0.03	0.37
Sapinero Mesa	Uninvaded	68	20	12	0.44	0.63	0.03	0.28
Soap Creek	Uninvaded	45	37	18	0.47	0.52	0.05	0.26
Taylor Park	Uninvaded	82	13	5	0.25	0.26	0.03	0.08
Willow Creek	Uninvaded	58	27	15	1.22	0.23	0.03	0.25
Woods Gulch	Uninvaded	48	40	12	0.51	0.42	0.02	0.30

Table A-25. (Continued). Soils raw data from 2002.

		1N NH4OAc ($cmol_c$/kg)				Exchangeable Bases ($cmol_c$/kg)			
Site	Population	Ca	Mg	Na	K	Ca	Mg	Na	K
Ohio Willow Creek	Invaded	3.69	0.96	0.09	0.30	3.4	0.7	0.1	0.1
Red Creek	Invaded	5.27	2.76	0.13	1.04	4.6	2.2	0.1	0.7
Sapinero Mesa	Invaded	4.80	2.09	0.24	1.15	4.3	0.8	0.1	0.5
Soap Creek	Invaded	5.40	2.04	0.16	0.66	4.6	1.8	0.1	0.6
Taylor Park	Invaded	2.11	0.49	0.12	0.09	1.9	0.3	0.1	0.0
Willow Creek	Invaded	6.31	4.16	0.19	0.75	5.0	3.9	0.2	0.6
Woods Gulch	Invaded	5.67	1.95	0.18	0.74	5.2	1.7	0.2	0.5
Ohio Willow Creek	Uninvaded	3.53	1.12	0.12	0.44	3.3	0.8	0.1	0.2
Red Creek	Uninvaded	5.28	2.65	0.14	1.09	4.8	1.8	0.1	0.7
Sapinero Mesa	Uninvaded	4.52	1.77	0.12	0.54	4.1	1.1	0.1	0.3
Soap Creek	Uninvaded	4.90	2.35	0.19	1.00	4.4	1.8	0.1	0.7
Taylor Park	Uninvaded	2.82	0.87	0.12	0.09	2.6	0.6	0.1	0.0
Willow Creek	Uninvaded	5.77	2.06	0.10	0.84	4.6	1.8	0.1	0.6
Woods Gulch	Uninvaded	5.39	2.02	0.16	0.75	4.9	1.6	0.1	0.5

Table A-26. Soils raw data from 2003.

Date Collected	Site	Population	pH	EC (ds/m)	%OM	C:N
5/23/2003	Red Creek	Invaded	7.3	0.5	2.4	13.04
7/7/2003	Red Creek	Invaded	7.0	0.7	2.9	12.06
7/31/2003	Red Creek	Invaded	7.1	0.6	3.0	11.72
8/31/2003	Red Creek	Invaded	7.1	0.8	3.1	15.57
5/23/2003	Red Creek	Uninvaded	6.6	0.4	3.4	13.52
7/7/2003	Red Creek	Uninvaded	6.6	0.5	2.8	12.25
7/31/2003	Red Creek	Uninvaded	6.6	0.5	4.1	13.02
8/31/2003	Red Creek	Uninvaded	6.8	0.5	4.7	12.74
5/23/2003	Sapinero Mesa	Invaded	6.4	0.5	0.5	12.12
7/7/2003	Sapinero Mesa	Invaded	6.7	0.7	2.9	12.66
7/31/2003	Sapinero Mesa	Invaded	6.6	0.5	3.1	14.44
8/31/2003	Sapinero Mesa	Invaded	6.6	0.7	2.3	10.11
5/23/2003	Sapinero Mesa	Uninvaded	6.6	0.4	3.0	11.91
7/7/2003	Sapinero Mesa	Uninvaded	6.6	0.4	2.3	18.55
7/31/2003	Sapinero Mesa	Uninvaded	6.7	0.4	2.4	13.74
8/31/2003	Sapinero Mesa	Uninvaded	6.7	0.6	3.0	11.14
5/23/2003	Soap Creek	Invaded	7.4	0.6	2.0	15.20
7/7/2003	Soap Creek	Invaded	7.4	0.5	2.8	13.65
7/31/2003	Soap Creek	Invaded	7.5	0.5	2.4	15.13
8/31/2003	Soap Creek	Invaded	7.6	0.6	2.2	11.65
5/23/2003	Soap Creek	Uninvaded	6.8	0.5	4.2	12.68
7/7/2003	Soap Creek	Uninvaded	6.6	0.6	5.1	13.81
7/31/2003	Soap Creek	Uninvaded	7.1	0.7	4.5	13.31
8/31/2003	Soap Creek	Uninvaded	6.4	0.4	4.1	11.31
5/23/2003	Woods Gulch	Invaded	5.8	0.3	6.5	14.68
7/8/2003	Woods Gulch	Invaded	5.9	0.4	*10.3	12.22
8/1/2003	Woods Gulch	Invaded	5.9	0.3	* 12.5	12.48
8/31/2003	Woods Gulch	Invaded	5.9	0.4	*11.3	11.92
5/23/2003	Woods Gulch	Uninvaded	6.4	0.3	7.8	12.91
7/8/2003	Woods Gulch	Uninvaded	6.2	0.5	6.4	13.43
8/1/2003	Woods Gulch	Uninvaded	6.3	0.4	6.0	12.25
8/31/2003	Woods Gulch	Uninvaded	6.2	0.6	7.2	12.77

* Expressed as weight loss on ignition

Table A-26. (Continued). Soils raw data from 2003.

