DISSERTATION

STREAMBANK, SOIL, AND VEGETATION RESPONSES TO GRAZING IN A MONTANE RIPARIAN ECOSYSTEM

Submitted by:

Leonard Warren Jolley

Graduate Degree Program in Ecology

In partial fulfillment of the requirements

For the degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Fall, 2006

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

UMI Number: 3246287

INFORMATION TO USERS

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleed-through, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

UMI®

UMI Microform 3246287
Copyright 2007 by ProQuest Information and Learning Company.
All rights reserved. This microform edition is protected against unauthorized copying under Title 17, United States Code.

ProQuest Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

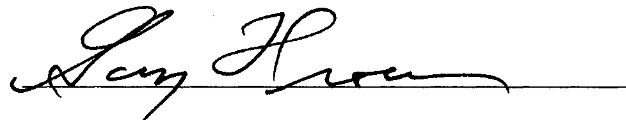
Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

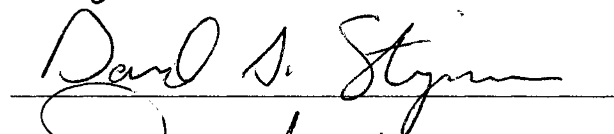
COLORADO STATE UNIVERSITY

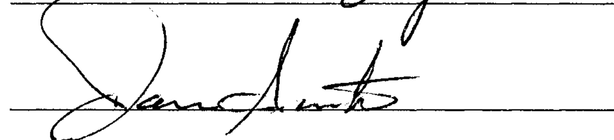
November 3 2006

WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY LEONARD WARREN JOLLEY ENTITLED STREAMBANK, SOIL, AND VEGETATION RESPONSES TO GRAZING IN A MONTANE RIPARIAN ECOSYSTEM BE ACCEPTED AS FULLFILING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

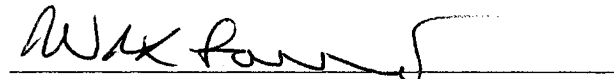
Committee on Graduate Work







Adviser



Department Head

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

ABSTRACT OF DISSERTATION

STREAMBANK, SOIL, AND VEGETATION RESPONSES TO GRAZING

IN A MONTANE RIPARIAN ECOSYSTEM

Riparian areas in the western United States represent 2% or less of the available public and private lands historically used for grazing. Riparian zones are frequently used by grazing livestock and by many wildlife species. Riparian vegetation also influences streambank stability, water quality, and sediment filtration. Riparian communities are often the most productive areas, with deeper and more fertile soils compared with the surrounding uplands. Understanding the impacts of present and past grazing use on riparian zones, and how this use has influenced soil and plant characteristics, may help managers better understand how grazing use may influence streambank stability, roots, and soil characteristics.

One part of this research effort was conducted with a mechanical hoof simulator to measure the direct chiseling impact of hoof prints on streambanks. The objective of this study was to relate the imprints from a hoof simulator on a streambank with variables such as soil texture, soil organic matter, plant community composition, root biomass, and root length density, and as influenced by grazing history.

A second study of soil matrix shear strength was conducted to further characterize resilience of streambank soils based on grazing use. The objective of this study was to

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

determine the shear strength of soil cores and evaluate soil and vegetative characteristics that could be used to predict shear strength.

Soil bulk density for the 0-10 cm depth increased as long-term grazing history increased from exclosures, to 8 years of grazing, to long-term (+ 40 years) grazing. Whereas, soil shear strength values also appeared to follow this trend, (increasing to more than twice the strength in long-term grazed areas compared to exclosures), the differences were not significant. Organic matter declined over these same paddocks. Hoof impacts were found to be significantly greater when the soil surface was wet. Length of fine roots was significantly greater in exclosures. *Carex* dominated plant communities appeared to have greater soil shear strength than grass dominated communities.

A third study was to relate riparian species root strength to root diameter to help explain soil-root matrix strength. Segments of riparian root samples were tested for tensile strength. Root diameter at the point of rupture was found to be highly correlated with root strength. Greater whole root strengths were found for species of sedges, rushes, and willows than for grasses and forbs. The observed pattern of root strength was greater for large roots of willows and least for grasses, with grass-like plants in the mid-range. The opposite was true for tensile strength values (force at failure/root cross-sectional area.)

These and similar findings have management implications for land managers and public agencies for both domestic and wild grazing animals. This research supports the recommendation that, all other things being equal, grazing to achieve less soil surface disturbance should occupy time periods when the soil is dryer. This research also supports the long-term relationship between grazing, soil bulk density, soil organic matter, and rooting pattern.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Results of soil shear strength within the three plant communities showed that the sedge/grass community would have the stronger soil strength when examined at the community level. This is partially explained by sedges root extension, root biomass, and root length density, all of which were greater in the sedge/grass community compared with the other two communities. The grass/rush community appeared to have the weakest soil stability (measured as shear strength, 50% less compared to the sedge/grass group). The grass/forb/shrub community had intermediate soil stability. These results indicated that individual root strength alone did not provide adequate explanation for soil stability (measured as soil shear strength) when compared at the plant community level. However, root abundance characteristics such as total root length, root biomass, and root length density may provide better predictive capabilities of soil stability when measured as soil shear strength within a plant community.

