THESIS

SOIL SHEAR RESISTANCE AND PLANT COMMUNITY RECOVERY AFTER DISTURBANCE IN A MONTANE RIPARIAN ECOSYSTEM

Submitted by

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ABSTRACT

SOIL SHEAR RESISTANCE AND PLANT COMMUNITY RECOVERY AFTER DISTURBANCE IN A MONTANE RIPARIAN ECOSYSTEM

Vegetation recovery after a severe cattle trampling disturbance was studied in a montane riparian community. The disturbance allowed for the successful establishment of cuttings of mountain willow (*Salix monticola* Bebb.). However, most of the planeleaf willow (*S. planifolia*) cuttings had very poor establishment. Weedy annual forbs were present after the first and second years following the grazing disturbance. But, after six years of recovery the weedy forbs had declined and the dominant sedge (*Carex* spp.) community returned. However, some introduced forbs still persisted after six years of protection from livestock grazing.

Season of trampling had significant effects on herbaceous species composition and rate of recovery. Plots trampled in the fall had greater recovery of herbaceous cover ($P = 0.05$) and native species ($P = 0.03$) as compared with late spring and early summer trampling disturbances.

A severe disturbance probably increased resource availability and weedy forbs quickly took advantage of these resources. Plots trampled in the late spring retained the greatest ($P = 0.0011$) cover of ruderal species (23%), even after six years of recovery. However, other trampled plots returned to a composition dominated by native grasses and sedge Mountain willow had greater survival ($P = 0.01$) and stem growth ($P=0.01$) compared with planeleaf

willow (*Salix planifolia* Pursh). Planeleaf willow's poor performance may have resulted from a combination of a deep water table depth, competition with adjacent plants, and poor transplantablity. Mountain willow tolerated lower water table depths and some competition from adjacent herbaceous plants.

Belowground root-soil cores for several herbaceous species from the montane riparian community were studied using shear resistance measurements as an indicator for erosion protection. Three important grasses, a rush (*Juncus* spp.), and two sedge species were compared at two depths from 0 to 10 and 10 to 20 cm. In addition, tests for bulk density, texture, belowground biomass, and organic matter content were made to establish relationships of these variables with vegetation type and soil shear resistance. Soil cores from vegetated areas were compared with unvegetated areas. These comparisons reveled a three-fold greater ($P = 0.003$) shear resistance (greater protection from erosion) for vegetated sites in the upper soil depth (0 to 10 cm). There was no significant difference between vegetated and unvegetated sites for the lower soil depth (10 to 20 cm).

Sedges and *Juncus* had greater ($P < 0.0001$) belowground shear resistance than grasses in the top 10 cm soil layer. Both categories of species had little effect on shear resistance below the 10 cm soil layer ($P = 0.1246$) where belowground biomass was much less. Sedges had three times greater ($P < 0.001$) shear resistance in the top 0 to 10 cm compared to the bottom 10 to 20 cm soil depth.

Covariate analysis showed that belowground plant biomass was the most influential component affecting shear resistance. Soil bulk density was also an important covariate. The top 10 cm of the soil layer had the largest concentration of root and rhizome biomass and lower bulk density compared to the 10 to 20 cm depth

ACKNOWLEDGMENTS

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CHAPTER I

TRAMPLING STUDY

CHAPTER SUMMARY

The effects of vegetation on bank stability following a severe trampling disturbance was studied in a montane riparian community. Overall willow establishment was very poor except for some of the mountian willow (*Salix monticola*) cuttings. Poor willow establishment may have been attributed to a combination of inadequate water table depth, competition with adjacent plants, and poor transplantability. Some weedy annual and introduced forbs flourished in the first and second year after the disturbance, but few persisted after six years of recovery. Season of trampling had significantly less effect on the amount of herbaceous cover (P=0.05) and native species cover (P = 0.03) in fall trampled plots as compared with late spring and early summer trampling disturbances.

INTRODUCTION

Riparian areas provide necessary forage and habitat for wildlife, aquatic organisms, native ungulates and domestic livestock. These valuable riparian communities are often disturbed, yet little is know about how riparian ecosystems respond to frequent anthropogenic and natural disturbances. Many of the riparian ecosystems in the western United States have been severely disturbed by such activities as heavy grazing by domestic livestock, recreational activities, road construction, logging, mining, agricultural developments, and water diversions (Elmore and Beschta 1987, Popolizio et al. 1994). However, grazing disturbances remain the primary cause for riparian degradation in the west (Elmore and Beschta 1987, Popolizio et al. 1994). Cattle contribute to declines in riparian community stability and water quality through removal of protective vegetation cover during grazing and decreased streambank stability by trampling (Leininger and Trlica 1986, Chaney et al. 1990, Schulz and Leininger 1990). These impacts have often arisen because of inappropriate livestock management.

Some disturbance in riparian systems may result in higher biotic diversity (Kauffman et al. 1995). Riparian plants have evolved to survive and reproduce under adverse conditions such as seasonal flooding, streambank erosion, fire, and grazing. A few studies have shown that degraded riparian areas tend to recover quickly when livestock are removed (Elmore and Beschta 1987, Painter et al. 1989, Schulz and Leiniger 1990, Clary 1995, Kauffman et al. 1995, Wheeler et al. 2002, Holland et al. 2005). A better understanding of the resilience of riparian vegetation to disturbance will be important in formulation of restoration plans for these important ecosystems.

Timing of trampling may have a greater effect on vegetation because damage from trampling alters the resources that are allocated to plant tissues throughout the growing season. Previous research (Zasada et al. 1994) indicates that plants trampled early in the spring may be vulnerable because of the damage to growing tissues. Trampling impact on plants could be less when plants are dormant or not actively growing.

The objective of this project was to determine the recovery of a montane riparian system following a single event of severe trampling disturbance by cattle during either the fall, spring, or summer. Recovery in plant species composition, richness, and cover following the acute disturbance was monitored over a six year period. Willow (*Salix* spp.) establishment from willow cuttings also was examined as an intervention for riparian recovery following disturbance. This research should further our understanding of vegetation recovery of a montane riparian system after a severe disturbance event.

Objectives:

The objectives of this study were:

1. To compare recovery in vegetation cover and species richness in areas disturbed by intensive cattle trampling at three different times during a growing season.
2. To determine survival and growth of two species of willow cuttings planted in these highly disturbed areas as compared with those planted in undisturbed control areas.

Hypothesis:

H_1: Areas disturbed in the fall by livestock in the montane riparian community along Sheep Creek would have greater recovery within six years than those disturbed during late spring or early summer.

H_2: Willow cuttings planted in disturbed areas would have greater survival and growth than those planted in undisturbed control areas.

METHODS AND MATERIALS

Site Location and Description

Roosevelt National Forest. The elevation of this study site is approximately 2500 m. Sheep Creek is classified as a C3 stream according to Rosgen (1994). The study took place within a large long-term grazing exclosure established in 1956 along Sheep Creek by the USDA Forest Service and the Colorado Division of Wildlife in an effort to protect and improve fish habitat (Stuber 1985). The major soil series in the study area is a Fluvaquent, characterized with flood plains, low terraces, and bottom lands (Wheeler et al. 2002). The texture of the surface and underlying soil layers is extremely variable as a result of repeated flooding and range from sandy loam to clay loam. The soil profile is commonly stratified with thin layers of gravel, sand, and clay. Riparian sedge (*Carex* spp.) communities found in this area have a thick organic peat layer about 10-20 cm thick (Wheeler et al. 2002).

The dominant woody species found in the Sheep Creek riparian area include planeleaf willow (*Salix planifolia* Pursh) and mountain willow (*S. monticola* Bebb.). Other willow species found in the area include Bebb’s willow (*S. bebbiana* Sarg.), Geyer's willow (*S. geyeriana* Anderss.), and narrowleaf willow (*S. exigua* Nutt.). Another commonly found shrub species is shrubby cinquefoil (*Dasiphora fruiticosa* (L) Rydb.). The herbaceous understory found in the area includes water sedge (*Carex aquatilis* Wahl.), Nebraska sedge (*C. nebraskensis* Dewey), beaked sedge (*C. utriculata* Boott), Kentucky bluegrass (*Poa pratensis* L.), bluejoint reedgrass (*Calamagrostis canadensis* (Michx.) P. Beauv.), tufted hairgrass (*Deschampsia caespitosa* (L.) Beauv.), mountain rush (*Juncus arcticus* Willd.), western yarrow (*Achillea lanulosa* Nutt.), white and red clover (*Trifolium repens* L. and *T. pratense* L.) and dandelion (*Taraxacum officinale* Wiggers) (Schulz and Leininger 1990, Popolizio et al. 1994).

Sampling Procedures

Nine intensely trampled paddocks were sampled to determine seasonal treatment effects on vegetation recovery. In addition, three control plots that were not trampled were also established. Treated plots were each intensely trampled at three different times during 1995 (Table 1). All of the twelve plots were approximately 4 X 3 m in size and were delineated on April 23, 1996. Three intensely trampled paddocks were disturbed in the late spring, three were trampled in early summer, while the remaining three were trampled in the fall (Table 1.1). Each disturbed paddock (plot) was fenced to hold livestock and trampled by five Holstein steers for four consecutive nights during each of the three seasons. Additionally, these same steers and trampling treatments dates coincide with other research going on in the area but not interfering with these trampled and control plots (Evans et al 2004, Pelster et al. 2004). Vegetation and

Table 1.1 Timing of intensely trampled treatments in 1995 for a montane riparian community.

Trampling Treatments	Dates of Disturbance (1995)
Late Spring	6/11 to 6/24
Early Summer	6/30 to 7/11
Fall	9/9 to 9/22
Control	Not Trampled

litter were mixed with wet soil, urine and manure by hoof action in these severely trampled treatments. The undisturbed control plots that had similar slopes, soils, and vegetation were selected within the riparian community near the trampled plots. After trampling, the seasonal disturbance plots remained ungrazed as this area remains in long-term exclusion from cattle grazing. The average distance of the plots from the creek was approximately 9 m.

Willow cuttings were obtained from a nearby willow stand downstream of the study site on May 8, 1996. The species selected for planting were planeleaf willow and mountain willow. A total of 20 willow stakes evenly placed were planted per plot. The willow stakes were cut while dormant and averaged 50 cm in length with an average diameter of 2 cm. Larger cuttings were preferred because Hussian and Trlica (1995) reported that larger willow stem cuttings sprouted better than did small ones in a loamy soil from their natural environment. Holes were made into the wet soil with a heavy 2.5 cm diameter steel bar with a pointed end for planting willow cuttings. Each willow stake was inserted approximately 25 cm into the soil and the soil was pressed firmly against each cutting to reduce light and air penetration into the holes that might affect root development. The average spacing between rows of cuttings and among each cutting was 25 cm. The willow plantings were monitored for three summers (1996, 1997, and 2001) to determine establishment, growth, and survival of both willow species in each treatment plot.

Groundwater depth was measured biweekly in 2002 from slotted polyvinyl chloride monitoring wells established adjacent to trampled plots. A gasoline powered auger with a 5 cm bit was used to drill holes through the soil to a depth of 1.5 meters. The slotted polyvinyl pipe was then inserted, screwed down to the bottom of the hole, and soil replaced around the edges of the hole and then tamped. Installation of all wells was completed in the fall of 2001 to allow for water in the wells to come to equilibrium after the disturbance. Three staff gauges were established above, below, and in between sampled area in the stream channel. Some wells represented multiple replications of trampled treatments due to theirclose proximity relative to the well location.

The natural recovery of vegetation was also determined in each of the trampled plots during these three summers. A 20 x 50 cm quadrat (Daubenmire 1959) was used to estimate plant cover by species (to the nearest 1%), as well as percentage of bare ground and litter. Visual estimates of cover were made during peak standing crop for each of the three growing seasons (1996, 1997, and 2001) in each trampled plot and in control plots. A total of twenty randomly placed 20 x 50 cm quadrats were sampled within each plot in each of the three years.

Experimental Design and Analysis

The trampling and willow experiments were designed as a randomized complete block experiments with three replications. The season of trampling was the main treatment and year of sampling was a subtreatment (Appendix Table 1.1). All data were analyzed using analysis of variance (ANOVA) and analysis of covariance (ANCOVA) procedures (SAS 1996) for a repeated measures design. The SAS (1996) statistical proc mixed program was used for all data analyses and covariate analyses. Significant differences among treatments were accepted at $P < 0.10$ and significant mean differences among treatments were compared using the Least Significant Difference (LSD) procedure.

RESULTS AND DISCUSSION

Environmental Conditions

Total precipitation was 630 cm in 1995 at Red Feather Lakes 15.5 km south of the research area (National Climatic Data Center 1998). Soil moisture at Sheep Creek in the summer of 1995 during the trampling treatments was unusually high. Only a limited amount of weather data could be found. However, Peck (1999) reported little correlation between weather patterns and yearly plant cover from 1988 to 1998. Above average precipitation in the years of this study may have helped plant recolinization following the intense trampling.

Cover and Bare Ground

Analysis of variance for differences in plant cover, litter cover, and bare ground for each of the first, second, and sixth year following the trampling disturbance showed that there were no significant differences among the trampling treatments at various seasons for herbaceous cover ($P = 0.49$), litter cover ($P = 0.61$), and bare ground ($P = 0.35$). However, a significant year effect for recovery in herbaceous cover ($P = 0.002$), litter cover ($P = 0.02$), and bare ground ($P = 0.03$) was observed (Appendix Table 1.1). A significant trampling treatment by year interaction was found for herbaceous cover ($P = 0.05$) (Appendix Table 1.1). Greater recovery in herbaceous cover was observed in the fall trampling treatment during the second year after severe trampling in 1995 (Figure 1.1 A) (Table 1.2). However, much of this cover was made up of ruderal weedy forb species that occurred during the first and second years following trampling disturbances such as fireweed (*E. angustifolium*) (2.8% cover), timothy (*Phleum pretense* L.) (2.6% cover) and Kentucky bluegrass (*P. pratensis*) (2.2% cover). Herbaceous cover in the fall trampling treatment was similar to that in controls by the sixth year as grass and forb cover in this treatment had been replaced by cover of the dominant sedge species.

Litter cover increased six years after the trampling disturbance; likely because of the productive dominant sedge and rush species that recolonized the disturbed areas. However, herbaceous plant cover declined somewhat in all trampling treatments by the sixth year as ruderal species had less cover (Figure 1.1 A). Litter cover increased significantly (P = 0.09) for the late spring and early summer trampling treatments by the sixth year of this study (Figure 1.1 B). Again, a significant year by trampling treatment effect was noted for litter cover as litter showed little change in fall trampled plots and in the control plots through the six years (Appendix Table 1.1).

Vegetation cover was expected to be greater for the control sites because these protected sites allowed for abundant plant growth in each year. However, total herbaceous vegetation cover was often similar among trampled and control treatments (Figure 1.1 A). The control treatment did have the least amount of bare ground compared with trampled sites (Figure 1.1 C). The control treatment had little change in herbaceous and litter cover over the six years of study (Figure 1.1 A and B). Shultz and Leininger (1990) found that vegetation cover of all species was greater in long term ungrazed exclosures than in grazed areas. They noticed similar amounts of bare ground, forb cover, and total tree cover in grazed and ungrazed riparian areas. They also noted that ungrazed areas had greater cover of litter, graminoids, and shrub species.

These data suggest that severe trampling might greatly influence plant species composition in the initial years following disturbance. But after six years of recovery, trampling had no lasting effects on cover of plants, litter, and bare ground except that more bare ground was present in areas that had previously been trampled in the early summer two years after trampling, but not six years later (Figure 1.1 C).

Grass and Shrub Cover

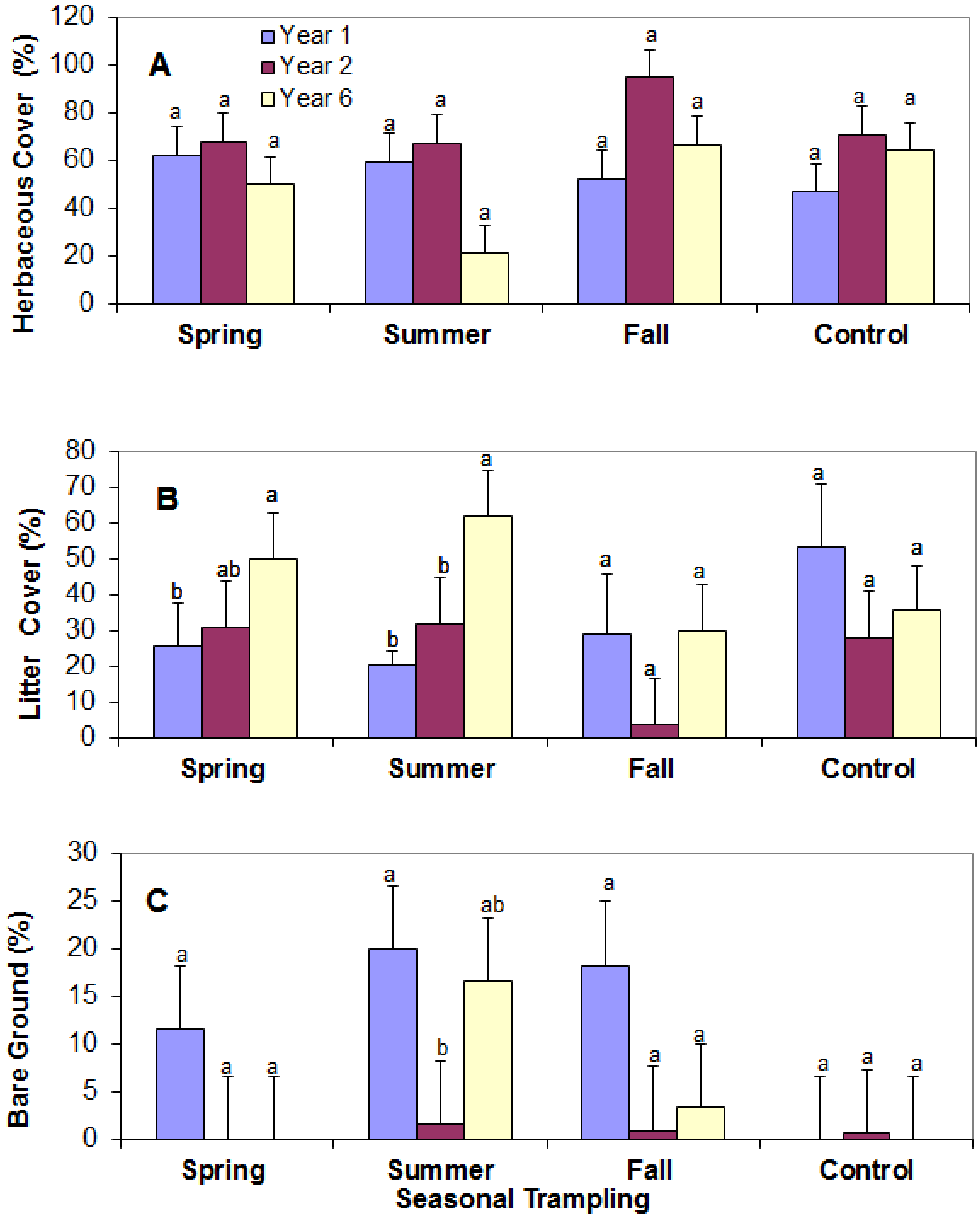


Figure 1.1. One, two, and six years of recovery in herbaceous cover (A), litter cover (B), and bare ground (C) after heavy trampling at three seasons in a montane riparian community. Similar letters above bars within a seasonal trampling treatment represent non-significant differences ($p > 0.10$) in recovery after one, two, and six years after the trampling event. Lines above bars represent 1 SE.

Table 1.2 Means and standard errors for herbaceous cover after heavy trampling at three seasons in a montane riparian community. Cover data were collected in the summer season in years 1, 2, and 6 after trampling. Standard errors are in parentheses and means within a row followed by different letters were significantly different ($p < 0.10$)

	Year 1	Year 2	Year 6
Herbaceous Cover			
Late Spring	62a(1.1)	68a(2.5)	50a(3.4)
Early Summer	60a(2.0)	67a(1.7)	21b(1.3)
Fall	52b(2.6)	95a(0.4)	66b(2.7)
Control	47b(3.9)	71a(4.6)	64a(2.7)
Overall Average	55a	75b	50a

Grass cover was not significantly affected by trampling treatments (P = 0.42) or the interaction between years and trampling treatments (P = 0.48) (Appendix Table 1.2). Grass cover was quite variable through time. Grass species found in the study were: Kentucky bluegrass (*P. pratensis* L.), bluejoint reedgrass (*C. canadensis*), tufted hairgrass (*D. caespitosa*), timothy (*Phleum pratense* L.), redtop (*Agrostis gigantea* Roth), bluegrass (*Poa* sp. L.), and alpine timothy (*Phleum alpinum* L.). Shrub cover was also not significantly affected by trampling treatments (P = 0.28) or the years by trampling treatments interaction (P = 0.76).

<u>Sedge Cover</u>

Sedge cover was not significantly affected by trampling treatments (P = 0.37) nor by year effects (P = 0.11). However, there was a significant year by trampling treatment interaction (P = 0.09) (Appendix Table 1.2). Sedge cover peaked in the late summer treatment in the second year following trampling with an average of 41% cover (Figure 1.2 A). The fall trampled plots also had high sedge cover (26%) two years following disturbance, and cover continued to increase to an average of 36% after six years of recovery. The fall trampled treatment and untrampled treatment showed a trend towards greater sedge cover after six years of recovery.