Date Collected	Site	Population	Total % (cmol$_c$/kg)			NaHCO3	
			N	C	TOC	P (mg/kg)	CEC
5/23/2003	Red Creek	Invaded	0.099	1.341	1.291	23.1	13.6
7/7/2003	Red Creek	Invaded	0.127	1.631	1.531	27.0	20.3
7/31/2003	Red Creek	Invaded	0.147	1.763	1.722	25.5	22.9
8/31/2003	Red Creek	Invaded	0.080	1.272	1.246	30.4	22.6
5/23/2003	Red Creek	Uninvaded	0.127	1.794	1.717	27.2	17.8
7/7/2003	Red Creek	Uninvaded	0.233	2.944	2.854	33.5	22.1
7/31/2003	Red Creek	Uninvaded	0.174	2.32	2.265	26.7	24.2
8/31/2003	Red Creek	Uninvaded	0.188	2.443	2.395	30.4	22.2
5/23/2003	Sapinero Mesa	Invaded	0.100	1.261	1.212	24.8	12.6
7/7/2003	Sapinero Mesa	Invaded	0.120	1.585	1.519	26.8	13.6
7/31/2003	Sapinero Mesa	Invaded	0.081	1.212	1.170	24.5	14.3
8/31/2003	Sapinero Mesa	Invaded	0.122	1.265	1.234	24.8	15.1
5/23/2003	Sapinero Mesa	Uninvaded	0.103	1.332	1.226	12.6	13.8
7/7/2003	Sapinero Mesa	Uninvaded	0.059	1.122	1.094	11.7	13.3
7/31/2003	Sapinero Mesa	Uninvaded	0.091	1.296	1.250	13.2	15.0
8/31/2003	Sapinero Mesa	Uninvaded	0.143	1.609	1.593	17.5	16.4
5/23/2003	Soap Creek	Invaded	0.074	1.601	1.125	18.6	19.1
7/7/2003	Soap Creek	Invaded	0.107	1.815	1.461	26.0	22.1
7/31/2003	Soap Creek	Invaded	0.062	1.521	0.938	20.5	22.9
8/31/2003	Soap Creek	Invaded	0.104	1.594	1.211	19.4	17.4
5/23/2003	Soap Creek	Uninvaded	0.162	2.115	2.054	25.6	24.1
7/7/2003	Soap Creek	Uninvaded	0.168	2.372	2.320	25.6	21.2
7/31/2003	Soap Creek	Uninvaded	0.179	2.505	2.383	25.0	25.8
8/31/2003	Soap Creek	Uninvaded	0.186	2.159	2.104	26.5	22.6
5/23/2003	Woods Gulch	Invaded	0.257	3.814	3.772	31.5	18.6
7/8/2003	Woods Gulch	Invaded	0.362	4.445	4.422	37.1	17.8
8/1/2003	Woods Gulch	Invaded	0.423	5.398	5.278	40.5	22.4
8/31/2003	Woods Gulch	Invaded	0.420	5.033	5.008	37.8	23.7
5/23/2003	Woods Gulch	Uninvaded	0.328	4.359	4.234	28.3	21.2
7/8/2003	Woods Gulch	Uninvaded	0.272	3.71	3.652	22.7	19.3
8/1/2003	Woods Gulch	Uninvaded	0.250	3.195	3.062	23.0	23.9
8/31/2003	Woods Gulch	Uninvaded	0.305	3.926	3.894	24.1	22.1

Table A-26. (Continued). Soils raw data from 2003.

			AB-DTPA Extract (mg/kg)							
Date Collected	Site	Population	NH4-N	NO3-N	P	K	Zn	Fe	Mn	Cu
5/23/2003	Red Creek	Invaded	4.6	3.6	15.6	410	0.93	8.9	12.4	2.04
7/7/2003	Red Creek	Invaded	4.6	10.5	17.2	404	1.22	10.3	10.6	1.15
7/31/2003	Red Creek	Invaded	4.1	14.5	15.8	564	1.06	11.0	8.06	1.05
8/31/2003	Red Creek	Invaded	3.1	24.2	16.8	497	1.11	11.0	8.84	0.73
5/23/2003	Red Creek	Uninvaded	5.0	4.1	14.8	548	1.37	15.1	9.51	2.94
7/7/2003	Red Creek	Uninvaded	5.6	2.7	16.8	484	2.85	22.7	12.0	1.54
7/31/2003	Red Creek	Uninvaded	5.2	5.4	13.6	408	2.06	17.5	7.79	1.14
8/31/2003	Red Creek	Uninvaded	3.9	4.3	15.3	588	2.02	18.1	9.15	0.91
5/23/2003	Sapinero Mesa	Invaded	4.5	3.7	15.0	466	0.87	17.8	17.5	1.90
7/7/2003	Sapinero Mesa	Invaded	4.8	13.7	18.0	429	1.30	13.5	16.3	1.55
7/31/2003	Sapinero Mesa	Invaded	6.7	8.1	14.0	505	3.61	11.7	15.7	0.91
8/31/2003	Sapinero Mesa	Invaded	2.7	13.4	14.4	533	0.80	14.2	7.72	1.94
5/23/2003	Sapinero Mesa	Uninvaded	3.9	8.5	8.0	236	0.61	11.1	10.4	0.96
7/7/2003	Sapinero Mesa	Uninvaded	4.1	3.6	6.0	195	0.61	8.8	10.6	1.74
7/31/2003	Sapinero Mesa	Uninvaded	5.0	6.5	7.2	299	0.52	10.7	11.1	1.00
8/31/2003	Sapinero Mesa	Uninvaded	2.8	9.9	12.4	276	0.85	17.6	5.14	1.84
5/23/2003	Soap Creek	Invaded	3.9	2.8	13.2	231	0.75	15.3	10.9	2.25
7/7/2003	Soap Creek	Invaded	3.5	7.7	16.2	264	1.38	19.1	8.78	1.49
7/31/2003	Soap Creek	Invaded	3.9	7.4	12.6	300	0.94	14.5	7.53	1.61
8/31/2003	Soap Creek	Invaded	2.9	10.2	9.2	431	1.95	42.0	3.72	1.67
5/23/2003	Soap Creek	Uninvaded	7.2	6.5	11.8	337	2.03	34.0	6.58	2.80
7/7/2003	Soap Creek	Uninvaded	6.5	2.4	12.0	350	2.52	33.8	8.71	2.44
7/31/2003	Soap Creek	Uninvaded	5.7	4.4	11.2	436	1.98	32.6	4.62	1.53
8/31/2003	Soap Creek	Uninvaded	3.1	6.3	8.7	413	1.92	41.1	3.60	1.88
5/23/2003	Woods Gulch	Invaded	4.0	7.6	14.5	203	11.6	78.0	19.1	2.23
7/8/2003	Woods Gulch	Invaded	5.1	3.4	18.0	218	12.3	101	19.8	1.09
8/1/2003	Woods Gulch	Invaded	4.5	9.7	16.6	277	12.2	93.9	12.7	2.14
8/31/2003	Woods Gulch	Invaded	2.8	8.9	16.2	208	15.1	118	13.2	1.37
5/23/2003	Woods Gulch	Uninvaded	4.4	7.6	13.6	253	5.56	53.5	9.67	2.95
7/8/2003	Woods Gulch	Uninvaded	5.0	2.9	12.2	251	4.70	49.7	16.3	1.76
8/1/2003	Woods Gulch	Uninvaded	4.2	5.6	8.7	249	3.81	45.1	5.69	1.55
8/31/2003	Woods Gulch	Uninvaded	3.2	4.9	10.8	285	5.48	58.8	11.4	1.36

APPENDIX B

EXPERIMENTAL STUDY STATISTICAL SUMMARY AND RAW DATA

Key to Symbols in Appendix B Tables

Water Trt = water treatment

- **1** = 30-Aug
- **2** = 15-Sep
- **3** = 4-Oct
- **4** = ½ 30-Aug & ½ 15-Sep
- **5** = ½ 30-Aug & ½ 4-Oct
- **6** = ½ 15-Sep & ½ 4-Oct
- **7** = 1/3 on each date
- **8** = No added Water

Soil Trt = surface soil treatment

- **id** = interspace disturbance
- **il** = interspace litter addition
- **ic** = interspace control (no surface soil treatment)
- **sd** = under-sage disturbance
- **sc** = under-sage control (no surface soil treatment)

Month = data collection date

- **1** = November 2003
- **2** = April 2004
- **3** = May 2004
- **4** = June 2004

Table B-1. ANOVA for cheatgrass density (on square root-transformed data)

The Mixed Procedure

Class Level Information

Class	Levels	Values
Month	4	1 2 3 4
Block	4	1 2 3 4
Water_trt	8	1 2 3 4 5 6 7 8
Soil_trt	5	id il ic sd sc

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Soil_trt	4	455	87.18	<.0001
Water_trt	7	21	0.78	0.6081
Water_trt*Soil_trt	28	455	1.42	0.0794
Month	3	455	11.55	<.0001
Month*Soil_trt	12	455	2.83	0.0009
Month*Water_Trt	21	455	1.45	0.0923
Month*Water_Tr*Soil_trt	84	455	1.07	0.3279

Table B-2. ANOVA for cheatgrass biomass (on log-transformed data)

The Mixed Procedure

Class Level Information

Class	Levels	Values
Block	4	1 2 3 4
Water_Trt	8	1 2 3 4 5 6 7 8
Soil_trt	5	ic id il sc sd

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Water_Trt	7	21	0.84	0.5674
Soil_trt	4	96	72.39	<.0001
Water_Trt*Soil_trt	28	96	1.47	0.0861

Table B-3. ANOVA for cheatgrass biomass:count (on log-transformed data)

The Mixed Procedure

Class Level Information

Class	Levels	Values
Block	4	1 2 3 4
Water_Trt	8	1 2 3 4 5 6 7 8
Soil_trt	5	ic id il sc sd

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Water_Trt	7	21	1.23	0.3312
Soil_trt	4	95	19.58	<.0001
Water_Trt*Soil_trt	28	95	0.91	0.6005

Table B-4. ANOVA for cheatgrass seed count (on non-transformed data)

The Mixed Procedure

Class Level Information

Class	Levels	Values
Block	4	1 2 3 4
Water_Trt	8	1 2 3 4 5 6 7 8
Soil_trt	5	ic id il sc sd

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Water_Trt	7	21	0.89	0.5305
Soil_trt	4	96	19.14	<.0001
Water_Trt*Soil_trt	28	96	1.01	0.4689

Table B-5. ANOVA for cheatgrass seed biomass (on non-transformed data)

The Mixed Procedure

Class Level Information

Class	Levels	Values
Block	4	1 2 3 4
Water_Trt	8	1 2 3 4 5 6 7 8
Soil_trt	5	ic id il sc sd

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Water_Trt	7	21	0.91	0.5150
Soil_trt	4	96	17.20	<.0001
Water_trt*Soil_trt	28	96	0.93	0.5660

Table B-6. ANOVA for cheatgrass seed biomass:seed count (on non-transformed data)

The Mixed Procedure

Class Level Information

Class	Levels	Values
Block	4	1 2 3 4
Water_Trt	8	1 2 3 4 5 6 7 8
Soil_trt	5	ic id il sc sd

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Water_Trt	7	21	0.91	0.5178
Soil_trt	4	96	9.98	<.0001
Water_Trt*Soil_trt	28	96	0.69	0.8724

Table B-7. Raw data for cheatgrass response variables (plant count, plant biomass, seed count, and seed biomass).