<u>Forb Cover</u>

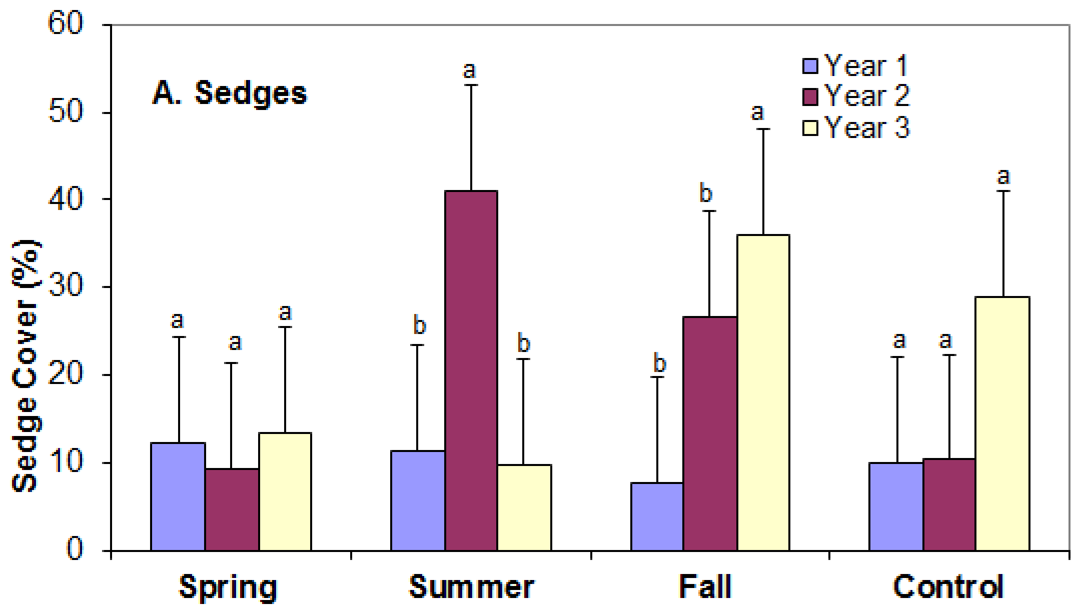
Trampling effects on forb species cover were more pronounced when species were categorized into functional groups (Appendix Tables 1.2 and 1.3). The interaction between trampling treatments and year of recovery significantly affected forb cover (P = 0.03) (Appendix Table 1.2). A significant interaction was also noted between functional groups, years of recovery and trampling treatments that can be attributed to changes in forb cover

(P = 0.07) (Appendix Table 1.3). Forb cover reached an average of 36% in the second year of recovery following trampling in the fall (Figure 1.2 B). Most of this increase in forb cover resulted from an increase in weedy species such as fireweed (*Epilobium angustifolium* L.) (5.7% cover), Canadian thistle (*Cirsium arvense* (L.) Scop.) (4.5% cover), common dandelion (*Taraxacum officinale* F.H. Wigg.) (2.3% cover), and clover (*Trifolium* spp.) (3.7% cover). Most of these species had much lower cover by the sixth year of recovery. Forbs declined somewhat in year six as weedy species were replaced by sedge species in the fall trampling treatment (Figure 1.2A).

Native and Ruderal Species Cover

Native herbaceous cover was slightly reduced by trampling treatments (Appendix Table 1.4 and 1.5) (Figure 1.3 A). Ruderal herbaceous cover was not affected (P = 0.11) by trampling treatments, but there was a small but significant year by treatment effect (P = 0.09) (Figure 1.3 B). Ruderal plant species had a slight trend to increase in early years following trampling. After two years of recovery the highest numerical ruderal species cover was in the fall trampling treatment with an average of 25% cover. After six years of recovery, ruderal species cover was still numerically higher in late spring and fall trampled areas compared to the early summer and control plots.

The native and ruderal forb cover was significantly affected by seasonal trampling treatments and the interaction between years and trampling treatments (Appendix Table 1.6 and 1.7) (Figure 1.4 A and 1.4 B). The fall season trampling treatment had significantly more (P = 0.03) ruderal forb cover in the second year of recovery as compared with the first year of recovery (Figure 1.4 B). Native forb species with the highest cover included: Virginia strawberry (*Fragaria virginiana* Duchesne ssp. *Glauca* (S. Watson) Staudt.)



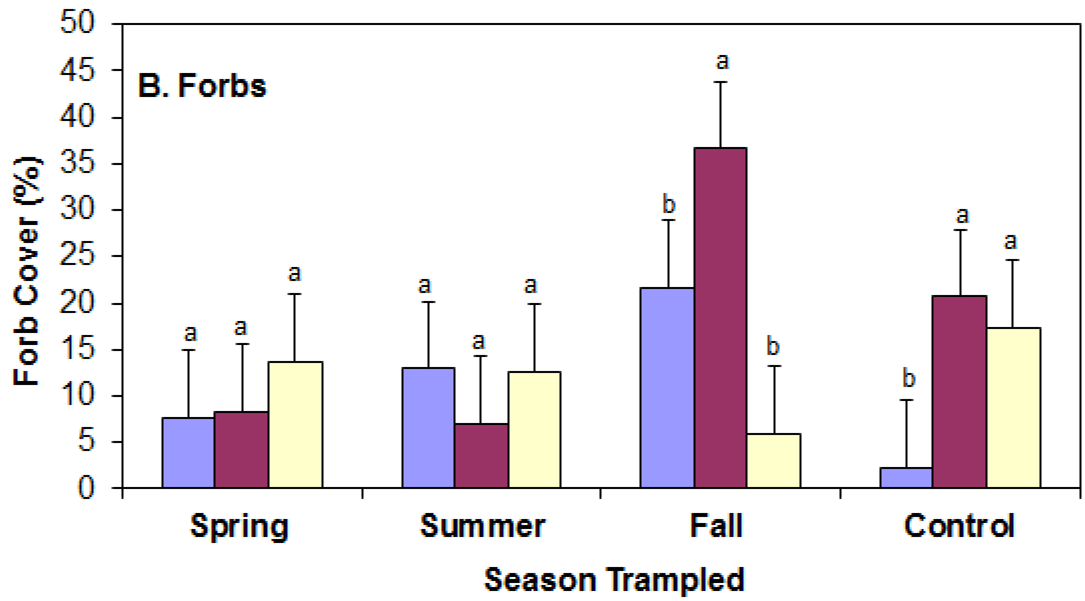


Figure 1.2. Effects of trampling on sedge (A) and forb (B) cover after one, two, and six years of recovery in a montane riparian community. Similar letters above bars within a seasonal trampling treatment represent nonsignificant differences ($p > 0.10$) in recovery after one, two, and six years after the trampling event. Lines above bars represent 1 SE.

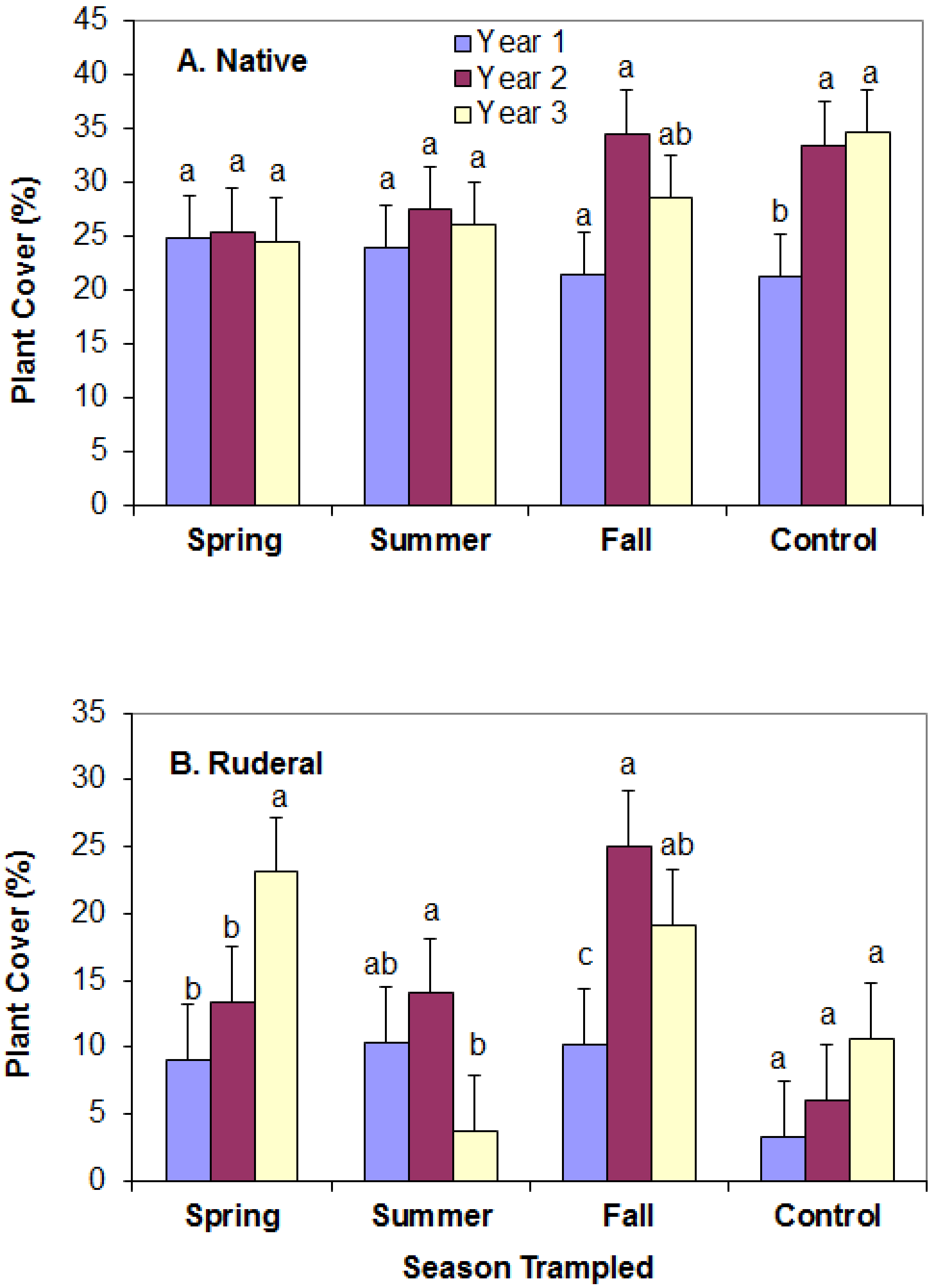


Figure 1.3. One, two, and six years of recovery for native (A) and ruderal (B) cover of all species after heavy trampling at three seasons in a montane riparian community. Similar letters above bars within a seasonal trampling treatment represent non-significant differences ($p > 0.10$) in recovery after one, two, and six years after the trampling event. Lines above bars represent 1 SE.

(7.4% cover), largeleaf avens (*Geum macrophyllum* Willd.) (6.3% cover), and western yarrow (*A. lanulosa*) (5.8% cover).

Native and Introduced Species Cover

Cover of all native species combined was not significantly affected by trampling treatments (i.e. season), however there was a significant year influence on their cover (P = 0.01) (Appendix Table 1.8) (Figure 1.5 A). Native species cover was slightly greater in the second year of recovery than in the first year. The interaction between trampling treatments and year of recovery significantly affected introduced species cover (P= 0.01) (Appendix Table 1.9). Introduced species cover peaked in the late spring trampling treatment in the sixth year of recovery with an average of 34% cover (Figure 1.5 B). The fall trampled treatment also had an increase in introduced species cover during the second and sixth year of recovery compared to year one. Introduced species with the highest cover included: Kentucky bluegrass (*P. pratensis*) (9.0% cover) and common dandelion (*T. officinale*) (5.2% cover). The late summer trampling treatment had the least numerical cover of introduced species after six years of recovery.

Native and Introduced Forbs

Native forbs

The interaction of trampling treatments by year of recovery significantly affected native forb cover (P = 0.06) (Appendix 1.10). After two years of recovery, native forb cover peaked in the fall trampled treatment (Figure 1.6 A). However after six year of recovery following trampling most seasonal treatments showed a decline in native forb cover while cover of native forbs in the control was unchanged. The greatest decline in native forb cover occurred in the fall trampled treatment. The following species contributed the most to

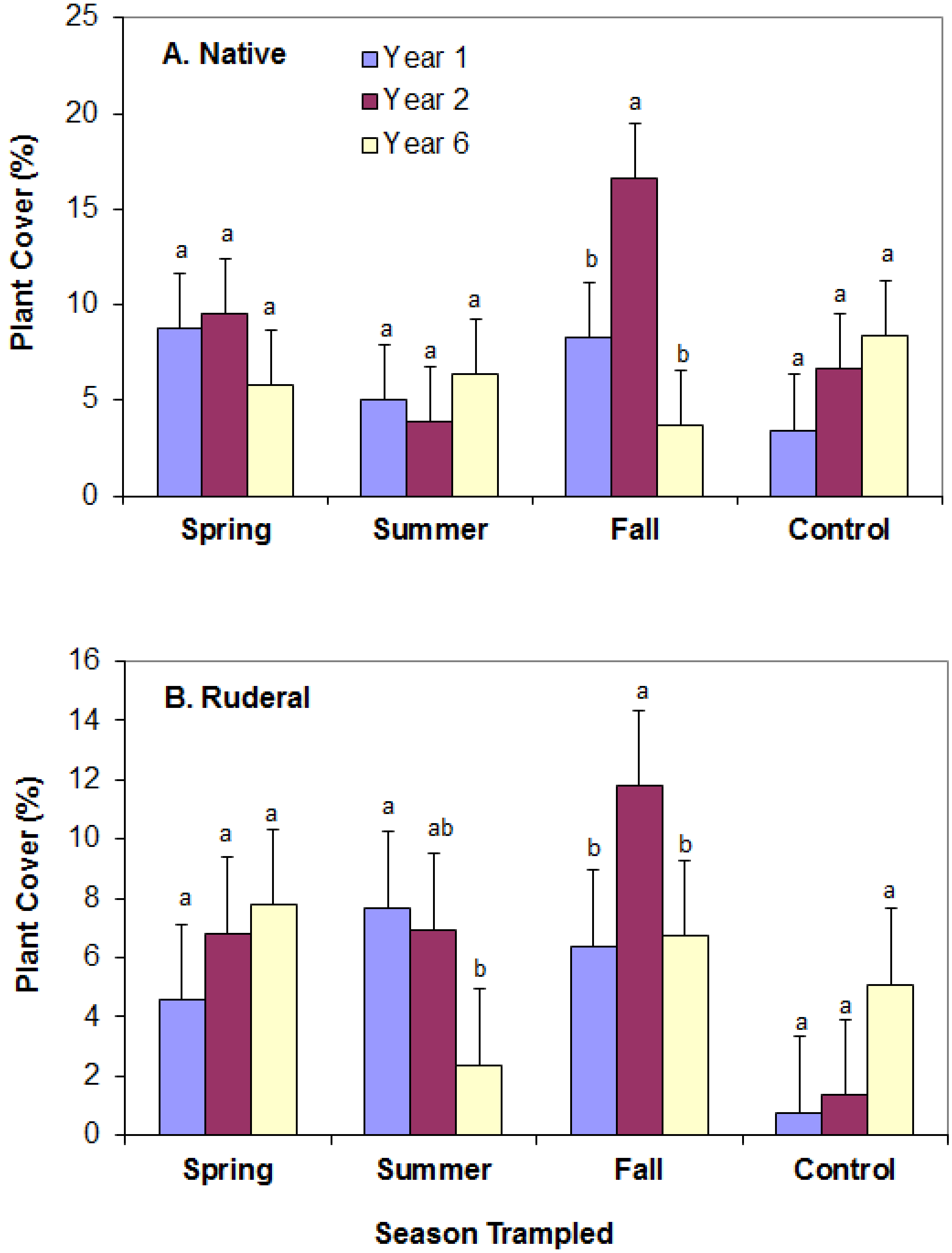


Figure 1.4. One, two, and six years of recovery for native (A) and ruderal (B) forb cover after heavy trampling at three seasons in a montane riparian community. Similar letters above bars within a seasonal trampling treatment represent non-significant differences (p > 0.10) in recovery after one, two, and six years after the trampling event. Lines above bars represent 1 SE.

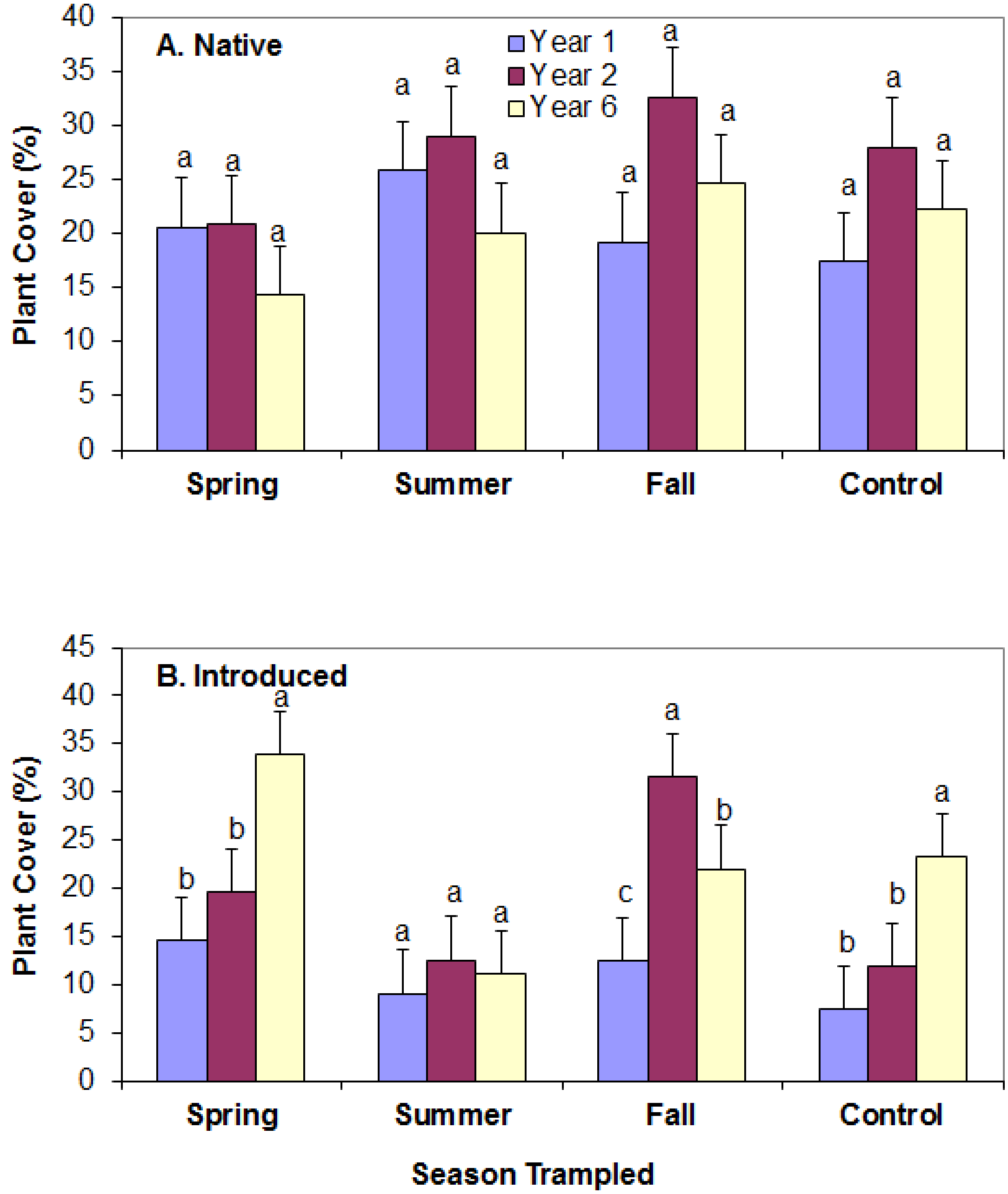


Figure 1.5. One, two, and six years of recovery for cover of native (A) and introduced (B) species after heavy trampling at three seasons in a montane riparian community. Similar letters above bars within a seasonal trampling treatment represent non-significant differences ($p > 0.10$) in recovery after one, two, and six years after the trampling event. Lines above bars represent 1 SE.