Month	Block	Water Trt	Soil Trt	Plant Count	Plant Biomass (g)	Seed Count	Seed Biomass (g)
1	1	1	i c	1	-	-	-
1	1	1	i d	14	-	-	-
1	1	1	i l	8	-	-	-
1	1	1	s c	0	-	-	-
1	1	1	s d	13	-	-	-
1	1	2	i c	9	-	-	-
1	1	2	i d	5	-	-	-
1	1	2	i l	15	-	-	-
1	1	2	s c	8	-	-	-
1	1	2	s d	20	-	-	-
1	1	3	i c	1	-	-	-
1	1	3	i d	22	-	-	-
1	1	3	i l	11	-	-	-
1	1	3	s c	3	-	-	-
1	1	3	s d	26	-	-	-
1	1	4	i c	2	-	-	-
1	1	4	i d	8	-	-	-
1	1	4	i l	8	-	-	-
1	1	4	s c	7	-	-	-
1	1	4	s d	3	-	-	-
1	1	5	i c	2	-	-	-
1	1	5	i d	8	-	-	-
1	1	5	i l	11	-	-	-
1	1	5	s c	0	-	-	-
1	1	5	s d	7	-	-	-
1	1	6	i c	1	-	-	-
1	1	6	i d	14	-	-	-
1	1	6	i l	10	-	-	-
1	1	6	s c	1	-	-	-
1	1	6	s d	16	-	-	-
1	1	7	i c	3	-	-	-
1	1	7	i d	6	-	-	-
1	1	7	i l	7	-	-	-
1	1	7	s c	3	-	-	-
1	1	7	s d	16	-	-	-
1	1	8	i c	0	-	-	-
1	1	8	i d	3	-	-	-
1	1	8	i l	1	-	-	-
1	1	8	s c	6	-	-	-
1	1	8	s d	5	-	-	-
1	2	1	i c	1	-	-	-
1	2	1	i d	19	-	-	-
1	2	1	i l	3	-	-	-
1	2	1	s c	1	-	-	-
1	2	1	s d	5	-	-	-
1	2	2	i c	0	-	-	-
1	2	2	i d	21	-	-	-
1	2	2	i l	9	-	-	-
1	2	2	s c	2	-	-	-

Table B-7. (Continued). Raw data for cheatgrass response variables (plant count, plant biomass, seed count, and seed biomass).

Month	Block	Water Trt	Soil Trt	Plant Count	Plant Biomass (g)	Seed Count	Seed Biomass (g)
1	2	2	s d	13	-	-	-
1	2	3	i c	12	-	-	-
1	2	3	i d	18	-	-	-
1	2	3	i l	6	-	-	-
1	2	3	s c	1	-	-	-
1	2	3	s d	13	-	-	-
1	2	4	i c	2	-	-	-
1	2	4	i d	11	-	-	-
1	2	4	i l	10	-	-	-
1	2	4	s c	2	-	-	-
1	2	4	s d	20	-	-	-
1	2	5	i c	4	-	-	-
1	2	5	i d	8	-	-	-
1	2	5	i l	6	-	-	-
1	2	5	s c	2	-	-	-
1	2	5	s d	11	-	-	-
1	2	6	i c	4	-	-	-
1	2	6	i d	32	-	-	-
1	2	6	i l	22	-	-	-
1	2	6	s c	8	-	-	-
1	2	6	s d	31	-	-	-
1	2	7	i c	1	-	-	-
1	2	7	i d	11	-	-	-
1	2	7	i l	13	-	-	-
1	2	7	s c	3	-	-	-
1	2	7	s d	18	-	-	-
1	2	8	i c	0	-	-	-
1	2	8	i d	14	-	-	-
1	2	8	i l	19	-	-	-
1	2	8	s c	2	-	-	-
1	2	8	s d	22	-	-	-
1	3	1	i c	1	-	-	-
1	3	1	i d	23	-	-	-
1	3	1	i l	5	-	-	-
1	3	1	s c	9	-	-	-
1	3	1	s d	12	-	-	-
1	3	2	i c	1	-	-	-
1	3	2	i d	9	-	-	-
1	3	2	i l	13	-	-	-
1	3	2	s c	6	-	-	-
1	3	2	s d	8	-	-	-
1	3	3	i c	2	-	-	-
1	3	3	i d	20	-	-	-
1	3	3	i l	3	-	-	-
1	3	3	s c	3	-	-	-
1	3	3	s d	24	-	-	-
1	3	4	i c	5	-	-	-
1	3	4	i d	14	-	-	-
1	3	4	i l	30	-	-	-

Table B-7. (Continued). Raw data for cheatgrass response variables (plant count, plant biomass, seed count, and seed biomass).

Month	Block	Water Trt	Soil Trt	Plant Count	Plant Biomass (g)	Seed Count	Seed Biomass (g)
1	3	4	s c	2	-	-	-
1	3	4	s d	13	-	-	-
1	3	5	i c	0	-	-	-
1	3	5	i d	22	-	-	-
1	3	5	i l	22	-	-	-
1	3	5	s c	4	-	-	-
1	3	5	s d	8	-	-	-
1	3	6	i c	1	-	-	-
1	3	6	i d	17	-	-	-
1	3	6	i l	12	-	-	-
1	3	6	s c	4	-	-	-
1	3	6	s d	17	-	-	-
1	3	7	i c	3	-	-	-
1	3	7	i d	6	-	-	-
1	3	7	i l	7	-	-	-
1	3	7	s c	1	-	-	-
1	3	7	s d	8	-	-	-
1	3	8	i c	1	-	-	-
1	3	8	i d	18	-	-	-
1	3	8	i l	7	-	-	-
1	3	8	s c	4	-	-	-
1	3	8	s d	3	-	-	-
1	4	1	i c	5	-	-	-
1	4	1	i d	26	-	-	-
1	4	1	i l	10	-	-	-
1	4	1	s c	7	-	-	-
1	4	1	s d	17	-	-	-
1	4	2	i c	7	-	-	-
1	4	2	i d	40	-	-	-
1	4	2	i l	21	-	-	-
1	4	2	s c	6	-	-	-
1	4	2	s d	24	-	-	-
1	4	3	i c	3	-	-	-
1	4	3	i d	13	-	-	-
1	4	3	i l	22	-	-	-
1	4	3	s c	3	-	-	-
1	4	3	s d	22	-	-	-
1	4	4	i c	1	-	-	-
1	4	4	i d	19	-	-	-
1	4	4	i l	11	-	-	-
1	4	4	s c	7	-	-	-
1	4	4	s d	10	-	-	-
1	4	5	i c	2	-	-	-
1	4	5	i d	23	-	-	-
1	4	5	i l	15	-	-	-
1	4	5	s c	4	-	-	-
1	4	5	s d	20	-	-	-
1	4	6	i c	2	-	-	-
1	4	6	i d	25	-	-	-

Table B-7. (Continued). Raw data for cheatgrass response variables (plant count, plant biomass, seed count, and seed biomass).