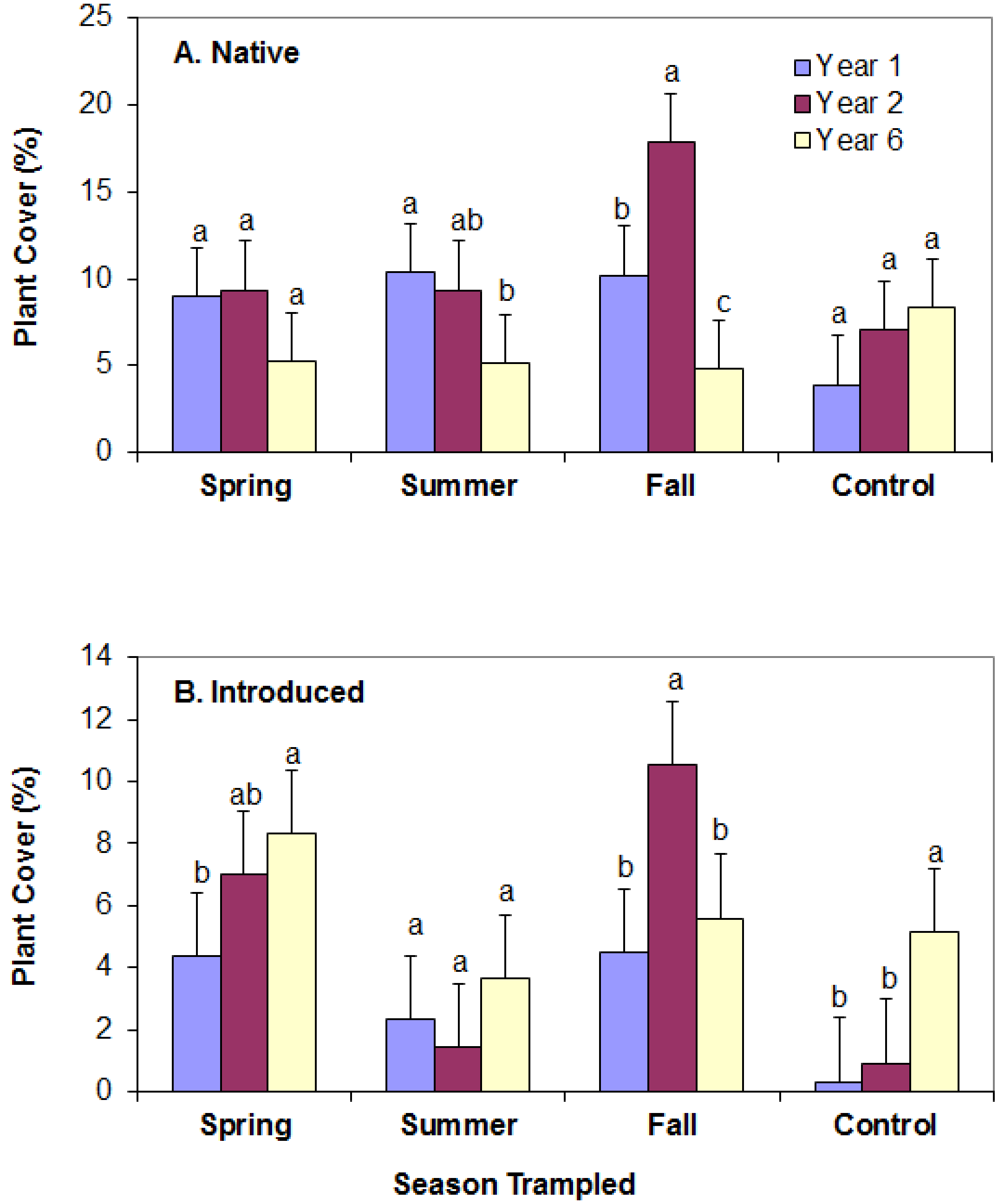


Figure 1.6. One, two, and six years of recovery in cover for native (A), and introduced (B) forbs after heavy trampling at three seasons in a montane riparian community. Similar letters above bars within a seasonal trampling treatment represent non-significant differences ($p > 0.10$) in recovery after one, two, and six years after the trampling event. Lines above bars represent 1 SE.

the cover of native forb species: fireweed (*E. angustifolium*) (5.7% cover), western yarrow (*A. lanulosa*) (3.2% cover), and horsetail (*Equisetum arvense* L.) (2.3% cover). Native forb cover decreased about 46% between year 2 and 6 in the recovery process after trampling, while introduced forbs increased somewhat.

Introduced Forbs

Introduced forb species showed an insignificant interaction between trampling and year of recovery (P = 0.11), but yearly changes were significant (P < 0.04) (Appendix 1.11). Introduced forb cover was greatest in the late spring trampled plots during year six, whereas plots trampled in the fall had greatest introduced forb cover in year two (Figure 1.6 B). The spring trampling treatment resulted in a steady increase of introduced forbs over the six years of recovery. The following species contributed the greatest amount to introduced forb cover: common dandelion (*T. officinale*) (5.2% cover), thistle (*Cirsium* spp.) (4.5% cover), and clover (*Trifolium* spp.) (3.8% cover). Introduced forbs also increased over the six year period in control plots.

Species Richness

There was a significant season of trampling by year interaction (P = 0.03) that affected species richness (Appendix Table 1.12) (Figure 1.7). The disturbances caused a numerical increase in species numbers the first (7.6 species) and second (10.6 species) years after trampling in fall trampled plots, as weedy annual species invaded these plots. All other treatments, including the control showed no significant changes in species richness in the first and second years after the severe disturbance. Although not significant as a treatment (P = 0.13), it was anticipated that richness would be greater in trampled areas than in untrampled control sites because of the decrease in competition from previously established plants on the trampled sites, addition of nutrients in manure, and invasion by ruderal species (Liddle 1975, McIntyre and Lavorel 1994, Tilman 1996, Palmer and Maurer 1997, Wiser et al. 1998, Meiners et al. 2002).

Belsky et al. (1999) in a review indicated that grazing effects on riparian areas resulted in increased species richness and diversity as a result of an influx of exotic species. However in this present study, only areas disturbed in the fall had numerically higher species richness caused by ruderals such as fireweed, Canadian thistle, dandelion and clover compared with undisturbed control sites (Figure 1.7). Areas disturbed in the fall may have had more openings for colonization for invading species during the first spring, but the season of trampling effects were not significant ($P = 0.24$). If this had occurred, then there may have been long term detrimental effects on the ecosystem (Kauffman et al. 1983, Perry et al. 2004, Parker et al. 2006, Tyler et al. 2007, Matthews et al. 2009). Green and Kauffman (1995) recorded substantially greater species richness (number of species in a region, site, or sample) in grazed areas compared with exclosures in both moist and dry riparian meadows in northeastern Oregon.

The present study showed lower species richness in control plots as compared with trampled plots during most years after disturbance (Figure 1.7). However, species richness in late summer and fall trampled plots had declined numerically after six years of recovery to levels near that of control plots. Peck (1999) observed that species richness was highest for total understory species, forbs, and exotic species in long-term grazed areas compared with three other grazing and protected treatments. She also found that forb richness averaged 62% of the total understory richness measured on four different grazing treatments at Sheep Creek. Based on these studies it may be possible to manipulate species

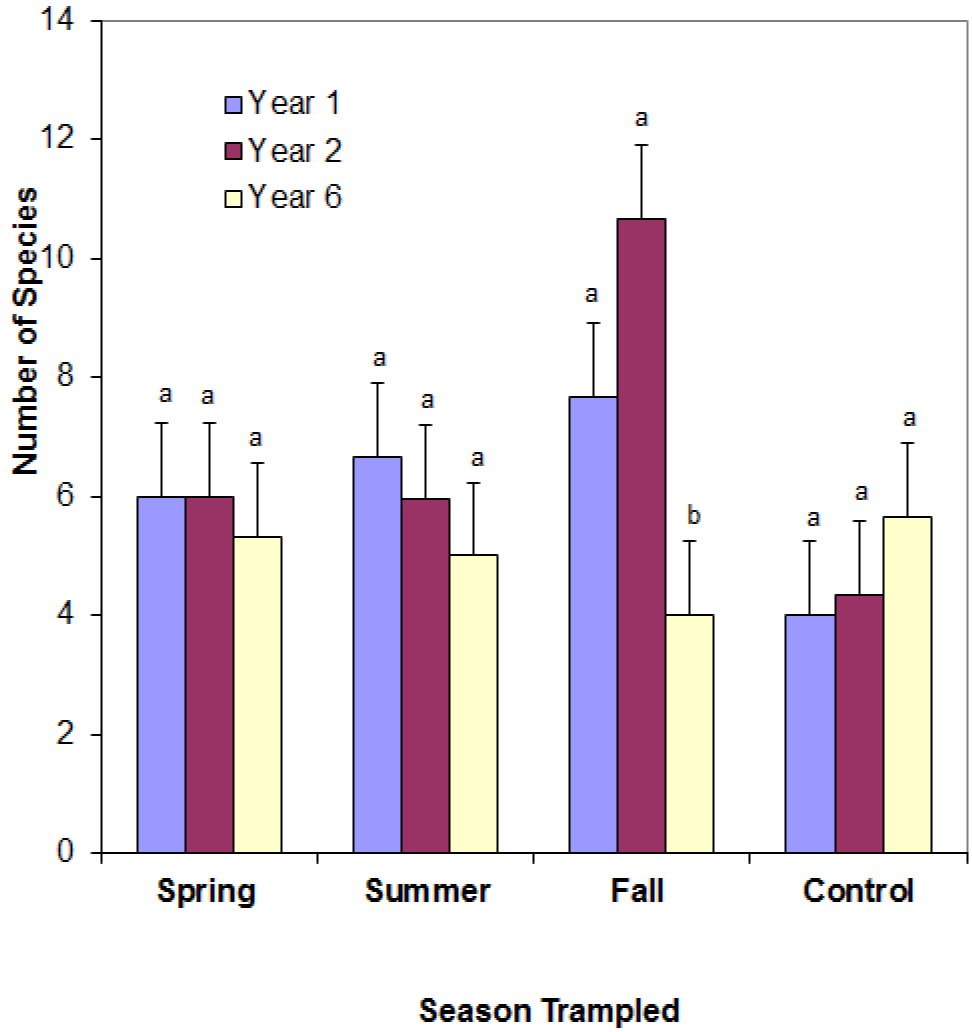


Figure 1.7. Species richness in seasonal trampling treatments after one, two and six years of recovery following disturbance. Species richness was calculated as the average number of species within each of the treatment plots. Similar letters above a seasonal treatment represent nonsignificant differences ($p > 0.10$) in recovery after one, two, and six years after seasonal trampling events. Lines above bars represent 1 SE.

populations through seasonal disturbance to encourage greater species diversity.

Willow Cuttings

Some willow cuttings may have been strongly affected by the seasonal trampling treatments and the severe disturbance to the soil (Appendix Tables 1.13 and 1.14). Cuttings of the two willow species had differing growth and survival during the six years of recovery. Mountain willow had about six times greater percent survival as that of planeleaf willow (Figure 1.8). Seasonal effects of trampling were usually not significant for either number of willow shoots (P = 0.11) or survival (P = 0.13) for planeleaf willow, but mountain willow cuttings were positively affected by previous trampled treatments (Figure 1.8) (Appendix Table 1.13). The season of trampling by willow species interaction significantly (P = 0.01) showed the number of living stems from willow cuttings differed (Appendix Table 1.13 and 1.14). Mountain willow cuttings had six times greater survival than did planeleaf willow cuttings after six years of recovery through time except in the fall trampling treatment where there was little mortality through time (Figure 1.8 and 1.9). Almost all of the mountain willow cuttings showed increasing mortality through time (Figure 1.8 A). There were no yearly differences in survival of planeleaf willow cuttings and few of the cuttings survived six years after planting (Figure 1.8 B).

The average number of surviving cuttings for mountain willow, excluding the fall treatment, was 26%. After six years of recovery, mountain willow stakes in the fall trampling treatment had an average of 45% surviving willow cuttings (Figure 1.8 A). The steady decline of living willow cuttings in all treatments might be attributed to unsuccessful establishment resulting from depth to water table, disease or insect effects, and competition with herbaceous species.

Mountain willow also had a much greater number of living stems than did planeleaf willow after the first year of recovery following trampling however both species had reduced stem numbers on cuttings after the first year of recovery following trampling (Figure 1.9). A steady decline occurred for both species in the years following the initial trampling disturbance, except in the fall trampling treatment where mountain willow had little mortality throughout the six years of study. Low water table levels at the research site may have contributed to the high mortality rates of both willow species. On average, all trampled areas had depths to water around 40 to 90 cm deep. It is unclear how much depth to water played a factor for willow survival as wells were neither established for each treatment and replication nor monitored throughout years data was collected. The initial trampling combined nutrients, urine, and manure with soil that may have facilitated willow establishment. However, in the second through the sixth year following trampling the depth to the water table may have contributed to the steep decline in willow survival for both species (Figure 1.8 and 1.9). Both species had very low numbers of living willow shoots by the end of the study (Figure 1.9), possibly because of low (below a 40 cm depth) water table levels and competition with herbaceous species.

It is unclear if willow cuttings planted in trampled areas had a greater rates of initial survival and greater numbers of stems than did those planted in undisturbed controls sites (Figures 1.8 and 1.9). Competition from established vegetation for water, nutrients, and space on the undisturbed sites may have reduced growth of planted willow cuttings in the control treatment. Hussian and Trlica (1995) noticed that growth of willow shoots declined substantially when water stress was imposed. They stated that propagation of riparian willows from stem cuttings could best be achieved in a moist natural soil. Without having a

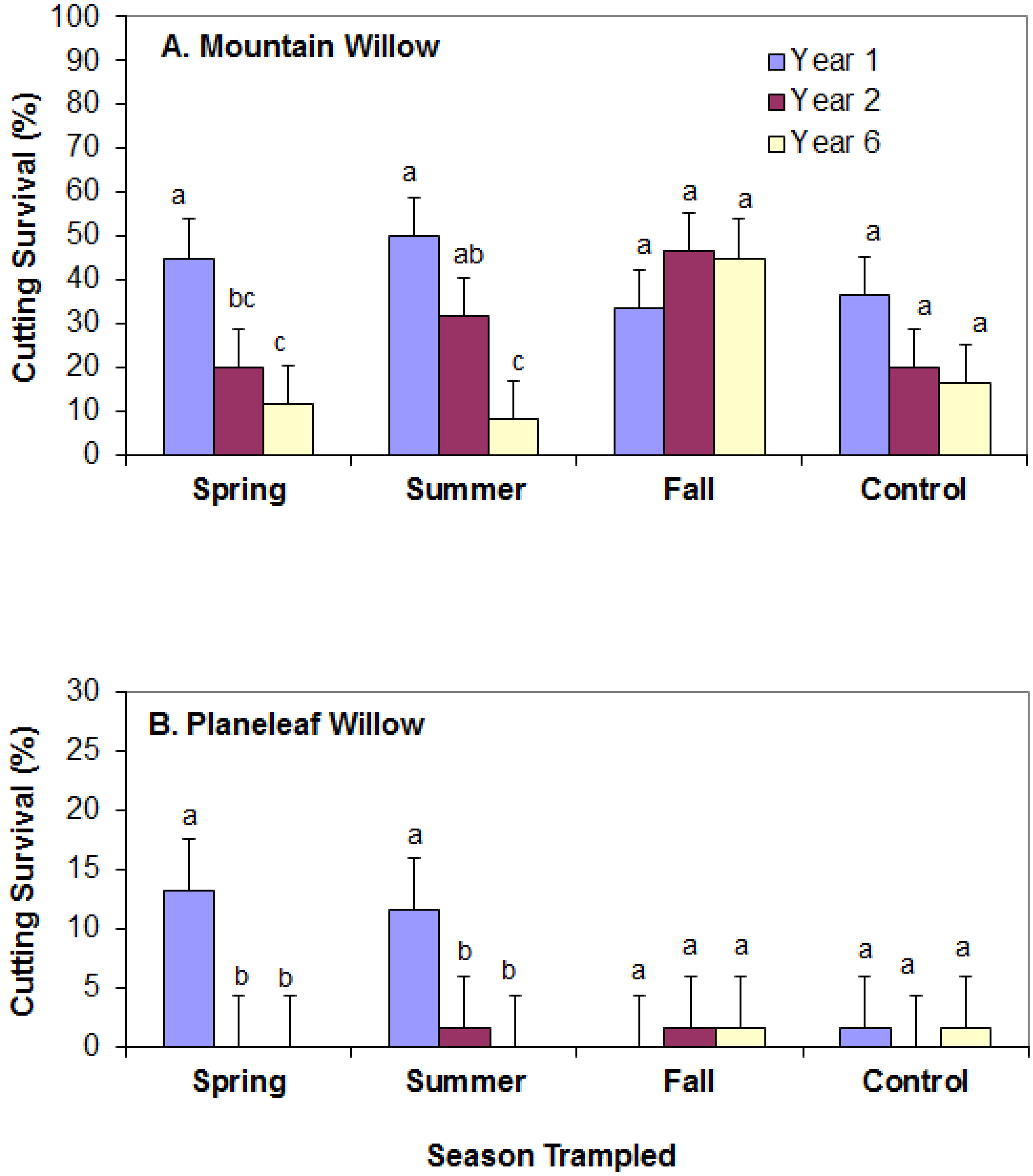


Figure 1.8. Survival of willow cuttings for mountain willow (A) and planeleaf willow (B) after one, two, and six years of recovery in a montane riparian community following severe trampling disturbance. Similar letters above bars within a seasonal trampling treatment represent nonsignificant differences ($P > 0.10$) in recovery after one, two, and six years following the trampling event. Lines above bars represent 1 SE.

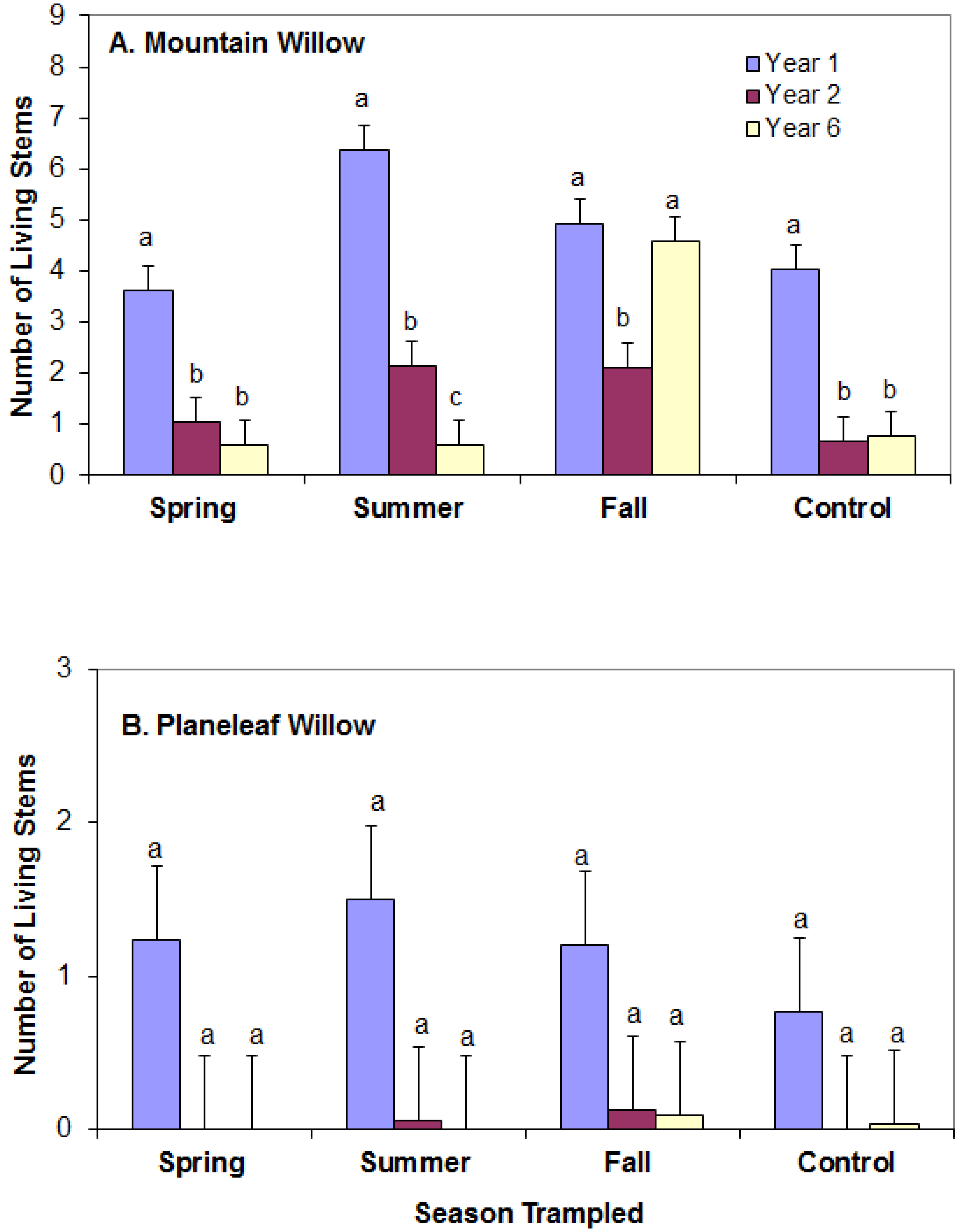


Figure 1.9. Number of shoots for willow cuttings of mountain willow (A) and planeleaf willow (B) after one, two, and six years of recovery following severe trampling disturbances in a montane riparian community. Similar letters above bars within a seasonal trampling treatment represent nonsignificant differences (P > 0.10) in recovery one, two, and six years after the trampling event. Lines above the bars represent 1 SE.

more substantiated water depth data, it is uncertain how much of an effect trampling had on willow stake survival and stem growth.

Mountain willow had greater survival and stem growth compared to planeleaf willow. Hussian and Trlica (1995) reported similar results with mountain willow having greater survival than planeleaf willow. In this present study, only the fall trampling treatment resulted in consistently greater establishment of mountain willow cuttings (Figure 1.8 B and 1.9 B). The areas trampled in the fall may have had less competition with native species during the first year of recovery compared with other seasonal treatments. However, without more in depth monitoring of the water table, seasonal hydrology and site conditions, it is uncertain if fall treatments had greater survival than other trampled treatments. Depth to water table may have been a factor improving the survival of the willows in the fall treatments. Without having established and monitored water table depths near treatments throughout the study it is unclear how much the season of trampling or plot water table depth affected willow stake survival and growth. These factors probably contributed to greater survival of mountain willow in the fall trampled treatments. The limited success of planeleaf willow cuttings might be associated with its transplant ability, deep water table depths, and poor growing conditions.

Competition between willow cuttings and herbaceous plants for water and nutrients may have negatively impacted the survival of willow cuttings. Comparing the willow cuttings survival with herbaceous cover indicated that, by the second year of recovery from trampling, herbaceous plant cover was at its greatest level. This and other factors may have led to the decline of many of the willow cuttings. The fall trampling treatment had the greatest increase in vegetation cover during the second year after trampling (Figure 1.1 A) and the number of new willow shoots declined (Figure 1.9). This dynamic change was also evident in the decrease of bare ground (Figure 1.1C). The areas of bare ground became less as herbaceous cover increased and herbaceous species may have competed effectively with the willow cuttings for soil water, nutrients, and space. This competition for resources may have contributed to the decline of willow cuttings.