Month	Block	Water Trt	Soil Trt	Plant Count	Plant Biomass (g)	Seed Count	Seed Biomass (g)
1	4	6	i l	21	-	-	-
1	4	6	s c	9	-	-	-
1	4	6	s d	11	-	-	-
1	4	7	i c	2	-	-	-
1	4	7	i d	7	-	-	-
1	4	7	i l	2	-	-	-
1	4	7	s c	7	-	-	-
1	4	7	s d	28	-	-	-
1	4	8	i c	0	-	-	-
1	4	8	i d	17	-	-	-
1	4	8	i l	10	-	-	-
1	4	8	s c	5	-	-	-
1	4	8	s d	20	-	-	-
2	1	1	i c	2	-	-	-
2	1	1	i d	25	-	-	-
2	1	1	i l	17	-	-	-
2	1	1	s c	4	-	-	-
2	1	1	s d	20	-	-	-
2	1	2	i c	8	-	-	-
2	1	2	i d	12	-	-	-
2	1	2	i l	11	-	-	-
2	1	2	s c	1	-	-	-
2	1	2	s d	10	-	-	-
2	1	3	i c	4	-	-	-
2	1	3	i d	23	-	-	-
2	1	3	i l	11	-	-	-
2	1	3	s c	3	-	-	-
2	1	3	s d	33	-	-	-
2	1	4	i c	7	-	-	-
2	1	4	i d	31	-	-	-
2	1	4	i l	20	-	-	-
2	1	4	s c	5	-	-	-
2	1	4	s d	1	-	-	-
2	1	5	i c	4	-	-	-
2	1	5	i d	7	-	-	-
2	1	5	i l	18	-	-	-
2	1	5	s c	0	-	-	-
2	1	5	s d	23	-	-	-
2	1	6	i c	1	-	-	-
2	1	6	i d	13	-	-	-
2	1	6	i l	9	-	-	-
2	1	6	s c	1	-	-	-
2	1	6	s d	23	-	-	-
2	1	7	i c	3	-	-	-
2	1	7	i d	11	-	-	-
2	1	7	i l	7	-	-	-
2	1	7	s c	3	-	-	-
2	1	7	s d	18	-	-	-
2	1	8	i c	0	-	-	-

Table B-7. (Continued). Raw data for cheatgrass response variables (plant count, plant biomass, seed count, and seed biomass).

Month	Block	Water Trt	Soil Trt	Plant Count	Plant Biomass (g)	Seed Count	Seed Biomass (g)
2	1	8	i d	10	-	-	-
2	1	8	i l	4	-	-	-
2	1	8	s c	6	-	-	-
2	1	8	s d	19	-	-	-
2	2	1	i c	1	-	-	-
2	2	1	i d	14	-	-	-
2	2	1	i l	16	-	-	-
2	2	1	s c	4	-	-	-
2	2	1	s d	5	-	-	-
2	2	2	i c	3	-	-	-
2	2	2	i d	19	-	-	-
2	2	2	i l	14	-	-	-
2	2	2	s c	2	-	-	-
2	2	2	s d	19	-	-	-
2	2	3	i c	9	-	-	-
2	2	3	i d	18	-	-	-
2	2	3	i l	5	-	-	-
2	2	3	s c	1	-	-	-
2	2	3	s d	11	-	-	-
2	2	4	i c	0	-	-	-
2	2	4	i d	6	-	-	-
2	2	4	i l	10	-	-	-
2	2	4	s c	4	-	-	-
2	2	4	s d	22	-	-	-
2	2	5	i c	2	-	-	-
2	2	5	i d	7	-	-	-
2	2	5	i l	10	-	-	-
2	2	5	s c	1	-	-	-
2	2	5	s d	12	-	-	-
2	2	6	i c	5	-	-	-
2	2	6	i d	32	-	-	-
2	2	6	i l	42	-	-	-
2	2	6	s c	9	-	-	-
2	2	6	s d	31	-	-	-
2	2	7	i c	0	-	-	-
2	2	7	i d	11	-	-	-
2	2	7	i l	14	-	-	-
2	2	7	s c	7	-	-	-
2	2	7	s d	23	-	-	-
2	2	8	i c	0	-	-	-
2	2	8	i d	14	-	-	-
2	2	8	i l	19	-	-	-
2	2	8	s c	5	-	-	-
2	2	8	s d	18	-	-	-
2	3	1	i c	4	-	-	-
2	3	1	i d	23	-	-	-
2	3	1	i l	13	-	-	-
2	3	1	s c	7	-	-	-
2	3	1	s d	18	-	-	-

Table B-7. (Continued). Raw data for cheatgrass response variables (plant count, plant biomass, seed count, and seed biomass).

Month	Block	Water Trt	Soil Trt	Plant Count	Plant Biomass (g)	Seed Count	Seed Biomass (g)
2	3	2	i c	0	-	-	-
2	3	2	i d	13	-	-	-
2	3	2	i l	11	-	-	-
2	3	2	s c	7	-	-	-
2	3	2	s d	6	-	-	-
2	3	3	i c	0	-	-	-
2	3	3	i d	18	-	-	-
2	3	3	i l	8	-	-	-
2	3	3	s c	7	-	-	-
2	3	3	s d	19	-	-	-
2	3	4	i c	3	-	-	-
2	3	4	i d	9	-	-	-
2	3	4	i l	22	-	-	-
2	3	4	s c	3	-	-	-
2	3	4	s d	14	-	-	-
2	3	5	i c	0	-	-	-
2	3	5	i d	21	-	-	-
2	3	5	i l	19	-	-	-
2	3	5	s c	13	-	-	-
2	3	5	s d	6	-	-	-
2	3	6	i c	7	-	-	-
2	3	6	i d	15	-	-	-
2	3	6	i l	13	-	-	-
2	3	6	s c	2	-	-	-
2	3	6	s d	7	-	-	-
2	3	7	i c	6	-	-	-
2	3	7	i d	10	-	-	-
2	3	7	i l	8	-	-	-
2	3	7	s c	2	-	-	-
2	3	7	s d	17	-	-	-
2	3	8	i c	1	-	-	-
2	3	8	i d	17	-	-	-
2	3	8	i l	8	-	-	-
2	3	8	s c	2	-	-	-
2	3	8	s d	11	-	-	-
2	4	1	i c	3	-	-	-
2	4	1	i d	17	-	-	-
2	4	1	i l	11	-	-	-
2	4	1	s c	8	-	-	-
2	4	1	s d	9	-	-	-
2	4	2	i c	6	-	-	-
2	4	2	i d	36	-	-	-
2	4	2	i l	25	-	-	-
2	4	2	s c	4	-	-	-
2	4	2	s d	20	-	-	-
2	4	3	i c	0	-	-	-
2	4	3	i d	12	-	-	-
2	4	3	i l	25	-	-	-
2	4	3	s c	2	-	-	-

Table B-7. (Continued). Raw data for cheatgrass response variables (plant count, plant biomass, seed count, and seed biomass).

Month	Block	Water Trt	Soil Trt	Plant Count	Plant Biomass (g)	Seed Count	Seed Biomass (g)
2	4	3	s d	10	-	-	-
2	4	4	i c	4	-	-	-
2	4	4	i d	8	-	-	-
2	4	4	i l	16	-	-	-
2	4	4	s c	4	-	-	-
2	4	4	s d	10	-	-	-
2	4	5	i c	0	-	-	-
2	4	5	i d	16	-	-	-
2	4	5	i l	14	-	-	-
2	4	5	s c	5	-	-	-
2	4	5	s d	27	-	-	-
2	4	6	i c	1	-	-	-
2	4	6	i d	20	-	-	-
2	4	6	i l	28	-	-	-
2	4	6	s c	7	-	-	-
2	4	6	s d	8	-	-	-
2	4	7	i c	5	-	-	-
2	4	7	i d	5	-	-	-
2	4	7	i l	10	-	-	-
2	4	7	s c	4	-	-	-
2	4	7	s d	19	-	-	-
2	4	8	i c	0	-	-	-
2	4	8	i d	13	-	-	-
2	4	8	i l	11	-	-	-
2	4	8	s c	7	-	-	-
2	4	8	s d	25	-	-	-
3	1	1	i c	3	-	-	-
3	1	1	i d	24	-	-	-
3	1	1	i l	22	-	-	-
3	1	1	s c	11	-	-	-
3	1	1	s d	25	-	-	-
3	1	2	i c	8	-	-	-
3	1	2	i d	8	-	-	-
3	1	2	i l	9	-	-	-
3	1	2	s c	2	-	-	-
3	1	2	s d	7	-	-	-
3	1	3	i c	4	-	-	-
3	1	3	i d	25	-	-	-
3	1	3	i l	12	-	-	-
3	1	3	s c	11	-	-	-
3	1	3	s d	36	-	-	-
3	1	4	i c	8	-	-	-
3	1	4	i d	18	-	-	-
3	1	4	i l	20	-	-	-
3	1	4	s c	5	-	-	-
3	1	4	s d	4	-	-	-
3	1	5	i c	4	-	-	-
3	1	5	i d	6	-	-	-
3	1	5	i l	14	-	-	-

Table B-7. (Continued). Raw data for cheatgrass response variables (plant count, plant biomass, seed count, and seed biomass).

Month	Block	Water Trt	Soil Trt	Plant Count	Plant Biomass (g)	Seed Count	Seed Biomass (g)
3	1	5	s c	0	-	-	-
3	1	5	s d	24	-	-	-
3	1	6	i c	0	-	-	-
3	1	6	i d	10	-	-	-
3	1	6	i l	4	-	-	-
3	1	6	s c	1	-	-	-
3	1	6	s d	22	-	-	-
3	1	7	i c	1	-	-	-
3	1	7	i d	10	-	-	-
3	1	7	i l	13	-	-	-
3	1	7	s c	3	-	-	-
3	1	7	s d	16	-	-	-
3	1	8	i c	3	-	-	-
3	1	8	i d	11	-	-	-
3	1	8	i l	4	-	-	-
3	1	8	s c	3	-	-	-
3	1	8	s d	22	-	-	-
3	2	1	i c	1	-	-	-
3	2	1	i d	18	-	-	-
3	2	1	i l	14	-	-	-
3	2	1	s c	2	-	-	-
3	2	1	s d	4	-	-	-
3	2	2	i c	2	-	-	-
3	2	2	i d	16	-	-	-
3	2	2	i l	11	-	-	-
3	2	2	s c	0	-	-	-
3	2	2	s d	26	-	-	-
3	2	3	i c	5	-	-	-
3	2	3	i d	15	-	-	-
3	2	3	i l	7	-	-	-
3	2	3	s c	0	-	-	-
3	2	3	s d	11	-	-	-
3	2	4	i c	0	-	-	-
3	2	4	i d	2	-	-	-
3	2	4	i l	10	-	-	-
3	2	4	s c	5	-	-	-
3	2	4	s d	25	-	-	-
3	2	5	i c	5	-	-	-
3	2	5	i d	8	-	-	-
3	2	5	i l	15	-	-	-
3	2	5	s c	0	-	-	-
3	2	5	s d	15	-	-	-
3	2	6	i c	5	-	-	-
3	2	6	i d	36	-	-	-
3	2	6	i l	41	-	-	-
3	2	6	s c	9	-	-	-
3	2	6	s d	32	-	-	-
3	2	7	i c	0	-	-	-
3	2	7	i d	12	-	-	-

Table B-7. (Continued). Raw data for cheatgrass response variables (plant count, plant biomass, seed count, and seed biomass).