CONCLUSIONS

This study showed that a montane riparian community could recover quickly after a severe trampling disturbance. This disturbance pulse may have allowed for a limited successful transplant and establishment of mountain willow cuttings. The majority of willow cuttings did poorly, but of the ones that did become established, mountain willow did better than planeleaf willow and particularly when planted into an area that had been disturbed the previous fall. Weedy annual forbs flourished in the first and second years following the disturbance. The weedy community had declined after six years of recovery and the dominant sedge community had returned. However, disturbance related changes in community composition had some lasting effects, such as greater introduced species composition that were still evident after six years of recovery.

The first hypothesis was that vegetation in the fall trampling treatment would have the greatest recovery within six years compared with late spring and early summer trampling treatments. The season of trampling disturbance had significant effects on herbaceous species composition and rate of recovery. Differences in recovery for the various seasonal trampling treatments were not entirely clear. The greatest short-term recovery of herbaceous cover and native species following the trampling disturbance was noted in the fall trampled treatment (Figure 1.2 B and 1.4 A). Therefore the first hypothesis was accepted.

The quick rebound of this riparian plant community from severe trampling disturbance resulted in minimal sustained damage. The severe disturbance probably increased resource availability, but left the trampled areas susceptible to invasion by weedy species. The ruderal species that increased in cover the first two years after disturbance were not permanent and were soon replaced by the native plant community composition. Only the late spring trampled treatment responded differently. The late spring trampled treatment retained 23% cover composition of ruderal species even after six years of recovery following trampling (Figure 1.3 B). The late spring trampling treatment resulted in 2.5 times greater ruderal species composition over the course of six years following the initial trampling disturbance. Ruderal species often do well when nutrient availability is high. Initially native and ruderal forbs had the greatest cover in the fall trampled treatments. With probable depletion of excess nutrients through time, both groups of forbs declined greatly. After six years of recovery, cover of the native plant community had regained dominance with a plant composition consisting primarily of native grasses and sedges.

Species composition was also altered significantly by the effects of trampling. Following the trampling events, the existing plant community composition was altered by an increase in forb cover. Liddle et al. (1975) found that an intermediate level of trampling was most effective in maintaining high species diversity by suppressing the more competitive dominant species. This resilience of riparian species to reoccupy the site quickly may be attributed to the fertility of the soils found at these sites, as well as the adaptation of grasses and sedges to tillering and rhizome establishment from asexual reproduction.

The second hypothesis of this study was that willow cuttings planted in disturbed areas would have greater survival and growth rates for both species than those planted in undisturbed control areas. Overall, willow cuttings probably did poorly in all treatments primarily because of inadequate growing conditions and a low water table. Successful transplanting of willows depends on roots reaching the water table and little competition with other plants for light, space, and nutrients (Patterson et al. 1981, Monsen 1983, Platts et al. 1983, Karrenberg et al. 2002, Schaff et al. 2002 and 2003, Gage and Cooper 2004, Woods and Cooper 2005, Pezeshki et al. 2007). Conroy and Svejcar (1991) reported that planting location was the best indicator of survival for cuttings of Geyer willow (*Salix geyeriana*). They noted that the highest survival of willow cuttings (73%) occurred in areas with the shallowest water table (27 cm). Conroy and Svejcar also noted that of the community types studied, willows planted into a Nebraska sedge / Nevada rush community had the greatest willow survival (68%), followed by a bare ground community (37%), and finally a tufted hairgrass / Nebraska sedge community type (34%). Eckert (1975) found 90% survival for willow cuttings planted in soils with water table depths of 30-90 cm and no survival in areas with a 180 cm deep water table. In the present study the average depth to water table was 70 cm in 2002 but varied greatly across treatment plot replications. This is a fairly deep depth to the water table for roots of some species to reach within a growing season and may account for much of the high mortality of willow cuttings.

Mountain willow in this study had greater survival and stem growth compared to planeleaf willow. Planeleaf willow probably did very poorly because of a combination of low water tables in the plots, competition with herbaceous plants in the immediate area, and poor transplantability. Mountain willow apparently can tolerate lower water table depths and some competition from surrounding herbaceous plants.

These results remain unclear if the fall trampled treatment can show greater willow cutting survival and growth even after six years of recovery following a severe trampling disturbance. Areas trampled in the fall season appeared to have created good growing conditions for mountain willow cuttings, but without more consistent monitoring of the water table depth from the onset of the project, results remain unclear.

Willow cuttings planted in trampled areas had greater success in growth of stems compared with those planted in undisturbed control sites. Initially, both species of willow cuttings planted in control sites did fairly well for the first growing season. After two growing seasons the effects of competition for space, water, and nutrients, and possibly the inability of sufficient roots to reach the water table, was evident in untrampled control sites as a severe decline occurred in both willow species survival and growth. After six years of recovery it was clear that untrampled control plots had willow survival comparable with trampled sites, except that areas trampled in the fall had the highest levels of survival of mountain willow. Based on the success of mountain willow cuttings on fall trampled sites, I accepted the hypothesis that trampled sites may have had some advantage for supplying willow cutting conditions needed for initial growth and survival.

Future Considerations

This study added to the small body of literature pertaining to recovery of riparian vegetation after a severe disturbance. The herbaceous community composition was very similar to control sites after six years of recovery. This is a rapid rate of community recovery following a severe disturbance.

One of the aspects that this study has shown is the importance of the seasonal use of riparian areas. Krueger (1996) mentioned that the season of grazing was more important than the intensity of grazing for riparian species. Other studies indicate that the timing of trampling did not have a consistent response on vegetation cover (Torn 2006). This study indicated that timing of a disturbance event could have a substantial effect on the composition of species and growth of willow cuttings during site recovery after a disturbance. However, more knowledge is needed to find growing conditions needed for willow cutting survival in montane riparian communities.

Based on the success of fall trampling and forb recruitment, further studies might investigate other plant community disturbances. Altering the current dominant plant communities might help diversify plant communities. Disturbances might offer greater opportunities to recruit willow and other riparian plant species. Caution, however, should be used in this approach as undesirable ruderal species might be a large component of the initially disturbed plant community. The presence of ruderal species may be an indication of earlier seed depositions which were dormant or suppressed by longer-lived more competitive native species (Richter and Stromberg 2004). Also plant morphology and growth rate characteristics help determine the rates of recovery and species composition (Whinam and Chilcott 2003).

Disturbance history may also be a factor as the legacy of past disturbances can influence the visibility of the riparian community patches to potential colonization of undesirable plants (Renne and Tracy 2007). Disturbance induced events may have to be on a larger and more persistent scale to alter riparian plant communities. Altering the local communities could eventually shift the dominance of colonization to favor new local populations. Persistent plant communities may need to be modified beyond a threshold that creates habitats that will favor a different plant community (Jakalaniemi et. al. 2005, Andres-abellan et al 2006).

Riparian community's species may be influenced more by edaphic conditions such as water table depth rather than influenced by species competition, trampling or grazing. Although other studies indicate Kentucky bluegrass was capable of recolonizing at comparable water tables levels, this study did not indicate an increase in herbaceous cover likely resulting from an intolerance of a seasonally low water table (Martin and Chambers 2001a, 2001b, 2002; Kluse and Diaz 2005). The dominant grasses in the surrounding areas may be incapable of recolonizing small disturbed areas because of limitation on reproductive methods or anaerobic soil conditions found in sedge/rush dominated community.

It is important to know which willow species are better adapted for transplanting, the growing conditions needed for these species, and competitive relations between willows and herbaceous species. Results of this study indicate that a disturbance in the fall season may facilitate mountain willow establishment from cuttings in disturbed riparian soils. Roots of willow cuttings must be able to reach the water table if the transplants are to survive. High levels of competition for available resources with ruderal species during the first two years following trampling may have contributed to the decline in survival of willow cuttings as well. Certain willow species can thrive in a community dominated by sedge species (Geyer willow) (Conroy and Svejcar 1991). Knowing this tolerance level is important to have successful willow establishment. Also using prerooted willow states could improve willow survival given an adequate water table depth (Schaff et al. 2002, Gage and Cooper 2004). Litter accumulations could also potentially suppress the dominant riparian grass/sedge community and allow for successful willow establishment (Xiong et al. 2001, Renofalt and Nilsson 2008). Future studies might incorporate additional disturbances such as fire, litter, herbicides, or mechanical treatments around the planting areas of willow cuttings to provide less competition for available resources and greater survival of willow cuttings.

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CHAPTER II

SOIL SHEAR RESISTANCE STUDY

CHAPTER SUMMARY

Although riparian vegetation is considered useful to increase streambank stability, species differences have rarely been quantified. Three grasses (*Poa pratensis*, *Calamagrostis canadensis*, *Deschampsia caespitosa*), a rush (*Juncus arcticus*), and two sedges (*Carex aquatilis*, *Carex nebraskensis*), were sampled at two soil depths (0 to 10 cm and 10 to 20 cm) in a montane riparian community to determine shear resistance as a measure of soil strength. Covariate analysis was used to compare shear resistance with bulk density, texture, belowground biomass, and organic matter content. Vegetated areas had a threefold greater shear resistance compared with unvegetated areas in the top 0 to 10 cm of soil. Sedges and a rush had greater shear resistance than grasses in the top 10 cm soil layer ($P < 0.0001$). Sedges had three times greater sheer resistance in the top 10 cm soil cores compared to the 10 to 20 cm soil depth. Covariate analysis revealed that shear resistance was affected primarily by belowground biomass; more roots and rhizomes resulted in greater sheer resistance.

INTRODUCTION

Soil and stream bank erosion is a growing concern in many western riparian areas. Previous reports express a need for restoration projects for degraded riparian communities (Elmore and Beschta 1987, GAO 1988). The associated functions of degraded riparian areas can be mitigated firstly by improving ground cover which then improves the associated water holding capability of the soil (Kauffman and Krueger 1984). Riparian areas are also the last terrestrial filter zone before water enters the aquatic phase. Filtering of sediments and nutrients helps to maintain a healthy riparian community and stream water quality (Pearce et al. 1997, 1998, Trlica et al. 2000). An understanding of factors such as rooting habits and belowground biomass of plants as they affect soil stability should provide for enlightened streambank erosion management of riparian areas.

Plants have long been associated with stabilization of slopes and reduction in soil erosion, but little is known about how actual root structure of montane riparian plant species affectthe stability of riparian streambanks (Jolley et al. 2001, Jolley 2006). It has generally been observed that an inverse relationship occurs between plant root abundance and bank erosion rate and that plant roots can be critical in stabilizing channel banks of rivers (Smith 1976), overall soil cohesion (Norris 2005, Pollen and Simon 2005), and reducing topsoil erosion (De Baets et al. 2006, Gyssels et al. 2006, Wynn and Mostaghimi 2006, Knapen et al. 2007). Conclusions from research of vegetation removal effects on soil slide frequency (Bishop and Stevens 1964, Corbett and Rice 1966, Gray 1977, Rice et al. 1969, Rice and Krammes 1970, Pollen 2007, Schwarz et al. 2009, Comino and Duretta 2010, Camino et al. 2010, Schwarz et al. 2010), engineering analyses (Brown and Sheu 1975), and laboratory strength measurements of rooted soils (Endo and Tsuruta 1969, Waldron 1977, Waldron and Dakessian 1981, Mickovski et al. 2009, Fan and Su 2008, Lodes et al. 2010) indicate that plant roots significantly increase the stability of soil on slopes. De Baets (2007 and 2008) indicated the potential of shear strength of various grass, trees and shrubs growing in the Mediterranean. Consequently when vegetation is removed, increased slide frequency occurs after a lag time in which existing plant roots in the soil profile decay (Rice et al. 1969). However, little or no research has been done to determine shear resistance for strength of plant roots of individual species within the soil profile.

Previous research using shear resistance has indicated a need to further our understanding of the mechanical and physical capabilities of soil-plant root matrices (Endo and Tsuruta 1969, Brown and Sheu 1975, Jolley 2006). Research has shown the capability of alder trees (*Alnus glutinosa* (L.) Gaertn.) (Endo and Tsuruta 1969), barley (*Hordeum vulgare* L.), alfalfa (*Medicago sativa* L.) (Manbeian 1973), western yellow pine (*Pinus ponderosa* Laws. var. *scopulorum* Engelm.) (Waldron and Dakessian 1982), hardinggrass (*Phalaris tuberosa* L.), Wimmera 62 ryegrass (*Lolium rigidium* Gaudin), orchardgrass (*Dactylis glomerata* L.), Blando brome (*Bromus mollis* L.), greenleaf sudangrass (*Sorghum bicolor* L. Moench var. *sudanense*), Anza wheat (*Triticum aestivum* cv. Anza), Topar intermediate wheatgrass (*Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey), lana vetch (*Vicia dasycarpa* Tenore.), and coast live oak (*Quercus agrifolia* Nee) (Waldron and Dakessian 1981) to increase the shear resistance of the soil through the mechanical reinforcement capabilities of plant roots.

Goldsmith (1998) studied the effective rooting strength of black willow (*Salix nigra* Marsh.), tussock sedge (*Carex stricta* Lam.), switch grass (Panicum virgatum L.), and cottonwood (*Populus deltoides* Bartr. ex Marsh.). She noted that switchgrass roots increased the shear resistance to 31.2 kPa compared to 6.6 kPa for unvegetated soils displaced at 7 cm. Relative shear strength for the species at the same depth (7 cm) was 472% for switchgrass, 445% for black willow, 262% for tussock sedge, and 216% for cottonwood. The rooting strength of these species resulted in a five-fold increase of shear resistance over unvegetated soils. Goldsmith (1998) reported that grass community soil shear resistance was great compared with other vegetation types. This study also clearly showed that rooting resistance for vegetated soils versus unvegetated soils results in a greater soil stabilizing capability with vegetated communities.

The objective of this present study was to determine the ability of several riparian grass, sedge, and rush species to enhance soil stability on streambanks susceptible to bank erosion and sloughing. The soil shear resistance beneath three riparian grasses and three grass-like species were determined. These data were compared with unvegetated disturbed interspace sites nearby. This research effort was further designed to increase our understanding of species characteristics that enhance streambank soil stability so managers might utilize this information when implementing restoration projects in similar areas.

Hypotheses:

H_1: Riparian grasses, sedges, and a rush would provide greater surface soil shear resistance than was found in unvegetated areas.

H_2: Sedges and a rush would provide greater soil shear resistance than grasses, because of the large roots and rhizomatous nature of these former species.

MATERIALS AND METHODS

Site Location and Description

The Sheep Creek study area is located 80 km northwest of Fort Collins, Colorado, in the Roosevelt National Forest. The elevation of this study site is approximately 2500 m, and is located lat 40º 56’46’’N and long 105º39’55’’W. The major soil series in the study area is a

Fluvaquent, characterized with flood plains, low terraces and bottom lands. Texture of the surface and underlying soil layers is extremely variable as a result of repeated flooding and ranges from sandy loam to clay loam. The soil profile is commonly stratified with thin layers of sand or clay. The sedge riparian communities found in this area often have a thick organic peat layer about 20 cm thick (Wheeler et al. 2002).

The dominant woody species found in the Sheep Creek riparian area include planeleaf willow(*Salix planifolia* Pursh) and mountain willow (*S. montichola* Bebb). Other willow species found in the area include Geyer's willow (*S. geyeriana* Anderss.) and narrowleaf willow (*S. exigua* Nutt.). Another commonly found shrub species is shrubby cinquefoil (*Dasiphora fruiticosa* (L) Rydb.). The herbaceous understory found in the area includes water sedge (*Carex aquatilis* Wahl.), Nebraska sedge (*C. nebraskensis* Dewey), beaked sedge (*C. utriculata* Boott), Kentucky bluegrass (*Poa pratensis* L.), bluejoint reedgrass (*Calamagrostis canadensis* (Michx.) P. Beauv.), tufted hairgrass (*Deschampsia caespitosa* (L.) P. Beauv.), mountain rush (*Juncus arcticus* Willd.), western yarrow (*Achillea lanulosa* Nutt.), white and red clover (*Trifolium repens* L. and *T. pratense* L.) and dandelion (*Taraxacum officinale* Wiggers) (Schulz and Leininger 1990, Popolizio et al. 1994).

Sampling Procedures

Cylindrical soil cores 5 cm in diameter and 20 cm long were collected from plant-soil matrix in Sheep Creek riparian exclosures in the summer, 2002. The cores were collected from dense populations of grass and sedge along the banks of Sheep Creek that had been protected from livestock grazing for more than 40 years. The unvegetated bare soil samples were taken in the interspaces of vegetated areas. These control samples were taken from areas that had little or no vegetation. Two important Carex and one Juncus species were chosen for sampling and included water sedge, Nebraska sedge, and mountain rush. The three grasses chosen were tufted hairgrass, Kentucky bluegrass and bluejoint reedgrass. Fifteen soil cores were collected for each grass, sedge, and rush species included in the study. In addition, 15 cores were taken in interspaces between living vegetation. Each core was subdivided into two soil depths (0 to 10 cm and 10 to 20 cm). Two additional core samples were taken adjacent to each grass, rush, and sedge, and in control areas, for bulk density and soil texture determinations.

Soil cores were hammered 20 cm into each plant crown and soil. The plant-soil core was extracted, placed in a cooler, and transported to a lab at Colorado State University (CSU). The top and bottom 10 cm segments of each core were separated in the lab before applying a shear force to each 10 cm core segment. These core samples provided a shearing area large enough to compare size and mass of plant belowground organs with sheer resistance data for each core segment.

A measured shear force was applied to the side of a cylinder until the subdivided cylinder failed at the 5 cm double ring metal core (Figure 1). A titanium steel plate was secured on the top of the shearing cylinder to keep the soil volume in each core the same during sampling of shear force needed for core failures. Pressure at a constant rate was applied onto a pin that pushed on the top 5 cm plate, until the core sheared. Shear force to failure should be directly related to soil resistance and plant species characteristics (Jolley 2006).

Belowground biomass for each sampled plant-soil core segment was determined at the conclusion of the shear force experiment. Roots and rhizomes were washed free from soil cores over screens of 60, 100, 200, and > 200 mesh sieves, composited, oven dried at 50˚C, and weighed to determine mass. The samples contained primarily roots, rhizomes, and root litter within each 10 cm core. Root crowns were removed to account for only the belowground plant organs. Subsamples of roots and rhizomes were ashed in a muffle furnace at 550˚C to determine ash-free root and rhizome weights. I will refer to these root and rhizome components incorporated in this analysis as belowground biomass.

Experimental Design

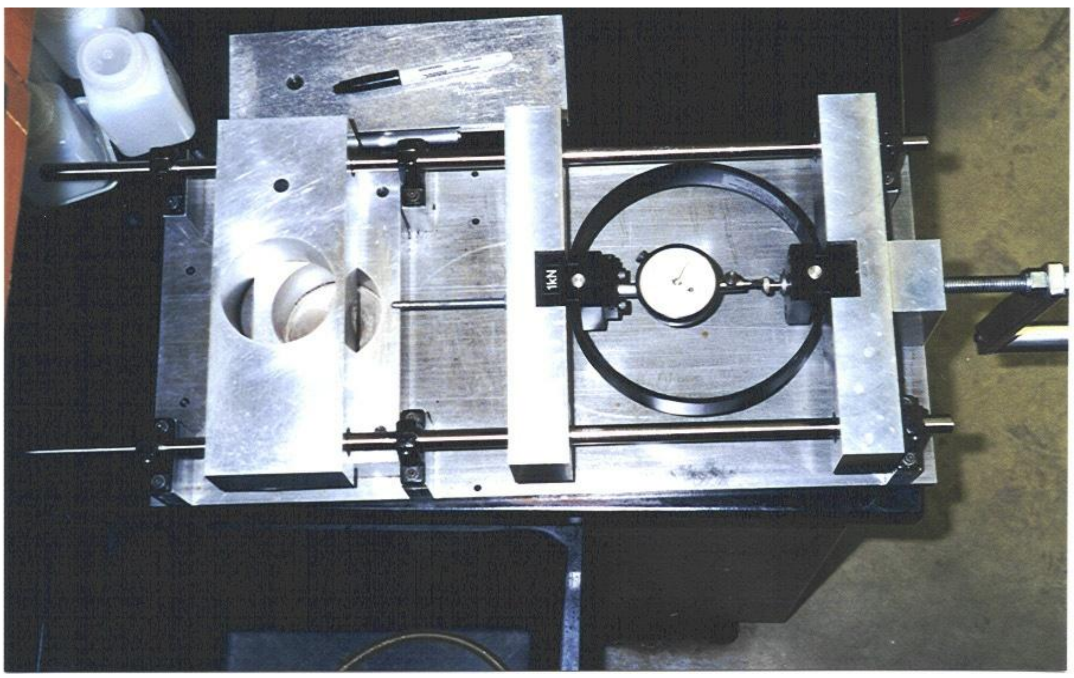

Figure 2.1. The shear resistance device used to measure soil-root core shear failure.

The soil stability experiment was designed as a randomized complete block experiment with 15 replications (Table 2.1). The species of grass, sedge, rush, or unvegetated controls were the main treatments. All data were analyzed using ANOVA procedures (SAS 1996). In addition, analysis of covariance (ANCOVA) was used to test shear resistance as affected

Table 2.1. Sources of variation and degrees of freedom (df) for each analysis of variance of independent and dependent variables

Sources of variation	df
Replications	14
Species (S)	6
Depth (D)	1
S x D	6
Error	182
Total	209

Table 2.2. Example of analysis of covariance used in data analysis.