Month	Block	Water Trt	Soil Trt	Plant Count	Plant Biomass (g)	Seed Count	Seed Biomass (g)
3	2	7	i l	20	-	-	-
3	2	7	s c	7	-	-	-
3	2	7	s d	22	-	-	-
3	2	8	i c	2	-	-	-
3	2	8	i d	11	-	-	-
3	2	8	i l	23	-	-	-
3	2	8	s c	9	-	-	-
3	2	8	s d	22	-	-	-
3	3	1	i c	5	-	-	-
3	3	1	i d	26	-	-	-
3	3	1	i l	18	-	-	-
3	3	1	s c	11	-	-	-
3	3	1	s d	18	-	-	-
3	3	2	i c	0	-	-	-
3	3	2	i d	11	-	-	-
3	3	2	i l	11	-	-	-
3	3	2	s c	4	-	-	-
3	3	2	s d	9	-	-	-
3	3	3	i c	1	-	-	-
3	3	3	i d	18	-	-	-
3	3	3	i l	8	-	-	-
3	3	3	s c	3	-	-	-
3	3	3	s d	24	-	-	-
3	3	4	i c	1	-	-	-
3	3	4	i d	9	-	-	-
3	3	4	i l	33	-	-	-
3	3	4	s c	5	-	-	-
3	3	4	s d	11	-	-	-
3	3	5	i c	1	-	-	-
3	3	5	i d	23	-	-	-
3	3	5	i l	27	-	-	-
3	3	5	s c	15	-	-	-
3	3	5	s d	8	-	-	-
3	3	6	i c	6	-	-	-
3	3	6	i d	20	-	-	-
3	3	6	i l	15	-	-	-
3	3	6	s c	2	-	-	-
3	3	6	s d	11	-	-	-
3	3	7	i c	6	-	-	-
3	3	7	i d	8	-	-	-
3	3	7	i l	13	-	-	-
3	3	7	s c	1	-	-	-
3	3	7	s d	19	-	-	-
3	3	8	i c	5	-	-	-
3	3	8	i d	18	-	-	-
3	3	8	i l	11	-	-	-
3	3	8	s c	6	-	-	-
3	3	8	s d	9	-	-	-
3	4	1	i c	2	-	-	-

Table B-7. (Continued). Raw data for cheatgrass response variables (plant count, plant biomass, seed count, and seed biomass).

Month	Block	Water Trt	Soil Trt	Plant Count	Plant Biomass (g)	Seed Count	Seed Biomass (g)
3	4	1	i d	10	-	-	-
3	4	1	i l	11	-	-	-
3	4	1	s c	8	-	-	-
3	4	1	s d	18	-	-	-
3	4	2	i c	4	-	-	-
3	4	2	i d	32	-	-	-
3	4	2	i l	26	-	-	-
3	4	2	s c	4	-	-	-
3	4	2	s d	20	-	-	-
3	4	3	i c	0	-	-	-
3	4	3	i d	15	-	-	-
3	4	3	i l	25	-	-	-
3	4	3	s c	4	-	-	-
3	4	3	s d	12	-	-	-
3	4	4	i c	4	-	-	-
3	4	4	i d	7	-	-	-
3	4	4	i l	17	-	-	-
3	4	4	s c	7	-	-	-
3	4	4	s d	5	-	-	-
3	4	5	i c	2	-	-	-
3	4	5	i d	9	-	-	-
3	4	5	i l	20	-	-	-
3	4	5	s c	4	-	-	-
3	4	5	s d	27	-	-	-
3	4	6	i c	0	-	-	-
3	4	6	i d	19	-	-	-
3	4	6	i l	32	-	-	-
3	4	6	s c	9	-	-	-
3	4	6	s d	18	-	-	-
3	4	7	i c	3	-	-	-
3	4	7	i d	7	-	-	-
3	4	7	i l	7	-	-	-
3	4	7	s c	6	-	-	-
3	4	7	s d	20	-	-	-
3	4	8	i c	0	-	-	-
3	4	8	i d	13	-	-	-
3	4	8	i l	13	-	-	-
3	4	8	s c	7	-	-	-
3	4	8	s d	27	-	-	-
4	1	1	i c	4	0.02	0	0
4	1	1	i d	17	0.23	27	0.0379
4	1	1	i l	21	0.27	35	0.0485
4	1	1	s c	7	0.12	11	0.0171
4	1	1	s d	28	0.41	38	0.0414
4	1	2	i c	7	0.08	1	0.001
4	1	2	i d	3	0.02	1	0.001
4	1	2	i l	6	0.05	2	0.0026
4	1	2	s c	3	0.02	5	0.0039
4	1	2	s d	13	0.41	43	0.0477

Table B-7. (Continued). Raw data for cheatgrass response variables (plant count, plant biomass, seed count, and seed biomass).

Month	Block	Water Trt	Soil Trt	Plant Count	Plant Biomass (g)	Seed Count	Seed Biomass (g)
4	1	3	i c	4	0.02	3	0.0033
4	1	3	i d	22	0.25	17	0.0245
4	1	3	i l	13	0.12	8	0.0118
4	1	3	s c	9	0.07	3	0.0035
4	1	3	s d	36	0.96	78	0.1018
4	1	4	i c	6	0.06	4	0.0049
4	1	4	i d	12	0.19	9	0.0084
4	1	4	i l	20	0.36	32	0.0423
4	1	4	s c	8	0.06	5	0.0063
4	1	4	s d	4	0.09	7	0.0092
4	1	5	i c	4	0.02	1	0.0011
4	1	5	i d	5	0.06	8	0.0103
4	1	5	i l	11	0.11	8	0.0121
4	1	5	s c	0	0	0	0
4	1	5	s d	29	1.23	54	0.0765
4	1	6	i c	3	0.02	8	0.0071
4	1	6	i d	12	0.21	29	0.0305
4	1	6	i l	11	0.14	14	0.0206
4	1	6	s c	1	0.01	0	0
4	1	6	s d	25	0.62	41	0.0472
4	1	7	i c	0	0	0	0
4	1	7	i d	7	0.07	8	0.0084
4	1	7	i l	6	0.05	15	0.0178
4	1	7	s c	3	0.01	1	0.0011
4	1	7	s d	21	0.66	114	0.1106
4	1	8	i c	1	0.01	0	0
4	1	8	i d	11	0.11	4	0.0042
4	1	8	i l	5	0.07	4	0.0052
4	1	8	s c	12	0.05	12	0.0074
4	1	8	s d	20	0.68	113	0.1362
4	2	1	i c	2	0.01	0	0
4	2	1	i d	19	0.56	122	0.1596
4	2	1	i l	18	0.17	31	0.0463
4	2	1	s c	missing	0.02	6	0.0081
4	2	1	s d	4	0.14	22	0.0286
4	2	2	i c	2	0.01	0	0
4	2	2	i d	14	0.3	27	0.0317
4	2	2	i l	10	0.05	3	0.0033
4	2	2	s c	0	0	0	0
4	2	2	s d	32	0.73	70	0.0825
4	2	3	i c	6	0.03	0	0
4	2	3	i d	17	0.22	14	0.0151
4	2	3	i l	7	0.05	5	0.0054
4	2	3	s c	1	0.01	0	0
4	2	3	s d	10	0.16	10	0.0118
4	2	4	i c	2	0.04	6	0.0061
4	2	4	i d	5	0.05	4	0.0041
4	2	4	i l	11	0.24	16	0.0176
4	2	4	s c	6	0.13	24	0.0335

Table B-7. (Continued). Raw data for cheatgrass response variables (plant count, plant biomass, seed count, and seed biomass).

Month	Block	Water Trt	Soil Trt	Plant Count	Plant Biomass (g)	Seed Count	Seed Biomass (g)
4	2	4	s d	27	0.99	157	0.183
4	2	5	i c	6	0.07	6	0.0066
4	2	5	i d	8	0.1	8	0.0078
4	2	5	i l	12	0.16	14	0.0169
4	2	5	s c	0	0	0	0
4	2	5	s d	19	0.66	112	0.1414
4	2	6	i c	5	0.57	115	0.1592
4	2	6	i d	30	1.38	122	0.1544
4	2	6	i l	32	1.69	247	0.3731
4	2	6	s c	7	0.18	31	0.043
4	2	6	s d	38	2.74	516	0.67
4	2	7	i c	0	0	0	0
4	2	7	i d	8	0.19	23	0.0314
4	2	7	i l	19	0.24	38	0.0455
4	2	7	s c	7	0.06	12	0.0141
4	2	7	s d	31	1.15	183	0.2386
4	2	8	i c	3	0.02	0	0
4	2	8	i d	12	0.36	52	0.0592
4	2	8	i l	20	0.37	44	0.065
4	2	8	s c	11	0.26	28	0.0282
4	2	8	s d	23	1.24	118	0.1248
4	3	1	i c	3	0.03	5	0.0066
4	3	1	i d	26	0.57	83	0.1128
4	3	1	i l	18	0.28	18	0.0278
4	3	1	s c	12	0.18	34	0.0431
4	3	1	s d	20	0.69	121	0.1987
4	3	2	i c	1	0.02	2	0.0017
4	3	2	i d	10	0.15	13	0.0168
4	3	2	i l	15	0.11	12	0.0142
4	3	2	s c	6	0.03	2	0.002
4	3	2	s d	20	0.07	57	0.0718
4	3	3	i c	2	0.01	0	0
4	3	3	i d	22	1.06	186	0.2275
4	3	3	i l	6	0.07	4	0.0057
4	3	3	s c	9	0.09	23	0.032
4	3	3	s d	26	0.57	71	0.0793
4	3	4	i c	2	0.05	3	0.0028
4	3	4	i d	11	0.25	37	0.0629
4	3	4	i l	32	0.62	91	0.1366
4	3	4	s c	8	0.14	23	0.0272
4	3	4	s d	12	0.4	75	0.1118
4	3	5	i c	2	0.01	0	0
4	3	5	i d	24	0.71	65	0.0949
4	3	5	i l	27	0.36	52	0.0758
4	3	5	s c	15	0.7	132	0.1641
4	3	5	s d	16	0.93	175	0.2578
4	3	6	i c	6	0.14	12	0.0161
4	3	6	i d	21	0.5	77	0.0883
4	3	6	i l	18	0.46	58	0.0665

Table B-7. (Continued). Raw data for cheatgrass response variables (plant count, plant biomass, seed count, and seed biomass).

Month	Block	Water Trt	Soil Trt	Plant Count	Plant Biomass (g)	Seed Count	Seed Biomass (g)
4	4	8	i l	14	0.16	17	0.0232
4	4	8	s c	6	0.12	29	0.0393
4	4	8	s d	34	1.49	223	0.25