Sources of variation	df
Replications	14
Species (S)	6
Depth (D)	1
S x D	6
Covariate (C)	1
C x D	1
C x S	6
Error	182
Total	217

by soil texture, bulk density, organic matter content, and belowground biomass (Table 2.2). ANCOVA's were performed for each of the species dependent variables separately. An elimination procedure using $P \leq 0.05$ was used to remove the least important covariates. Significant differences among treatments were accepted at $P \leq 0.05$. Differences among treatments were compared using the LSD procedure ($P \leq 0.05$).

RESULTS AND DISCUSSION

Soil Shear Resistance as Affected by Species and Depth

Analysis of variance revealed that shear resistance was influenced significantly by species ($P < 0.0001$), depth ($P < 0.0001$), and the species by depth interaction ($P =<0.0072$) (Appendix Table 2.1). All species had greater shear resistance at 0 to 10 cm than the 10 to 20 cm soil depth (Figure 2.2). For example water sedge had a 2½ times greater shear resistance in the upper 0 to 10 cm soil depth than the 10 to 20 cm depth. Species were ranked greatest to least for shear resistance at the 0 to 10 cm depth: water sedge, mountain rush, bluejoint reedgrass, Nebraska sedge, tufted hairgrass, Kentucky bluegrass, and unvegetated control. The ranking from greatest to least shear resistance at 10 to 20 cm depth was: bluejoint reedgrass, water sedge, Nebraska sedge, tufted hairgrass, mountainrush, Kentucky bluegrass and unvegetated control. Only the unvegetated control had no significant difference in the shear resistance between the top 0 to 10 cm of the soil core and the lower10 to 20 cm segment.

The species by depth interaction was likely caused by root stratification throughout the soil horizon. This is most evident when vegetated cores were compared with the unvegetated control sample (Figure 2.2). The lack of significant belowground biomass in the control samples explained why no significant difference occurred in shear resistance between the top 0 to 10 cm and the 10 to 20 cm soil depth. Sedges, rush and grass species had greater shear resistance as compared with the unvegetated control samples at the 0 to 10 cm depth (Figure 2.3). The difference in core shear resistance resulted in an expression of root stratification in the soil and will be discussed further in the covariate analysis section.

Analysis of variance showed a significant type (vegetated or control) effect ($P = 0.003$), a significant depth effect ($P = 0.008$), and a significant type by depth interaction ($P = 0.032$) (Appendix 2.2). The type categories were all vegetated cores versus the unvegetated control cores. As predicted, soil cores (0 to 20 cm) with vegetation had more than 2½ times greater shear resistance than soil cores without any vegetation. Shear resistance for the upper 0 to 10 cm soil depth was 3 times greater when vegetation was present as compared with bare interspace control areas (Figure 2.3). At the 10 to 20 cm depth, cores with vegetation did not have significantly different shear resistance than the unvegetated soil cores. This probably resulted from the small amount of biomass that was present in the deeper cores of vegetated areas as compared with the surface 10 cm cores.

Grass-like species (sedges and rush) provided greater ($P < 0.0001$) shear resistance in the 0 to 10 cm soil depth than did grasses. Vegetation type (grass or grass-like) had little effect ($P = 0.1246$) on shear resistance when data for both depths were compared, but depth ($P < 0.0001$) and the type by depth ($P = 0.0499$) interaction significantly affected shear resistance (Appendix Table 2.3). This analysis revealed a significant difference for shear resistance in grass-like vegetation versus grasses in the top 0 to 10 cm depth, but no

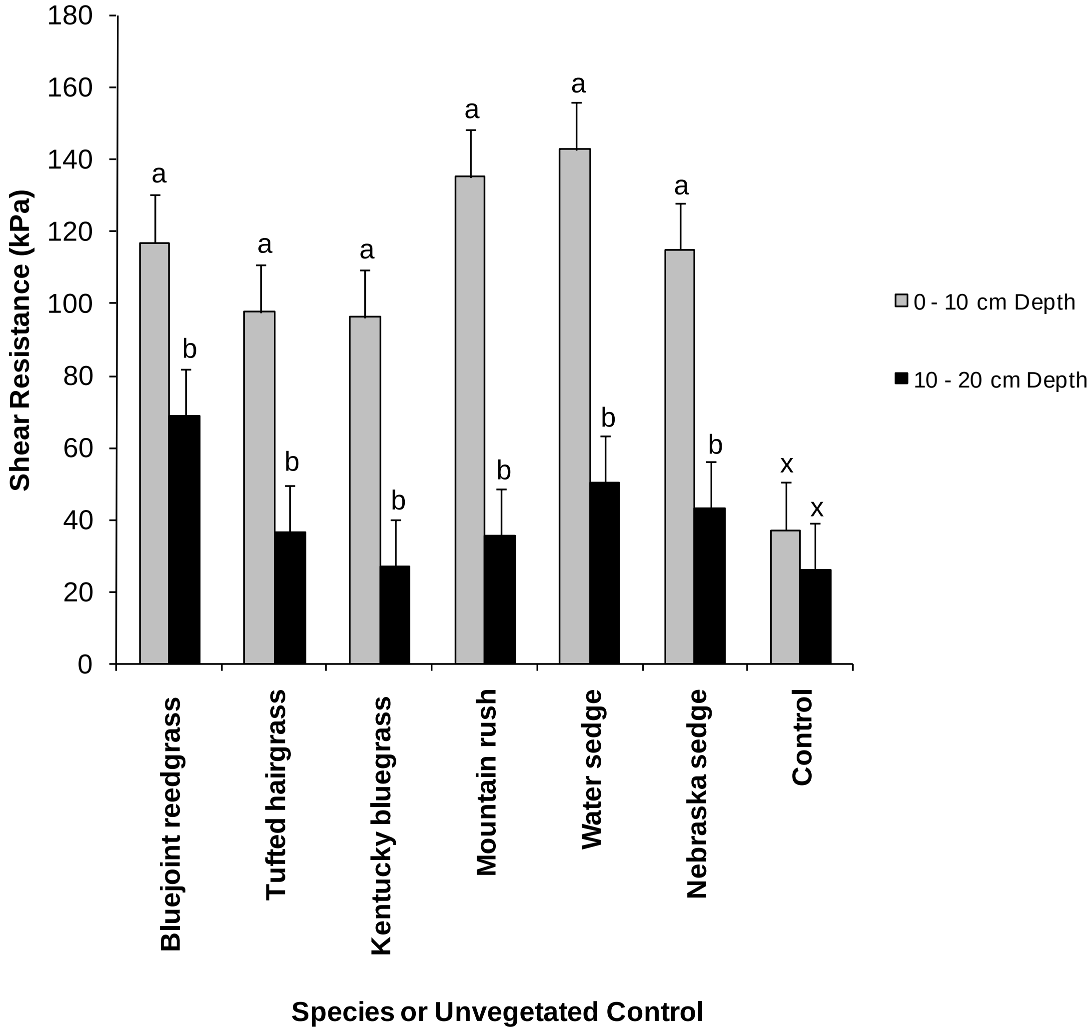

Figure 2.2. Least square means for shear resistance for all grass, grass-like, and control cores from 0 to 10 and 10 to 20 cm depths. Similar letters above each pair of bars represent nonsignificant differences ($p > 0.05$). Lines above bars represent 1 SE.

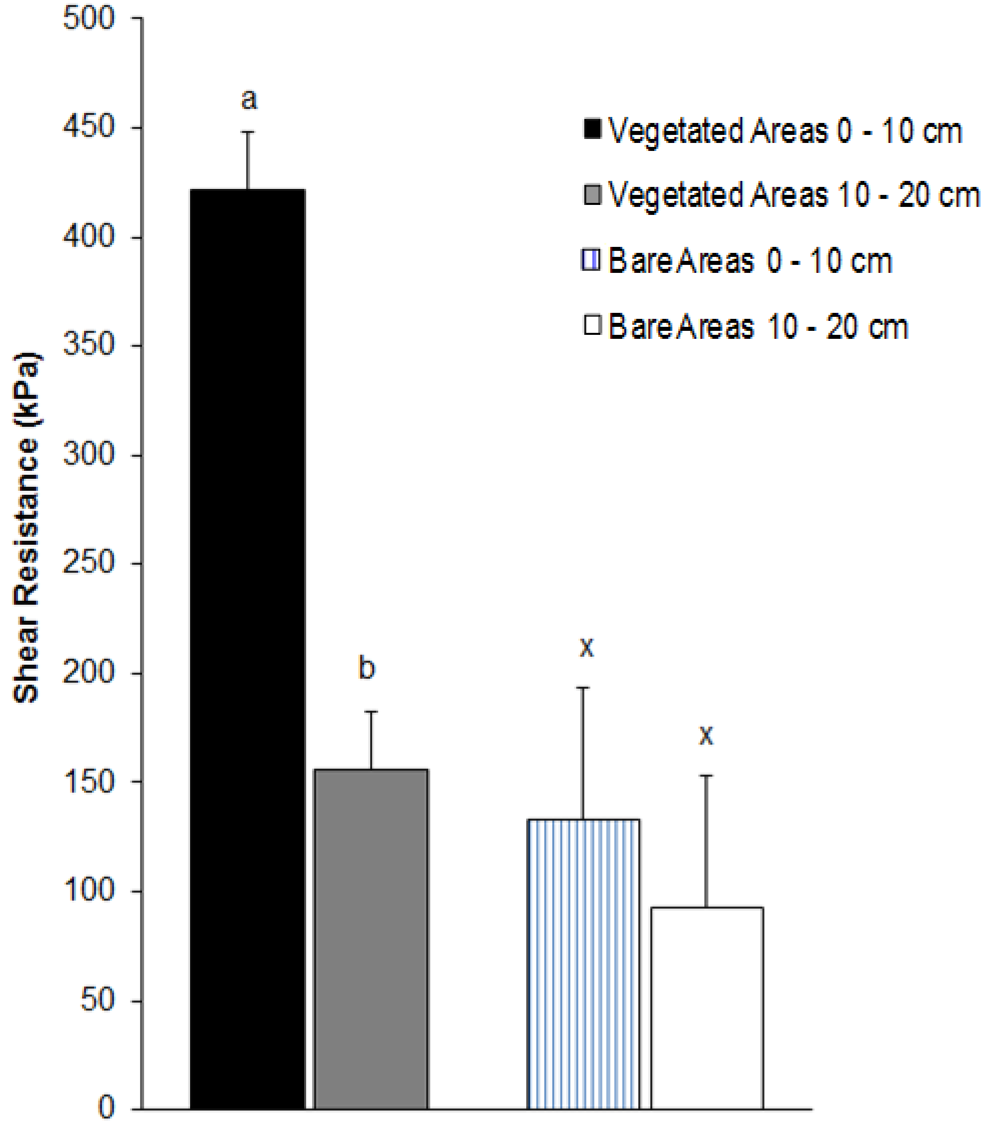

Figure 2.3. Least square means for shear resistance for soil cores of all grasses and grass-like (rush and sedges) species combined and unvegetated cores compared at 0 to 10 cm and 10 to 20 cm soil depths. Similar letters above a pair of bars represent nonsignificant differences ($p > 0.05$). Lines above bars represent 1 SE.

differences at the 10 to 20 cm depth (Figure 2.4). Sedges had 3 times greater shear resistance in the top 0 to 10 cm compared to the bottom 10 to 20 cm depth. Grass-like species had 2.4 times greater shear resistance in the top 0 to 10 cm compared to the lower 10 to 20 cm depth. As previously mentioned, the shear resistance below 10 cm was negligible. Both grasses and grass-like species had very similar results with significantly less belowground biomass and lower shear resistance below 10 cm.

Covariate Analysis and Other Independent Variables

Analyses of covariance for shear resistance as the dependent variable were conducted to determine if changes in shear resistance were affected by variations in the independent variables of bulk density, organic matter, belowground biomass, and soil texture.

Analysis of covariance revealed that when data for shear resistance were adjusted for differences in bulk density, a significant interaction (P = 0.0330) with depth and bulk density affected shear resistance (Appendix 2.4). Bulk density values for vegetated cores were greater at 10 to 20 cm depth then at the 0 to 10 cm depth (Figure 2.5). As expected, soils located deeper in the profile had consistently greater bulk density than those nearer to the surface where density values were unusually low, probably because of excessive hydration and high organic matter. There was no difference between bulk density of the unvegetated control and vegetated soil samples at the 10 to 20 cm depth. Covariate analysis revealed that bulk density still influenced shear resistance at different depths (Appendix Table 2.4). Adjusting shear resistance for bulk density revealed that the 0 to 10 cm depth had twice as much shear resistance as the 10 to 20 cm of soil depth (Figure 2.8).

Further analysis revealed that belowground biomass of all species (P = 0.0001) and

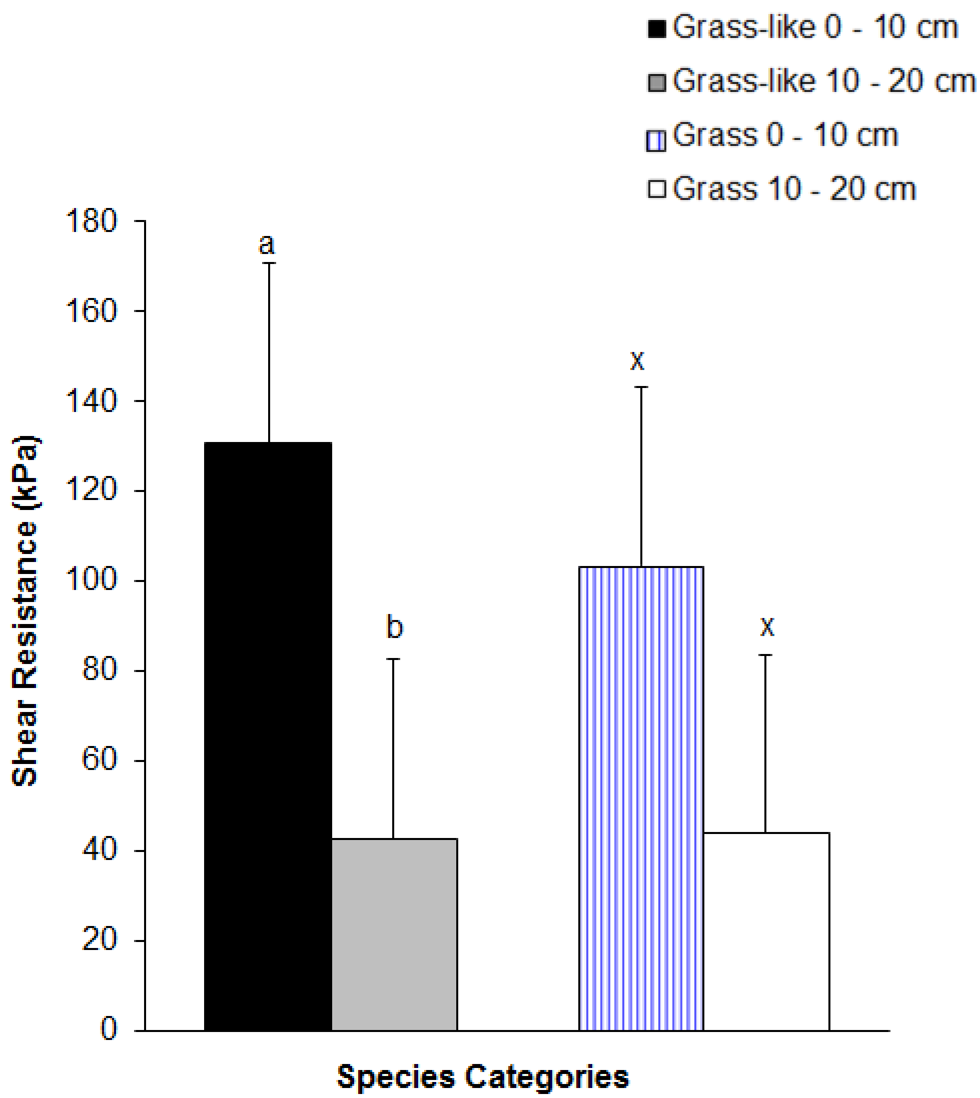

Figure 2.4. Least square means for shear resistance for all grass-like species, and all grasses combined compared at 0 to 10 and 10 to 20 cm depths. Similar letters above a pair of bars represent nonsignificant differences ($p > 0.05$) within a species category. Lines above bars represent 1 SE.

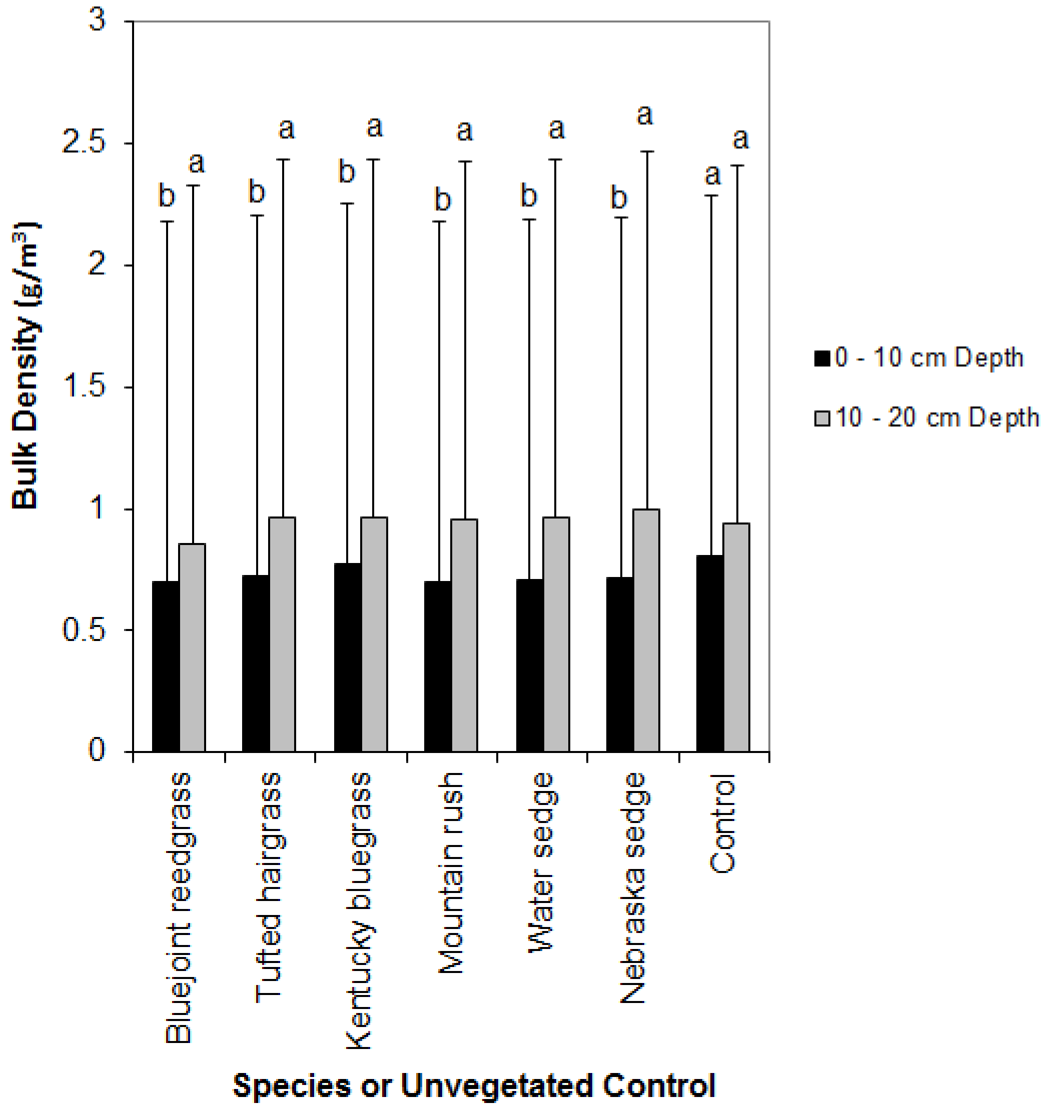

Figure 2.5. Least square means for soil bulk density for all grass, sedge, rush, and control cores from 0 to 10 and 10 to 20 cm depths. Similar letters above a pair of bars represent nonsignificant differences ($p > 0.05$) within a pair of values. Lines above bars represent 1 SE.

depth ($P < 0.0497$) both affected shear resistance, but little difference for the interaction of belowground biomass by depth ($P = 0.0556$) for shear resistance was found (Figure 2.6) (Appendix 2.5). Belowground biomass was the only independent variable in this covariate analysis that significantly influenced shear resistance. The top 10 cm of soil contained the majority of root mass as was expected. Although there was no significant species by belowground biomass interaction, Figure 2.6 shows that the top 10 cm layer of soil had more grasslike species root and rhizome mass than was found under grasses. In the top 10 cm of soil, grass-like species had an average of 31 kg/m^3 of root and rhizome material as compared with grasses that had an average of 24 kg/m^3 and control (bare interspaces) with 19 kg/m^3. Only bluejoint reedgrass that had large root systems and the unvegetated control cores had no significant difference in shear resistance between the top 0 to 10 cm and the bottom 10 to 20 cm depth in soil cores. There was a significant decrease in belowground biomass below 10 cm in most soil cores; belowground biomass was often about half of that in the 0 to 10 cm depth. Root and rhizome biomass for grasses and grass-like plants in this riparian community was most abundant in the top 10 cm (Figure 2.6). Manning et al. (1989) observed a rapid decline in root mass and lengths with depths to 40 cm below the soil surface for Nebraska sedge, mountain rush, Douglas sedge (*C. douglasii* Boott), and Nevada bluegrass (*Poa nevadensis* Vasey) in various intermountain meadows. Fibrous grass roots have been shown to get longer and less abundant per unit mass at increasing depths (Smoliak et al. 1972, Bartos and Sims 1974, Svejar and Chistiansen 1987).

Previous field and lab experiments that compared fallow fields with various grass, legume, and tree roots have shown that tree roots cores have significantly greater shear resistance compared to areas without vegetation (Waldron 1977, Waldron and Dakessian

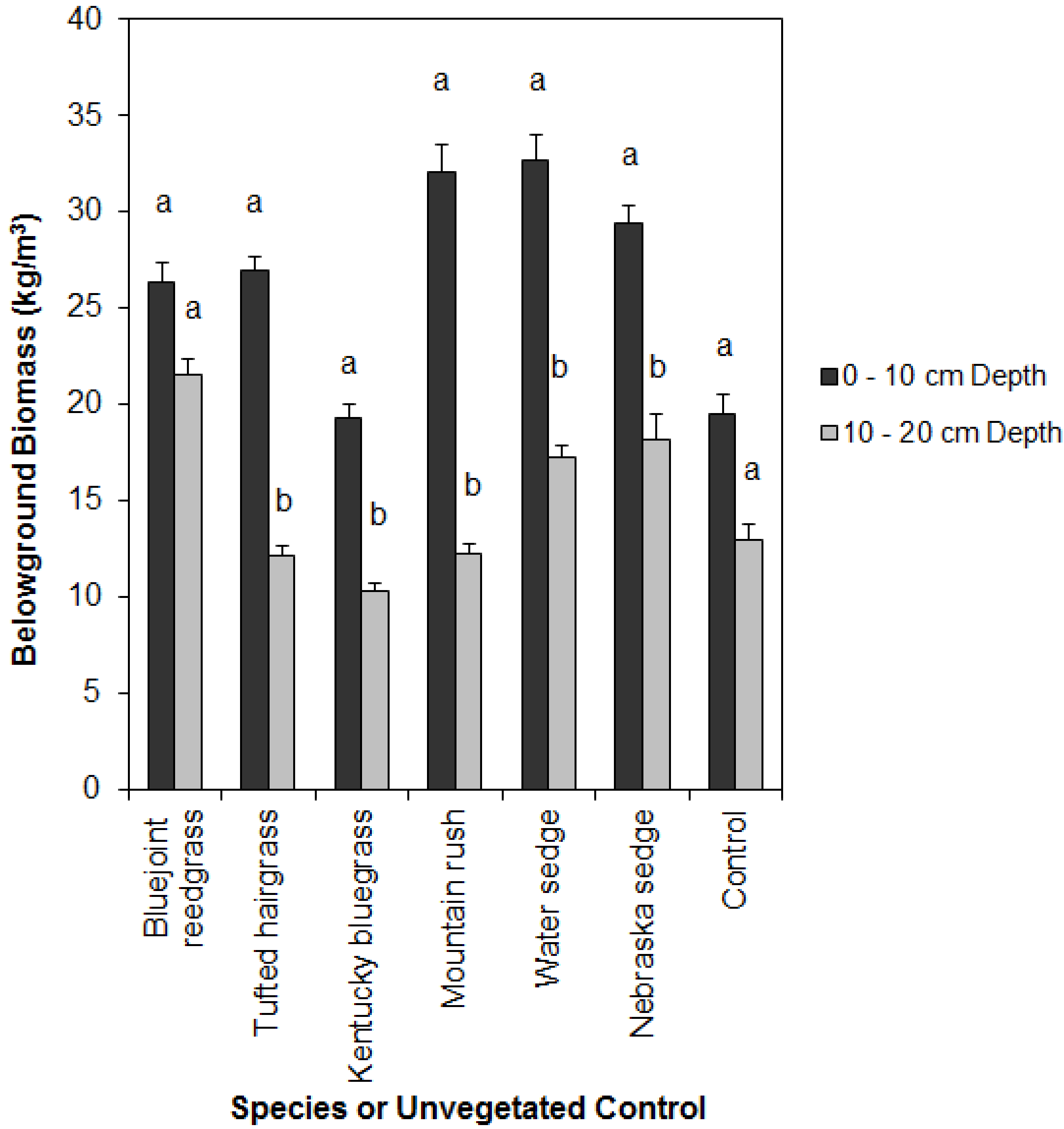

Figure 2.6. Least square means for belowground biomass for all grass, sedge, rush, and unvegetated control samples from 0 to 10 and 10 to 20 cm depths. Similar letters above a pair of bars represent nonsignificant differences ($P > 0.05$) within the pair. Lines above bars represent 1 SE.

1981, 1982). Roots increased soil shear resistance through mechanical reinforcement (Rice, Corbett et al. 1969, Gray 1973, Pollen 2007, Fan and Su 2008, Mickovski et al. 2009, Lodes et al. 2010, Comino and Duretta 2010, Comino et al. 2010). Below the 10 cm zone, root biomass of herbaceous grasses and grass-like species in this riparian community declined significantly and the associated shear resistance of soil cores also decreased.

Shear resistance adjusted for belowground biomass revealed a strong influence caused by root and rhizome biomass (Figure 2.7) (Appendix 2.5). Clearly the belowground biomass had a major influence on shear resistance at both soil depths. Belowground biomass had the greatest effect on shear resistance in the top 10 cm of the soil where biomass was much greater.

Organic matter and ash were not significant independent variables in covariate analysis. Organic matter was typically concentrated in the top horizon of the soil profile as expected (Appendix 2.6 and 2.7).

Examination of soil texture as a potential influence on soil core shear resistance did not show any significant influence. Sand and then silt had the greatest concentrations in these soils. Variations in sand, silt, and clay percentages in these core samples did not influence the level of shear resistance (Appendix 2.8 and 2.9). Differences in these typically variable soil textures were not found to significantly influence soil shear resistance. Covariate analysis revealed that slight differences in soil texture had very little influence on affecting shear resistance of individual species and depth of samples.

Combining independent variables into a covariate analysis revealed that root biomass and bulk density combined had the greatest influence ($P < 0.001$) on shear resistance and accounted for 68 % of the variation in shear resistance (Appendix 2.11). Of the covariate

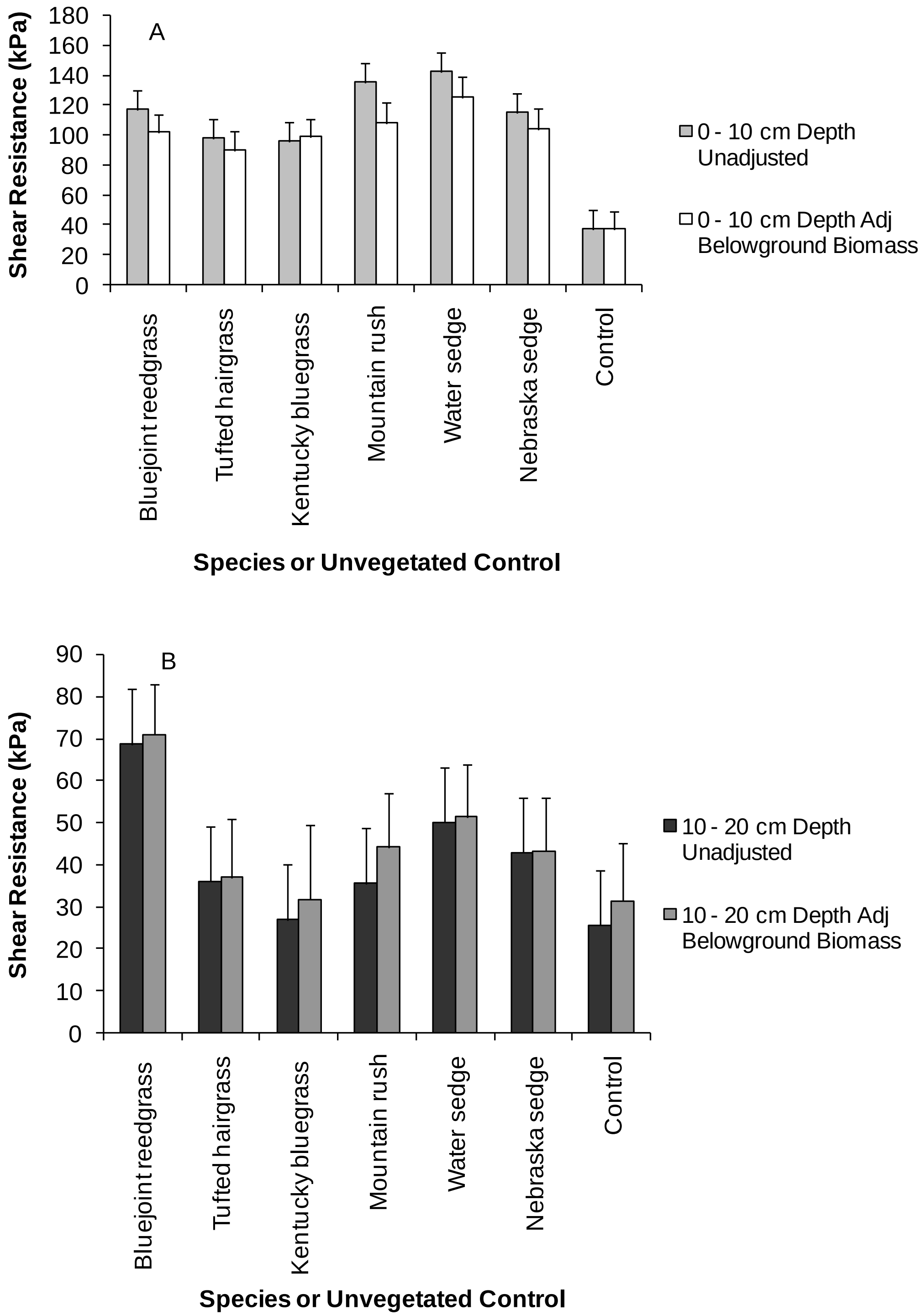

Figure 2.7. Adjusted and unadjusted shear resistance for root biomass for all grass, grass-like species, and unvegetated control samples from 0 to 10 (A) and 10 to 20 (B) cm depths. Lines above bars represent 1 SE.

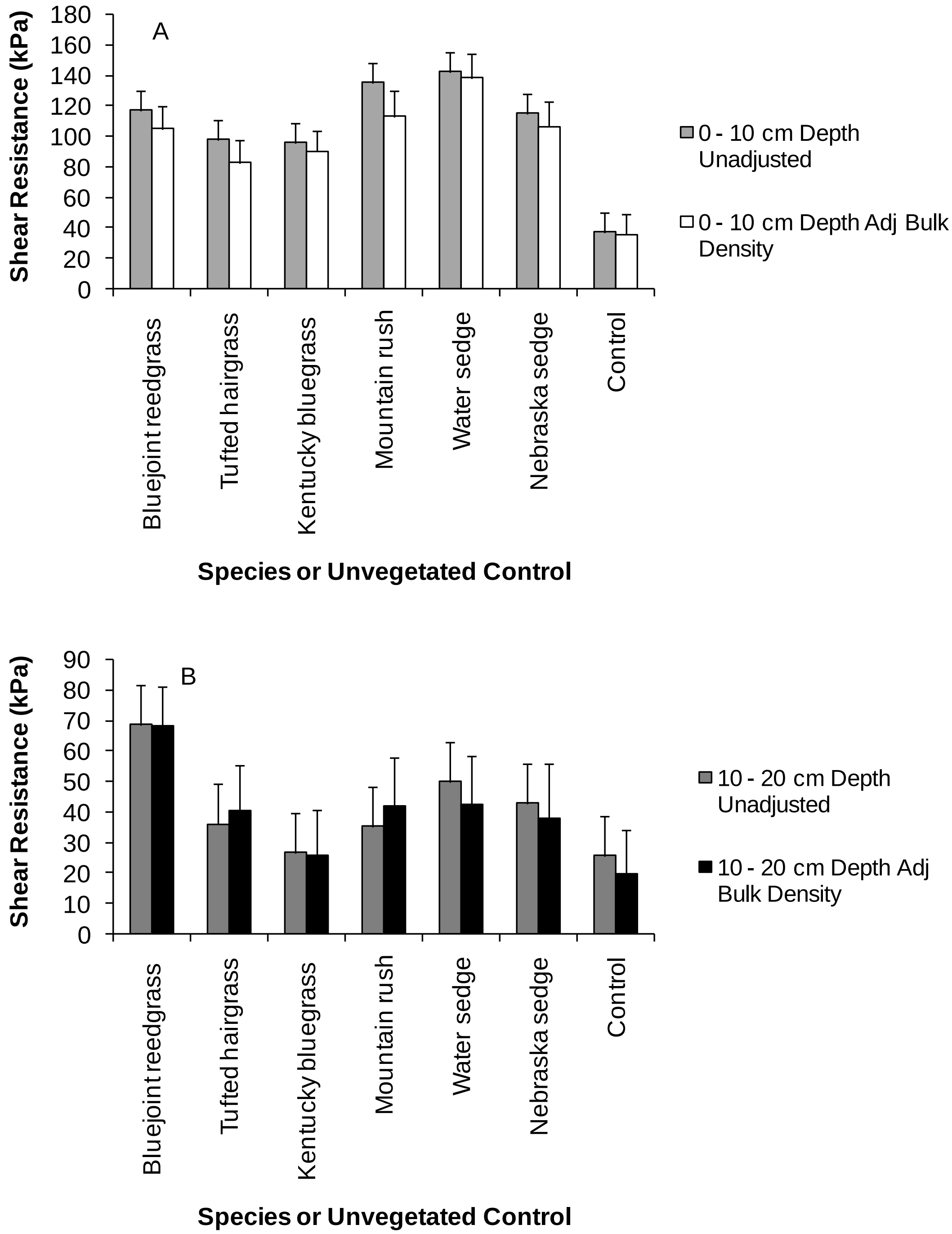

Figure 2.8. Adjusted and unadjusted shear resistance for bulk density for all grass, grass-like species, and unvegetated control samples from 0 to 10 and 10 to 20 cm depths. Lines above bars represent 1 SE.2.6 and 2.7. Covariate adjustments had little influence on species and depth effects for shear resistance.

variables tested, belowground biomass and bulk density combined explained most of the variability in soil core shear resistance. Other combinations of independent variables were tried but no combination explained more of the variability in soil core shear resistance as did belowground biomass and bulk density. As indicated in Figure 2.6, belowground biomass followed a distinct influence on shear resistance. Belowground biomass influenced the shear resistance by binding the soil matrix together. Bulk density had a significant influence because this soil property changes with depth. Figure 2.8 shows that bulk density had a distinct pattern of increasing with depth and contributing to a greater level of shear resistance at deeper depths.

CONCLUSIONS

Streambank erosion potential was assessed with use of shear resistance measurements of soil cores taken from several herbaceous species within a montane riparian community. It was assumed that grasses or grass-like plants would differentially influence streambank erosion potential. Comparisons of shear resistance for soil cores for three grasses, a rush, and two sedges were made. Samples for soil bulk density, texture, belowground biomass, and organic matter content were measured to determine relationships of these variables with vegetation types and soil shear resistance.

The first hypothesis tested was that grasses, sedges, and a rush would provide greater soil shear resistance than would be found in unvegetated interspace (control) areas. A clear distinction between vegetated and unvegetated soil shear resistance was confirmed for the top 10 cm of soil. Vegetated areas had 3 times greater shear resistance compared with unvegetated interspace areas in the top 10 cm of the soil, but this difference was no longer evident at the 10 to 20 cm soil depth. Plant roots and rhizomes of these species resulted in a distinctly greater shear resistance in surface soil and should help prevent stream bank and overland flow erosion much better than unvegetated areas. These results confirmed previous research indicating the importance of the rooting matrix of plants in helping sustain stable soil structure (Endo and Tsuruta 1969, Waldron 1977, Waldron and Dakessian 1981, Goldsmith 1998, Simon and Collison 2001, Wynn et al. 2004).

The second hypothesis was that sedges and a rush species would have greater shear resistance when compared with grass species. This hypothesis was accepted as the two sedge species had greater belowground biomass that resulted in greater shear resistance in the top 10 cm soil layer as compared with grasses. Mountain rush had lower shear resistance than the two sedges found in the riparian area. There was no significant difference between grasses or sedges in shear resistance below the 10 cm soil layer. This was not a surprise based on findings of previous research that showed no significant herbaceous species difference in shear resistance below 10 cm (Kuramoto and Bliss 1970, Bernard and Fiala 1986, Manning et al. 1989).

These results and previous research indicate that sedge species have greater total root mass (Kuramoto and Bliss 1970) and root lengths of various sizes per volume of soil in various riparian communities types as compared with grasses (Manning et al. 1989). Manning et al. (1989) observed that Nebraska sedge produced 382 cm/cm^3 of roots in the top 41 cm of the soil profile and mountain rush had only 134 cm/cm^3 of roots in the same profile level in various intermountain meadows. Manning also noted that in the one grass community (*Poa nevadensis* Vasey ex Scribn.) compared to the sedge and rush community types ranked lowest in terms of root length densities and root biomass.

Covariate analysis revealed that although belowground biomass significantly influenced shear resistance, there was no significant associated species difference in belowground biomass. Belowground biomass was associated with differences in shear resistance at 0 to 10 cm and 10 to 20 cm. The top 10 cm of the soil was more than twice as strongly influenced by belowground biomass than the 10 to 20 cm segment. Although species differences in belowground biomass were not significant, water sedge and mountain rush had the greatest influence on shear resistance in the top 10 cm soil layer. Belowground biomass and bulk density were the only covariates that had a significant influence on shear resistance. Bulk density increased significantly at the deeper depths. The top 10 cm of the soil had the greatest concentration of root biomass and lower bulk density.

Further research should involve using sedges, rushes, and grasses in various combinations that deter grazing or are grazing resistant on reclamation areas. Using various species in combination or exclusively could show which species are likely better candidates to serve dual purposes of being both a good soil stabilizer and being grazing resistant. Sedge belowground biomass and sheer resistance proved to be greater than grasses in the top 10 cm in this study. This knowledge would allow managers to use some sedges in reclamation projects that can adequately create soil stabilizing features and reduce the impact of grazing in these areas. Knowing which species are capable of reducing grazing impacts, or can tolerate grazing, in reclamation projects would allow better management concerns to be met. Species could be selected for use that either have very low palatability or have physical characteristics that reduce grazing preference. Knowing which species or combination of species are capable of limiting grazing or tolerating grazing while being effective soil stabilizers would allow restoration managers to be more effective in management.

Knowledge of rooting system shapes and rooting strategies of different grass and sedge species may also contribute to greater understanding of which species in combination could contribute more in reinforcing slopes on reclamation projects (Stokes et al. 2009). Knowing rooting size variability could contribute more to knowledge of species capabilities and range of variability. Previous research indicates that root size, diameter, and branching pattern can contribute to greater soil shear resistance (Operstein and Frydman 2000, Gray and Barker 2004, De Baets et al. 2007, Dupuy et al. 2005, Mickovski et al. 2007, Reubens et al. 2007, Tosi 2007, Fan and Su 2008, Schwarz et al. 2009, Lodes et al. 2010, Schwarz et al. 2010, Yu et al. 2010). I did not measure the rooting size variability in this study but future studies should consider analyzing root size variability of plant species to determine how this variable might affect rooting shear resistance.

Comparing native and introduced species may also show the more effective species or combination of species capable of establishing soil holding characteristics and forage for grazing animals. Although native species might be preferred, introduced species may establish greater soil stabilizing features faster than some native species in some situations. Given the growing conditions necessary, some introduced species might mimic the rooting and soil stabilizing characteristics of better native species and have more rapid establishment. Knowing which species, native or introduced, are most effective and capable of quick establishment of a soil stabilizing root system and provide effective cover on reclamation sites could help insure more effective restoration and minimize erosion.

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APPENDIX A: TRAMPLING STUDY

Appendix Table 1.1 Analysis of variance for each three types of cover as affected by seasonal trampling in a montane riparian community.

Sources of variation	df	MS	p-value
Cover Type			
Herbaceous Cover			
Season Trampled (S)	3	2.44	0.49
Year Sampled (Y)	2	26.01	0.01
S x Y	6	2.80	0.04
Error	11	0.99	
Litter Cover			
Season Trampled (S)	3	1.48	0.60
Year Sampled (Y)	2	11.58	0.01
S x Y	6	2.28	0.08
Error	11	1.00	
Bare Ground			
Season Trampled (S)	3	1.18	0.35
Year Sampled (Y)	2	4.22	0.02
S x Y	6	0.95	0.48
Error	11	0.99	

Appendix Table 1.2. Analysis of variance for herbaceous cover by functional group for seasonal trampling treatments in a montane riparian community with a six year recovery period.

Sources of Variation	df	MS	p-value
Total	88		
Cover by Functional Group			
Grasses			
Season Trampled (S)	3	1.024	0.42
Year Sampled (Y)	2	0.498	0.61
S x Y	6	0.957	0.48
Error	24	0.997	
Sedges + Grasslike			
Season Trampled (S)	3	2.118	0.37
Year Sampled (Y)	2	4.780	0.11
S x Y	6	1.943	0.09
Error	24	0.917	
Forbs			
Season Trampled (S)	3	2.747	0.49
Year Sampled (Y)	2	5.651	0.20
S x Y	6	3.157	0.03
Error	24	0.993	
Shrubs			
Season Trampled (S)	3	0.777	0.28
Year Sampled (Y)	2	0.646	0.30
S x Y	6	0.505	0.76
Error	24	0.917	

Appendix Table 1.3. Analysis of variance for herbaceous cover by functional group for seasonal trampling treatments in a montane riparian community with a six year recovery period.

Sources of variation	df	MS	p-value
Total	88		
Season Trampled (S)	3	2	0.71
Years Sampled (Y)	2	1	0.01
S x Y	6	1.669	0.18
Functional Group (F)	3	<. 0001	<. 0001
Y x F	6		0.6981
S x F	9		0.3909
Y x S x F	18		0.0668
Error	47	0.982	

Appendix Table 1.4. Analysis of variance for native species cover in a montane riparian community as affected by seasonal trampling.

Sources of variation	df	MS	p-value
Total	36		
Season Trampled (S)	3	0.784	0.71
Years Sampled (Y)	2	11.947	0.01
S x Y	6	1.669	0.18
Error	24	0.982	

Appendix Table 1.5. Analysis of variance for ruderal species cover in a montane riparian community as affected by seasonal trampling.

Sources of variation	df	MS	p-value
Total	36		
Season Trampled (S)	3	7.971	0.10
Years Sampled (Y)	2	11.957	0.03
S x Y	6	2.749	0.05
Error	24	0.978	

Appendix Table 1.6. Analysis of variance for native forb species cover in a montane riparian community as affected by seasonal trampling.

Sources of variation	df	MS	p-value
Total	36		
Season Trampled (S)	3	2.098	0.53
Years Sampled (Y)	2	5.974	0.14
S x Y	6	2.655	0.05
Error	24		

Appendix Table 1.7. Analysis of variance for ruderal forb species cover in a montane riparian community as affected by seasonal trampling.

Sources of variation	df	MS	p-value
Total	36		
Season Trampled (S)	3	2.791	0.29
Years Sampled (Y)	2	1.780	0.41
S x Y	6	1.873	0.13
Error	24		

Appendix Table 1.8. Analysis of variance for native species cover in a montane community as affected by seasonal trampling.

Sources of variation	df	MS	p-value
Total	36		
Season Trampled (S)	3	0.856	0.54
Years Sampled (Y)	2	6.258	0.01
S x Y	6	1.112	0.39
Error	24	0.984	

Appendix Table 1.9. Analysis of variance for introduced species cover in a montane riparian community as affected by seasonal trampling.

Sources of variation	df	MS	p-value
Total	36		
Season Trampled (S)	3	11.15	0.15
Years Sampled (Y)	2	86.14	0.01
S x Y	6	4.85	0.01
Error	24	0.99	

Appendix Table 1.10. Analysis of variance for native forb species cover in a montane riparian community as affected by seasonal trampling.

Sources of variation	df	MS	p-value
Total	36		
Season Trampled (S)	2	0.038	0.02
Years Sampled (Y)	3	1.828	0.57
S x Y	6	2.539	0.06
Error	24	0.966	

Appendix Table 1.11. Analysis of variance for introduced forb species cover in a montane riparian community as affected by seasonal trampling.

Sources of variation	df	MS	p-value
Total	36		
Season Trampled (S)	3	4.957	0.14
Years Sampled (Y)	2	0.088	0.04
S x Y	6	2.057	0.11
Error	24	0.966	

Appendix Table 1.12. Analysis of variance for species richness in a montane riparian community as affected by seasonal trampling.

Sources of variation	df	MS	p-value
Total	36		
Season Trampled (S)	3	4.240	0.24
Years Sampled (Y)	2	5.821	0.13
S x Y	6	2.509	0.03
Error	24	0.831	

Appendix Table 1.13. Analysis of variance for survival of willow cuttings in a montane riparian community as affected by seasonal trampling.

Sources of variation	df	MS	p-value
Total	71		
Years Sampled (Y)	2	129.670	0.01
Season Trampled (S)	3	13.107	0.13
S x Y	6	5.201	0.20
Willow Species (P)	1	216.106	0.01
P x Y	2	13.046	0.06
S x P	3	20.194	0.01
S x P x Y	6	4.306	0.30
Error	852	1.083	

Appendix Table 1.14. Analysis of variance for the number of willow shoots on cuttings in a montane riparian community as affected by seasonal trampling.

Sources of variation	df	MS	p-value
Total	71		
Season Trampled (S)	2	80.417	0.11
Willow Species (P)	3	6.549	0.01
S x P	6	2.339	0.52
Year Sampled (Y)	1	155.458	0.01
P x Y	2	14.977	0.40
S x Y	3	7.171	0.51
S x P x Y	6	1.928	0.01
Error	852	1.083	

APPENDIX B: SOIL SHEAR RESISTANCE STUDY

Appendix Table 2.1. Analysis of variance for shear resistance for herbaceous species (vegetation) and an unvegetated control sampled at two depths (0-10 cm and 10-20 cm) in a montane riparian community.

Sources of variation	df	MS	p-value
Total			
Type (T)	1	2490741.339	0.0032
Depth (D) (0 – 10) and (10 – 20) cm	1	2333700.463	0.0080
T x D	1	182605.670	0.0320
Vegetation			
Depth 0 - 10	1	117.2	<. 0001
Depth 10 - 20	1	43.4	<. 0001
Control			
Depth 0 – 10	1	37.1	0.0505
Depth 10 - 20	1	25.7	0.1543

Appendix Table 2.2. Analysis of variance for shear resistance at two depths (0-10 cm and 10-20 cm) comparing all herbaceous species combined with unvegetated controls sampled in a montane riparian community.

Sources of variation	df	MSE	p-value
Species (S)	6	34169.586	0.0001
Depth (D) (0 – 10) and (10 – 20) cm	1	697098.530	<.0001
S x D	6	6496.119	0.0072
Species (S) by Depth (D) (cm)		Mean	
Bluejoint reedgrass			
Depth 0 - 10	1	111.2	<. 0001
Depth 10 - 20	1	73.6	<. 0001
Tufted hairgrass			
Depth 0 - 10	1	93.9	<. 0001
Depth 10 - 20	1	39.4	0.0066
Kentucky bluegrass			
Depth 0 - 10	1	92.6	<. 0001
Depth 10 - 20	1	38.7	0.0417
Baltic rush			
Depth 0 - 10	1	128.8	<. 0001
Depth 10 - 20	1	34.4	0.0076
Water sedge			
Depth 0 - 10	1	134.1	<. 0001
Depth 10 - 20	1	57.9	0.0002
Nebraska sedge			
Depth 0 - 10	1	110.1	<. 0001
Depth 10 - 20	1	48.9	0.0013
Control			
Depth 0 - 10	1	37.4	0.0053
Depth 10 - 20	1	29.2	0.0522

Appendix Table 2.3. Analysis of variance for shear resistance comparing vegetation type (grasses or grass-like) three grasses with three sedge species sampled at two depths (0-10 cm and 10-20 cm) in a montane riparian zone.

Sources of variation	df	MS	p-value
Total			
Type (T)	1	22032.4	0.1246
Species (S) (Type)	5	15204.2	0.1669
Depth (D) (0 – 10) and (10 – 20)cm	1	969700.6	<. 0001
T * D	1	9104.3	0.0499
Grasses			
Depth 0 - 10	1	372.4	<. 0001
Depth 10 - 20	1	158.0	<. 0001
Sedges			
Depth 0 – 10	1	471	<. 0001
Depth 10 - 20	1	154	<. 0001

Appendix Table 2.4. Analysis of covariance for shear resistance for grasses, grass-like plants, and unvegetated control core samples at 0 – 10 cm and 10 – 20 cm depths as affected by bulk density.

Sources of variation	df	MS	p-value
Total			
Species (S)	6	31521.952	0.5900
Depth (D) (0 – 10) and (10 – 20) cm	1	61815.776	0.0008
S * D	6	40937.600	0.1534
Bulk Density (BD)	1	22441.481	0.1874
BD * D	1	116672.160	0.033
BD * S	6	12537.140	0.8101

Appendix Table 2.5. Analysis of covariance for shear resistance for grasses, grass-like plants, and unvegetated control core samples at 0 – 10 cm and 10 – 20 cm depths as affected by root biomass.

Sources of variation	df	MS	p-value
Total			
Species (S)	6	72677.108	0.1624
Depth (D) (0 – 10) and (10 – 20) cm	1	182624.529	0.0497
S * D	6	46587.890	0.0716
Root biomass (RB)	1	448901.243	0.0001
RB * D	1	87088.920	0.0556
RB * S	6	26688.540	0.3400

Appendix Table 2.6. Analysis of covariance for shear resistance of grasses, grass-like species,and unvegetated control core samples at 0 – 10 and 10 - 20 cm depth as affected by soil organic matter.

Sources of variation	df	MS	p-value
Total			
Species (S)	6	32639.594	0.7640
Depth (D) (0 – 10) and (10 – 20) cm	1	229642.861	0.0486
S * D	6	58284.990	0.0617
Organic Matter (OM)	1	872.867	0.7504
OM * D	1	4505.120	0.6905
OM * S	6	8728.670	0.9322

Appendix Table 2.7. Analysis of covariance for shear resistance for grasses, grass-like species and unvegetated control core samples at 0 – 10 and 10 – 20 cm depth as affected by ash content.

Sources of variation	df	MS	p-value
Total			
Species (S)	6	20531.280	0.9364
Depth (D) (0 – 10) and (10 – 20) cm	1	277856.656	0.0455
S * D	6	68437.600	0.0310
Ash (A)	1	3444.504	0.4454
A * D	1	12726.000	0.5023
A * S	6	5938.800	0.9735

Appendix Table 2.8. Analysis of covariance for shear resistance for grasses, grass-like species, and unvegetated control core samples at 0 – 10 and 10 – 20 cm depths as affected by clay content.

Sources of variation	df	MS	p-value
Total			
Species (S)	6	57850.601	0.6728
Depth (D) (0 – 10) and (10 – 20) cm	1	1708751.32	0.0001
S * D	6	86344.180	0.0077
Clay (C)	1	55194.069	0.1278
C * D	1	45241.040	0.2037
C * S	6	22620.520	0.5582

Appendix Table 2.9. Analysis of covariance for shear resistance for grasses, grass-like, and unvegetated control core samples at 0 – 10 and 10 - 20 cm depths as affected by silt content.

Sources of variation	df	MS	p-value
Total			
Species (S)	6	164004.729	0.0680
Depth (D) (0 – 10) and (10 – 20) cm	1	2563182.822	0.0001
S * D	6	81190.460	0.0101
Silt (Si)	1	57941.205	0.1427
Si * D	1	35028.660	0.2588
Si * S	6	25524.760	0.4690

Appendix Table 2.10. Analysis of covariance for shear resistance for grasses, grass-like, and unvegetated control core samples at 0 – 10 and 10 - 20 cm depth as affected by sand content.

Sources of variation	df	MS	p-value
Total			
Species (S)	6	98699.220	0.3082
Depth (D) (0 – 10) and (10 – 20) cm	1	56752.052	0.4078
S * D	6	82249.350	0.0094
Sand (Sa)	1	67601.908	0.1031
Sa * D	1	46146.500	0.1946
Sa * S	6	23887.600	0.5149

Appendix Table 2.11. Analysis of covariance for shear resistance for grasses, grass-like species, and unvegetated control core samples at 0 – 20 cm depth as affected by both belowground biomass and bulk density.

Sources of variation	df	MS	p-value
Total			
Root biomass * Bulk density	2	67932.0	< 0.0001
Error	203	2663.410	

Appendix Table 2.12 A. Data set containing values from seasonal trampling of vegetation samples. Variables correspond for each column number at top of each column in Appendix Table 2.12 A

Year	Year of Species Inventory: 1 = 1996, 2 = 1997, 3 = 2001
Treatment	Season of Trampling: 1 = Late Spring, 2 = Early Summer, 3 = Fall, 4 = Control
Rep	Replication number: 1 through 3
Placov	Average (%) Plant Cover
Litter	Average (%) Litter Cover
Bare	Average (%) Bare Ground Cover
Richness	Average (%) Species Richness
Totgrass	Aveage (%) Total grass species combined
Totsedge	Average (%) Total sedge species combined
Totshrub	Average (%) Total shrub species combined
Totforb	Average (%) Total forb species combined

Appendix Table 2.12 A. (Continued)

Year	Treatment	Rep	Placov	Litter	Bare	Richness	Totgrass
1	1	1	60	5	35	6	19
1	1	2	72	28	0	6	9
1	1	3	55	45	0	6	0
1	2	1	58	12	30	9	11
1	2	2	45	25	30	6	0
1	2	3	76	24	0	5	45
1	3	1	44	10	46	6	5
1	3	2	75	16	9	10	10
1	3	3	38	62	0	7	16
1	4	1	50	50	0	4	2
1	4	2	15	85	0	2	0
1	4	3	76	24	0	6	3
2	1	1	90	10	0	5	60
2	1	2	54	46	0	5	7
2	1	3	60	40	0	8	21
2	2	1	69	26	5	6	0
2	2	2	53	47	0	7	3
2	2	3	80	20	0	3	4
2	3	1	95	3	2	9	37
2	3	2	98	1	1	12	17
2	3	3	92	8	0	11	7
2	4	1	88	12	0	6	30
2	4	2	30	70	0	1	0
2	4	3	95	3	2	6	18
3	1	1	70	30	0	6	50
3	1	2	20	80	0	4	3
3	1	3	60	40	0	6	23
3	2	1	10	70	20	3	0
3	2	2	28	42	30	10	6
3	2	3	26	74	0	2	0
3	3	1	60	30	10	5	0
3	3	2	90	10	0	2	72
3	3	3	50	50	0	5	0
3	4	1	48	52	0	5	3
3	4	2	60	40	0	5	0
3	4	3	85	15	0	7	1

Appendix Table 2.12 A. (Continued)

Year	Treatment	Rep	Totsedge	Totshrub	Totforb
1	1	1	2	0	12
1	1	2	8	8	2
1	1	3	27	1	9
1	2	1	8	0	21
1	2	2	18	5	13
1	2	3	8	0	5
1	3	1	15	3	21
1	3	2	3	8	27
1	3	3	5	0	17
1	4	1	12	0	0
1	4	2	15	0	0
1	4	3	3	0	7
2	1	1	15	0	6
2	1	2	11	5	4
2	1	3	2	0	15
2	2	1	45	6	9
2	2	2	3	0	11
2	2	3	75	0	1
2	3	1	22	14	21
2	3	2	35	6	40
2	3	3	23	0	49
2	4	1	5	0	8
2	4	2	3	0	0
2	4	3	23	0	54
3	1	1	7	0	25
3	1	2	11	0	3
3	1	3	22	0	13
3	2	1	6	0	7
3	2	2	7	3	31
3	2	3	16	0	0
3	3	1	43	7	7
3	3	2	13	0	0
3	3	3	52	0	11
3	4	1	9	0	7
3	4	2	40	0	11
3	4	3	38	0	34

Appendix Table 2.12 B. Data set containing values from seasonal trampling of vegetation samples. Variables correspond for each column number at top of each column in Appendix Table 2.12B

Year	Year of Species Inventory: 1 = 1996, 2 = 1997, 3 = 2001
Treatment	Season of Trampling: 1 = Late Spring, 2 = Early Summer, 3 = Fall, 4 = Control
Rep	Replication number: 1 through 3
FNative	Native Forbs Only (%) compared with FInvasive
FInvasive	Invasive Forbs Only (%)
F2Native	Native Forbs Only (%) compared with F2Ruderal
F2Ruderal	Ruderal Forbs Only (%)
A1Native	Native species forbs, grasses and sedges (%) compared with A1Ruderal
A1Ruderal	Ruderal species forbs, grasses, and sedges (%)
A2Native	Native species forbs, grasses and sedges (%) compared with A2
A2Invasive	Invasive species forbs, grasses and sedges (%)

Appendix Table 2.12 B. (Continued)

Year	Treatment	Rep	FNative	FInvasive	F2Native	F2Ruderal	A1Native
1	1	1	10.2	6.4	11.75	4.85	18.25
1	1	2	8.25	0.6	5.1	3.75	31.2
1	1	3	8.35	6.05	9.3	5.1	24.9
1	2	1	12.15	5.4	5.35	12.2	25.45
1	2	2	17.35	0.7	7.35	10.7	26.5
1	2	3	1.65	0.9	2.35	0.2	19.9
1	3	1	12.75	3.35	7.3	8.8	21.15
1	3	2	10.05	5.1	9.7	5.45	28.6
1	3	3	7.75	4.95	7.75	4.95	14.5
1	4	1	2.5	0	1.95	0.55	19.25
1	4	2	3.15	0.05	2.15	1.05	18.85
1	4	3	6	0.9	6.2	0.7	25.5
2	1	1	11.65	9.5	11.2	9.95	21.35
2	1	2	6.55	1.55	6.9	1.2	23.1
2	1	3	9.85	10	10.55	9.3	31.8
2	2	1	11.85	3.45	5.3	10	28.35
2	2	2	14.95	0.8	5.45	10.3	28.4
2	2	3	1.2	0.1	0.8	0.5	25.6
2	3	1	21.95	4.85	5.75	21.05	39.95
2	3	2	14.2	11.45	16.6	9.05	39.55
2	3	3	17.3	15.35	27.4	5.25	24.15
2	4	1	4.85	0.6	3.25	2.2	31.9
2	4	2	1.8	0.2	1.8	0.2	23.8
2	4	3	14.5	1.95	14.8	1.65	44.7
3	1	1	9.3	14.4	10.95	12.75	27
3	1	2	0.15	1.85	0.15	1.85	21.65
3	1	3	6.25	8.65	6.15	8.75	24.95
3	2	1	2.1	3.75	3.85	2	26.95
3	2	2	7.6	4.3	8.05	3.85	24.65
3	2	3	5.65	2.85	7.2	1.3	26.75
3	3	1	2.45	8	2.3	8.15	20.2
3	3	2	7.85	0.25	6.15	1.95	40.5
3	3	3	4.15	8.55	2.6	10.1	24.85
3	4	1	0	3.85	0	3.85	25.05
3	4	2	10.55	2	10.55	2	33.4
3	4	3	14.45	9.6	14.65	9.4	45.4

Appendix Table 2.12 B. (Continued)

Year	Treatment	Rep	A1Ruderal	A2Native	A2Invasive
1	1	1	12.7	12.05	20.65
1	1	2	7.5	29.2	9.5
1	1	3	7.05	20.35	13.55
1	2	1	14.9	26.25	14.9
1	2	2	12.2	31.8	6.9
1	2	3	4.05	19.25	5.4
1	3	1	9.45	24.45	6.15
1	3	2	9.55	21.65	16.5
1	3	3	11.6	11.35	14.75
1	4	1	1.3	16.6	3.95
1	4	2	2.3	13.65	7.5
1	4	3	6.35	21.95	10.8
2	1	1	20.95	15	27.9
2	1	2	6.6	21.25	9.1
2	1	3	12.55	26.15	21.8
2	2	1	13.95	30.45	11.95
2	2	2	15.3	31.6	12.1
2	2	3	12.8	24.85	13.55
2	3	1	30.55	47	23.5
2	3	2	23.1	31	34.9
2	3	3	21.45	19.65	36.15
2	4	1	3.85	24.55	11.2
2	4	2	3	20.1	6.7
2	4	3	11.25	39.25	17.85
3	1	1	28.65	12.35	44.95
3	1	2	1.85	10.3	13.2
3	1	3	38.8	20.1	43.65
3	2	1	2.1	23.5	7.3
3	2	2	7.1	20.05	12.2
3	2	3	2.05	16.7	13.85
3	3	1	18.45	18.65	19.95
3	3	2	21.65	36.8	23.65
3	3	3	17.25	18.2	22.35
3	4	1	7.7	13.15	19.6
3	4	2	2.85	21.35	14.9
3	4	3	21.45	31.95	35.1

Appendix Table 2.12 C. Data set containing values from seasonal trampling of vegetation samples. Variables correspond for each column number at top of each column in Appendix Table 2.12B.

Year	Year of Species Inventory: 1 = 1996, 2 = 1997, 3 = 2001
Treatment	Season of Trampling: 1 = Late Spring, 2 = Early Summer, 3 = Fall, 4 = Control
Rep	Replication number: 1 through 3
Sp	Native Forbs Only (%) compared with FInvasive
Tliving	Average number of surviving cuttings
Lshoots	Average number of living willow stems

Appendix Table 2.12 C. (Continued)

Year	Treatment	Rep	Sp	Tliving	Lshoots
1	1	1	1	10	5.8
1	1	2	1	7	1.2
1	1	3	1	10	3.9
1	2	1	1	10	6.4
1	2	2	1	10	8.2
1	2	3	1	10	4.5
1	3	1	1	10	6.2
1	3	2	1	10	3.8
1	3	3	1	9	4.8
1	4	1	1	8	5.7
1	4	2	1	4	1.1
1	4	3	1	10	5.3
2	1	1	1	4	1.7
2	1	2	1	0	0
2	1	3	1	8	1.4
2	2	1	1	8	2.1
2	2	2	1	9	3.8
2	2	3	1	2	0.5
2	3	1	1	8	2.3
2	3	2	1	10	1.4
2	3	3	1	9	2.6
2	4	1	1	6	1.4
2	4	2	1	0	0
2	4	3	1	6	0.6
3	1	1	1	5	1.4
3	1	2	1	1	0.1
3	1	3	1	1	0.3
3	2	1	1	0	0
3	2	2	1	5	1.8
3	2	3	1	0	0
3	3	1	1	9	3.9
3	3	2	1	9	4.3
3	3	3	1	9	5.6
3	4	1	1	4	1
3	4	2	1	0	0
3	4	3	1	6	1.3
1	1	1	2	0	0

Appendix Table 2.12 C. (Continued)

Year	Treatment	Rep	Sp	Tliving	Lshoots
1	1	2	2	5	3
1	1	3	2	3	0.7
1	2	1	2	2	1.4
1	2	2	2	1	0.6
1	2	3	2	4	2.5
1	3	1	2	4	2.5
1	3	2	2	0	0
1	3	3	2	4	1.1
1	4	1	2	2	0.9
1	4	2	2	0	0
1	4	3	2	5	1.4
2	1	1	2	0	0
2	1	2	2	0	0
2	1	3	2	0	0
2	2	1	2	0	0
2	2	2	2	0	0
2	2	3	2	1	0.2
2	3	1	2	1	0.4
2	3	2	2	0	0
2	3	3	2	0	0
2	4	1	2	0	0
2	4	2	2	0	0
2	4	3	2	0	0
3	1	1	2	0	0
3	1	2	2	0	0
3	1	3	2	0	0
3	2	1	2	0	0
3	2	2	2	0	0
3	2	3	2	0	0
3	3	1	2	1	0.3
3	3	2	2	0	0
3	3	3	2	0	0
3	4	1	2	0	0
3	4	2	2	0	0
3	4	3	2	1	0.1

Appendix Table 2.12 D. Data set containing values from core samples including shear stress measurements and covariate values. Variables correspond for each column number at top of each column in Appendix Table 2.12B

Column Number	Variable description for raw data
1	Replication
2	Species: 1 = bluejoint reedgrass; 2 = Tufted hairgrass; 3 = Kentucky Bluegrass; 4 = Baltic Rush; 5 = Water Sedge; 6 = Nebraska Sedge; 7 = Unvegetated Control
3	Soil Depth: 1 = 0 – 10 cm; 2 = 10 – 20 cm
4	Percent Ash(%)
5	Organic Matter (%)
6	Rootbiomass (kg/m^3)
7	Clay (%)
8	Sand (%)
9	Silt (%)
10	Bulk Density (g/m3)
11	Shear Resistance (kPa)

Appendix Table 2.12 D. (Continued)

Rep	Sp	Depth	Ash	OM	Root biomass	Clay	Sand	Silt	Bulk Density	Sheer Resistance
1	1	1	33.3	66.7	13.4	15.9	61.1	22.9	0.7	59.5
1	1	2	27.8	72.2	13.1	8.4	83.1	8.5	0.7	8.3
1	2	1	23.5	76.5	30.6	15.9	61.1	22.9	0.8	100.6
1	2	2	39.4	60.6	7.5	8.4	83.1	8.5	1.1	29.1
1	3	1	32.5	67.5	28.3	15.9	61.1	22.9	0.8	115.0
1	3	2	22.5	77.5	17.4	8.4	83.1	8.5	1.0	26.1
1	4	1	21.5	78.5	42.0	15.9	61.1	22.9	0.8	147.8
1	4	2	27.2	72.8	21.0	8.4	83.1	8.5	0.9	34.3
1	5	1	68.1	31.9	9.5	15.9	61.1	22.9	0.8	88.1
1	5	2	21.2	78.9	19.5	8.4	83.1	8.5	1.0	40.5
1	6	1	44.3	55.7	26.1	15.9	61.1	22.9	0.7	214.9
1	6	2	30.2	69.8	12.1	8.4	83.1	8.5	1.0	32.1
1	7	1	40.0	60.0	10.9	15.9	61.1	22.9	1.1	17.7
1	7	2	39.5	60.6	4.1	8.4	83.1	8.5	1.0	5.6
2	1	1	30.9	69.1	39.2	16.0	65.0	19.0	0.6	177.1
2	1	2	38.4	61.6	17.4	14.5	66.1	19.4	0.8	39.1
2	2	1	61.1	39.0	26.6	16.0	65.0	19.0	1.0	138.2
2	2	2	37.6	62.4	24.6	14.5	66.1	19.4	0.6	42.5
2	3	1	23.5	76.5	21.8	16.0	65.0	19.0	0.7	82.0
2	3	2	30.9	69.1	18.3	14.5	66.1	19.4	0.9	38.0
2	4	1	22.9	77.1	40.0	16.0	65.0	19.0	0.7	111.9
2	4	2	42.4	57.6	7.3	14.5	66.1	19.4	1.0	37.7
2	5	1	38.5	61.5	62.1	16.0	65.0	19.0	0.5	163.2
2	5	2	44.3	55.7	25.4	14.5	66.1	19.4	0.9	25.6
2	6	1	32.1	67.9	33.4	16.0	65.0	19.0	0.8	73.8
2	6	2			18.5	16.0	65.0	19.0	1.0	61.2
2	7	1	26.6	73.5	17.7	16.0	65.0	19.0	0.8	36.7
2	7	2	42.6	57.4	10.7	14.5	66.1	19.4	1.0	18.2
3	1	1	21.1	78.9	29.2	5.7	92.1	2.1	0.6	116.1

Appendix Table 2.12 D. (Continued)

Rep	Sp	Depth	Ash	OM	Root biomass	Clay	Sand	Silt	Bulk Density	Sheer Resistance
3	1	2	38.9	61.1	15.7	6.3	85.1	8.5	0.8	39.5
3	2	1	5.0	95.1	35.1	5.7	92.1	2.1	0.7	137.1
3	2	2	66.3	33.8	6.2	6.3	85.1	8.5	1.2	55.7
3	3	1	39.2	60.8	15.2	5.7	92.1	2.1	1.0	61.0
3	3	2	39.5	60.5	11.4	6.3	85.1	8.5	0.8	29.6
3	4	1	30.4	69.6	23.6	5.7	92.1	2.1	0.7	94.5
3	4	2	52.1	47.9	9.5	6.3	85.1	8.5	0.9	56.9
3	5	1	5.4	94.6	59.1	5.7	92.1	2.1	0.7	98.7
3	5	2	35.5	64.5	13.9	6.3	85.1	8.5	0.9	29.7
3	6	1	36.7	63.3	41.7	5.7	92.1	2.1	0.7	167.6
3	6	2	40.7	59.4	11.2	6.3	85.1	8.5	1.1	21.8
3	7	1	43.2	56.8	38.9	5.7	92.1	2.1	0.9	75.6
3	7	2	55.5	44.5	10.8	6.3	85.1	8.5	0.6	29.2
4	1	1	40.1	59.9	45.1	6.7	87.1	6.2	0.5	329.4
4	1	2	28.6	71.5	29.7	6.7	87.1	6.2	0.7	75.4
4	2	1	32.9	67.2	25.7	14.0	64.0	22.0	0.7	98.8
4	2	2	44.6	55.4	10.6	6.7	87.1	6.2	1.0	38.1
4	3	1	18.6	81.4	26.2	14.0	64.0	22.0	0.7	72.8
4	3	2	42.9	57.1	19.6	6.7	87.1	6.2	0.8	40.6
4	4	1	11.3	88.8	81.3	14.0	64.0	22.0	0.5	293.5
4	4	2	55.9	44.1	21.9	6.7	87.1	6.2	1.0	44.7
4	5	1	44.3	55.7	59.7	14.0	64.0	22.0	0.5	124.1
4	5	2	32.0	68.0	30.1	6.7	87.1	6.2	0.9	42.1
4	6	1	11.0	89.0	34.0	14.0	64.0	22.0	0.8	103.4
4	6	2	28.6	71.5	30.1	6.7	87.1	6.2	1.0	31.8
4	7	1	36.8	63.3	40.1	14.0	64.0	22.0	0.6	24.6
4	7	2	0.0	0.0	38.9	6.7	87.1	6.2	0.9	57.4
5	1	1	12.9	87.1	17.2	14.0	66.4	19.6	1.0	53.8
5	1	2	21.5	78.5	43.1	13.6	70.1	16.4	0.8	146.5
5	2	1	23.2	76.8	21.3	14.0	66.4	19.6	0.9	47.0
5	2	2	30.8	69.3	9.7	13.6	70.1	16.4	1.0	12.5

Appendix Table 2.12 D. (Continued)

Rep	Sp	Depth	Ash	OM	Root biomass	Clay	Sand	Silt	Bulk Density	Sheer Resistance
5	3	1	20.6	79.4	41.1	14.0	66.4	19.6	0.6	57.6
5	3	2	50.4	49.6	14.9	13.6	70.1	16.4	0.7	27.1
5	4	1	20.7	79.3	22.2	14.0	66.4	19.6	0.9	37.8
5	4	2	37.5	62.5	5.3	13.6	70.1	16.4	1.1	20.4
5	5	1	28.3	71.7	19.4	14.0	66.4	19.6	0.9	58.4
5	5	2	24.4	75.6	9.7	13.6	70.1	16.4	1.0	23.6
5	6	1	32.6	67.4	22.8	14.0	66.4	19.6	0.7	131.2
5	6	2	46.3	53.7	7.2	13.6	70.1	16.4	1.0	19.5
5	7	1	34.9	65.1	5.4	14.0	66.4	19.6	1.1	25.0
5	7	2	57.8	42.2	4.2	13.6	70.1	16.4	1.1	27.3
6	1	1	33.8	66.2	21.8	12.5	72.1	15.4	0.7	83.2
6	1	2	24.2	75.8	25.7	11.6	73.0	15.4	0.9	269.8
6	2	1	39.7	60.3	19.2	12.5	72.1	15.4	0.6	78.4
6	2	2	23.0	77.0	30.7	11.6	73.0	15.4	0.8	36.8
6	3	1	55.8	44.2	14.4	12.5	72.1	15.4	1.0	47.5
6	3	2	78.9	21.1	5.5	11.6	73.0	15.4	1.1	22.0
6	4	1	25.9	74.1	36.9	12.5	72.1	15.4	0.7	117.3
6	4	2	52.0	48.0	26.6	11.6	73.0	15.4	0.9	35.0
6	5	1	22.4	77.6	21.9	12.5	72.1	15.4	0.8	129.5
6	5	2	25.0	75.0	26.5	11.6	73.0	15.4	0.9	131.8
6	6	1	50.6	49.4	22.5	12.5	72.1	15.4	0.9	58.2
6	6	2	29.9	70.1	18.0	11.6	73.0	15.4	0.9	51.4
6	7	1	44.9	55.1	10.7	12.5	72.1	15.4	0.8	10.0
6	7	2	42.0	58.0	12.8	11.6	73.0	15.4	1.0	25.6
7	1	1	21.7	78.3	57.5	6.0	75.5	18.5	0.9	27.8
7	1	2	44.1	55.9	21.7	5.9	68.0	26.1	1.3	86.7
7	2	1	50.3	49.7	33.1	6.0	75.5	18.5	0.8	111.6
7	2	2	53.3	46.7	7.9	5.9	68.0	26.1	1.1	38.6
7	3	1	36.7	63.3	25.2	6.0	75.5	18.5	1.0	243.0
7	3	2	28.8	71.2	12.1	5.9	68.0	26.1	1.2	35.6
7	4	1	35.2	64.8	30.2	6.0	75.5	18.5	1.0	170.4

Appendix Table 2.12 D. (Continued)

Rep	Sp	Depth	Ash	OM	Root biomass	Clay	Sand	Silt	Bulk Density	Sheer Resistance
7	4	2	60.0	40.0	18.0	5.9	68.0	26.1	1.0	18.4
7	5	1	28.7	71.3	4.6	6.0	75.5	18.5	0.8	146.1
7	5	2	45.9	54.1	34.6	5.9	68.0	26.1	1.0	88.1
7	6	1	32.4	67.7	61.2	6.0	75.5	18.5	0.7	193.8
7	6	2	22.6	77.4	19.4	5.9	68.0	26.1	1.2	65.8
7	7	1	22.2	77.8	41.5	6.0	75.5	18.5	0.8	144.6
7	7	2	42.7	57.3	40.5	5.9	68.0	26.1	1.0	98.6
8	1	1	37.6	62.4	37.8	18.3	57.7	24.0	0.8	116.1
8	1	2	17.9	82.1	37.0	18.7	59.7	21.6	1.0	29.0
8	2	1	31.5	68.5	23.0	18.3	57.7	24.0	0.9	73.4
8	2	2	64.5	35.5	4.4	18.7	59.7	21.6	1.0	20.9
8	3	1	20.1	80.0	15.8	18.3	57.7	24.0	0.8	53.7
8	3	2	62.1	37.9	6.2	18.7	59.7	21.6	1.0	11.7
8	4	1	33.6	66.5	18.1	18.3	57.7	24.0	0.9	115.7
8	4	2	62.6	37.4	6.7	18.7	59.7	21.6	1.0	23.6
8	5	1	40.3	59.7	27.1	18.3	57.7	24.0	0.9	328.6
8	5	2	22.3	77.7	15.9	18.7	59.7	21.6	1.1	130.0
8	6	1	30.2	69.8	19.1	18.3	57.7	24.0	0.8	51.6
8	6	2	43.2	56.8	8.5	18.7	59.7	21.6	1.0	40.3
8	7	1	50.8	49.2	5.0	18.3	57.7	24.0	0.8	0.1
8	7	2	57.0	43.0	11.2	18.7	59.7	21.6	1.0	4.7
9	1	1	46.8	53.3	44.1	13.6	65.7	20.8	0.8	214.6
9	1	2	48.2	51.8	23.2	13.6	65.0	21.4	1.3	134.3
9	2	1	38.6	61.4	26.1	13.6	65.7	20.8	0.9	72.0
9	2	2	60.3	39.7	5.1	13.6	65.0	21.4	1.1	27.0
9	3	1	25.6	74.4	15.5	13.6	65.7	20.8	1.1	101.8
9	3	2	55.5	44.6	1.9	13.6	65.0	21.4	1.3	27.1
9	4	1	31.6	68.4	35.8	13.6	65.7	20.8	0.9	207.1
9	4	2	41.5	58.5	18.1	13.6	65.0	21.4	1.0	91.7
9	5	1	31.7	68.3	30.4	13.6	65.7	20.8	0.9	123.8
9	5	2	27.7	72.3	7.0	13.6	65.0	21.4	1.2	11.1

Appendix Table 2.12 D. (Continued)

Rep	Sp	Depth	Ash	OM	Root biomass	Clay	Sand	Silt	Bulk Density	Sheer Resistance
9	6	1	41.1	58.9	19.4	13.6	65.7	20.8	1.0	70.1
9	6	2	48.9	51.1	9.5	13.6	65.0	21.4	1.2	70.3
9	7	1	36.5	63.5	13.7	13.6	65.7	20.8	0.9	56.6
9	7	2	44.5	55.5	9.0	13.6	65.0	21.4	1.0	15.0
10	1	1	21.8	78.2	24.8	13.5	61.7	24.8	0.7	207.4
10	1	2	37.2	62.8	23.6	6.3	86.1	7.6	0.9	86.2
10	2	1	8.8	91.2	35.0	13.5	61.7	24.8	0.5	149.0
10	2	2	34.6	65.4	13.1	6.3	86.1	7.6	1.1	29.6
10	3	1	17.0	83.0	35.1	13.5	61.7	24.8	0.5	201.6
10	3	2	38.2	61.8	10.9	6.3	86.1	7.6	1.0	29.3
10	4	1	25.8	74.2	35.1	13.5	61.7	24.8	0.7	60.2
10	4	2	50.0	50.0	12.3	6.3	86.1	7.6	1.0	24.7
10	5	1	49.5	50.5	42.3	13.5	61.7	24.8	0.6	269.8
10	5	2	32.2	67.8	21.8	6.3	86.1	7.6	0.8	45.2
10	6	1	26.3	73.7	28.2	13.5	61.7	24.8	0.6	89.7
10	6	2	37.6	62.4	9.6	6.3	86.1	7.6	1.1	20.4
10	7	1	41.6	58.4	24.3	13.5	61.7	24.8	0.5	35.3
10	7	2	44.1	55.9	17.8	6.3	86.1	7.6	0.7	10.2
11	1	1	32.7	67.3	15.2	8.7	87.1	4.2	0.8	152.9
11	1	2	37.7	62.4	12.8	16.5	57.6	25.8	0.4	29.2
11	2	1	26.7	73.3	45.3	8.7	87.1	4.2	0.5	217.8
11	2	2	55.2	44.8	18.2	16.5	57.6	25.8	0.8	34.5
11	3	1	32.3	67.7	2.6	8.7	87.1	4.2	0.4	119.1
11	3	2	44.7	55.3	14.9	16.5	57.6	25.8	0.8	29.2
11	4	1	32.9	67.1	69.8	8.7	87.1	4.2	0.4	158.3
11	4	2	44.9	55.1	13.0	16.5	57.6	25.8	1.0	28.5
11	5	1	32.2	67.8	54.2	8.7	87.1	4.2	0.5	209.6
11	5	2	49.9	50.1	15.1	16.5	57.6	25.8	0.9	52.1
11	6	1	33.0	67.0	55.1	8.7	87.1	4.2	0.4	124.8
11	6	2	63.4	36.6	12.6	16.5	57.6	25.8	0.9	27.0
11	7	1	49.0	51.0	44.3	8.7	87.1	4.2	0.5	66.2

Appendix Table 2.12 D. (Continued)

Rep	Sp	Depth	Ash	OM	Root biomass	Clay	Sand	Silt	Bulk Density	Sheer Resistance
11	7	2	38.3	61.7	11.3	16.5	57.6	25.8	0.8	29.8
12	1	1	24.5	75.5	21.3	13.9	42.1	44.0	0.6	69.2
12	1	2	36.6	63.4	44.5	23.0	37.0	40.0	0.9	26.6
12	2	1	41.0	59.0	27.9	13.9	42.1	44.0	0.7	79.8
12	2	2	69.5	30.6	14.7	23.0	37.0	40.0	1.0	36.6
12	3	1	32.9	67.2	10.3	13.9	42.1	44.0	0.7	74.8
12	3	2	47.4	52.6	3.7	23.0	37.0	40.0	1.0	29.2
12	4	1	39.8	60.2	0.7	13.9	42.1	44.0	0.6	96.3
12	4	2	49.1	50.9	8.4	23.0	37.0	40.0	1.0	22.6
12	5	1	33.5	66.5	31.3	13.9	42.1	44.0	0.6	143.7
12	5	2	42.6	57.4	11.6	23.0	37.0	40.0	1.0	35.3
12	6	1	41.0	59.0	35.6	13.9	42.1	44.0	0.7	95.1
12	6	2	45.3	54.7	10.7	23.0	37.0	40.0	1.0	41.5
12	7	1	46.0	54.0	10.1	13.9	42.1	44.0	0.7	19.2
12	7	2	39.4	60.6	7.6	23.0	37.0	40.0	0.9	13.2
13	1	1	29.3	70.7	12.7	18.9	36.0	45.0	0.5	72.0
13	1	2	47.4	52.6	9.3	20.9	40.0	39.0	0.8	15.7
13	2	1	45.5	54.5	39.2	18.9	36.0	45.0	0.5	48.3
13	2	2	54.1	45.9	13.4	20.9	40.0	39.0	0.9	40.7
13	3	1	30.9	69.2	16.2	18.9	36.0	45.0	0.6	81.2
13	3	2	44.1	55.9	7.9	20.9	40.0	39.0	0.9	35.9
13	4	1	28.4	71.6	26.4	18.9	36.0	45.0	0.4	266.1
13	4	2	19.8	80.2	3.1	20.9	40.0	39.0	0.8	33.5
13	5	1	41.2	58.8	23.5	13.9	42.1	44.0	0.5	62.2
13	5	2	57.0	43.0	11.3	20.9	40.0	39.0	1.0	24.9
13	6	1	32.9	67.1	17.7	18.9	36.0	45.0	0.5	53.1
13	6	2	39.7	60.3	5.4	20.9	40.0	39.0	0.9	40.9
13	7	1	30.8	69.2	6.4	18.9	36.0	45.0	1.0	7.2
13	7	2	42.0	58.0	3.4	20.9	40.0	39.0	1.1	4.6
14	1	1	29.0	71.0	5.7	6.3	80.2	13.5	0.7	59.8
14	1	2	71.5	28.5	4.2	12.4	71.8	15.9	1.0	36.4

Appendix Table 2.12 D. (Continued)

Rep	Sp	Depth	Ash	OM	Root biomass	Clay	Sand	Silt	Bulk Density	Sheer Resistance
14	2	1	37.6	62.5	6.0	6.3	80.2	13.5	1.1	33.2
14	2	2	85.6	14.5	10.6	12.4	71.8	15.9	1.1	20.4
14	3	1	42.7	57.3	8.2	6.3	80.2	13.5	1.1	37.7
14	3	2	53.6	46.4	3.2	12.4	71.8	15.9	1.1	19.8
14	4	1	20.0	80.1	11.6	6.3	80.2	13.5	0.7	99.3
14	4	2	38.1	61.9	5.2	12.4	71.8	15.9	0.9	29.1
14	5	1	62.7	37.3	38.5	6.3	80.2	13.5	1.0	98.8
14	5	2	29.7	70.3	1.5	12.4	71.8	15.9	1.1	53.1
14	6	1	42.6	57.4	13.1	6.3	80.2	13.5	0.8	187.7
14	6	2	32.3	67.8	5.4	12.4	71.8	15.9	1.0	85.4
14	7	1	38.9	61.1	8.6	6.3	80.2	13.5	1.1	15.7
14	7	2	35.0	65.0	1.6	12.4	71.8	15.9	1.0	12.1
15	1	1	37.9	62.1	10.0	15.2	59.6	25.2	0.7	15.0
15	1	2	35.5	64.5	1.9	16.0	56.0	28.0	0.8	6.7
15	2	1	31.5	68.5	9.9	15.2	59.6	25.2	0.5	79.5
15	2	2	39.1	60.9	5.9	16.0	56.0	28.0	0.8	79.2
15	3	1	35.6	64.4	13.6	15.2	59.6	25.2	0.7	92.1
15	3	2	63.4	36.6	6.5	16.0	56.0	28.0	0.9	3.4
15	4	1	30.6	69.4	7.6	15.2	59.6	25.2	0.7	51.9
15	4	2	47.8	52.2	7.9	16.0	56.0	28.0	0.9	30.8
15	5	1	23.3	76.7	7.0	15.2	59.6	25.2	0.7	94.8
15	5	2	65.4	34.6	14.6	16.0	56.0	28.0	0.9	17.8
15	6	1	27.3	72.8	10.9	15.2	59.6	25.2	0.6	108.1
15	6	2	29.9	70.1	31.4	16.0	56.0	28.0	0.8	34.3
15	7	1	33.7	66.3	13.6	15.2	59.6	25.2	0.7	21.5
15	7	2	52.3	47.7	10.3	16.0	56.0	28.0	1.0	34.7