Leonard Warren Jolley
Graduate Degree Program in Ecology
Colorado State University
Fort Collins, CO 80523
Fall 2006

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

ACKNOWLEDGEMENTS

I wish to express my sincere and heartfelt thanks to the faculty with whom I interacted, and from whom I learned so much. I thank my committee: Gary Frasier, Dave Steingraeber, Ellen Wohl, Jim Smith, and especially Joe Trlica as my major advisor for the inspiration and feedback they provided. My special thanks for Joe Trlica for taking on a graduate student well past the norm in age, and keeping faith the studies would come to fruition. I also appreciated the support and counsel provided by Dan Binkley of the Graduate Degree Program in Ecology, Wayne Leininger and Ed Redente of what was formerly the Rangeland Ecosystem Science Department.

I also appreciate the help and friendship of Daryl Mergen, Rob Pearce, Tana Allshouse, and Barbara Oskroba in this journey.

The graduate funding and time provided by my employer US Department of Agriculture Natural Resources Conservation Service and by several supervisors over the years, has been extraordinary, and it is my hope that I can repay them and the taxpayers through my career.

And finally, I thank God for my wonderful wife Maria, and for my family, as they have been steadfast in their support.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

TABLE OF CONTENTS

List of Tables..ix
List of Figures...xi
CHAPTER I 1
BACKGROUND 2
HYPOTHESIS AND OBJECTIVES 6
RESEARCH APPROACH 7
LITERATURE CITED 9
CHAPTER II 13
INTRODUCTION 14
STUDY AREA 16
MATERIALS AND METHODS 17
Streambank Morphology 19
Experimental Design and Data Analysis 20
RESULTS AND DISCUSSION 22
Plant Communities 22
Principal Component Analysis 24
CONCLUSIONS 25
MANAGEMENT IMPLICATIONS 26
LITERATURE CITED 27
CHAPTER III 38
STUDY AREA 43
MATERIALS AND METHODS 44
Hoof Simulator 45
Shear Strength 47
Data Analyses 49
RESULTS AND DISCUSSION 51
Grazing Histories 51
Hoof Simulator 52
Shear Test Study 54
CONCLUSIONS 58
LITERATURE CITED 61
CHAPTER IV 74
INTRODUCTION 75
STUDY AREA 78
MATERIALS AND METHODS 79
Experimental Design and Data Analyses 82
RESULTS AND DISCUSSION 84
Root Tensile Strength and Extension 84
Root Diameters 85
Root Extension 85
Root Morphology and Anatomy 88
Correlations Among Root Variables 94
CONCLUSIONS 94
LITERATURE CITED 99

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

CHAPTER V 116
SUMMARY AND CONCLUSIONS 118
FUTURE RESEARCH NEEDS AND RECOMMENDATIONS 120
LITERATURE CITED 123
APPENDIX A SHEEP CREEK MAP 126
APPENDIX B CHAPTER II 128
APPENDIX C CHAPTERS III & IV 144

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

List of Tables

Table 2.1. Means for plant and soil variables for streambank paddocks that were grazed at three intensities in 1995 36

Table 2.2. Correlation Matrix resulting from a reduced set of variables using PCA..... 37

Table 3.1. Means and standard errors for soil and plant characteristics found to be significantly different at $p \leq 0.10$. Standard errors are in parentheses and means followed by a different letter are significantly different ($p \leq 0.10$)........... 71

Table 3.2. Root characteristics for vegetation lifeforms of riparian plant species at Sheep Creek, Colorado. Different letters within a row indicate significant differences ($p \leq 0.10$) among life form means for root characteristics analyzed. Standard errors are in parentheses below the mean. 72

Table 3.3. Results of stepwise linear regression analyses for dependent variables hoof simulator impact and soil shear strength. The complete data set was used before grazing history stratification of data was conducted........... 73

Table 4.1. Regression relationship of force at tensile failure with root diameter for riparian species, where x = root diameter (mm) and y = force (Newtons)............ 109

Table 4.2. Root characteristics for five vegetation classes of riparian species, 1996.... 110

Table 4.3. Results of simple linear regression showing relationship of extension/elasticity at root tensile failure and root cross-section (mm^2) of major riparian plant species and lifeforms at Sheep Creek, Colorado................. 111

Table 4.4. Individual riparian species ranking in descending order for root tensile failure, force/cross sectional area, and root extension at root tensile failure. Plant life form is in column to the right of species code 112

Table 4.5. Summarized rankings for force at root failure of plant lifeforms of Table 4.4. Rankings in second column are compared by cross sectional area (tensile strength)........ 112

Table 4.6. Root characteristics for major riparian plant species at Sheep Creek, Colorado. Standard errors are in parentheses below the mean........ 113

Table 4.7. Means and standard errors of variables for the results of the three vegetation groups formed from the cluster analysis. These groups were derived to compare vegetation, soil, and root characteristics found along a riparian area at Sheep Creek, Colorado. Standard errors are in parentheses and means within a row followed by different letters were significantly different ($p < 0.05$)........ 114

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 4.8. Results of stepwise multiple linear regression analyses showing relationship of shear soil strength and weighted values for root tensile failure, and root cross-section (mm^2), root extension at root tensile failure, and canopy and soil variables for major plant life at Sheep Creek, Colorado................ 115

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

List of Figures

Figure 1.1. Exclosure and pin-table adjacent to Sheep Creek, 1996.................... 12

Figure 2.1. Cattle grazing on a moderately grazed and trampled grass-like plant community paddock on the streambank of Sheep Creek........................... 31

Figure 2.2. A streambank profile for Sheep Creek on two dates of measurement for paddocks with no grazing... 32

Figure 2.3. An example of streambank profile for Sheep Creek before and after a heavy intensity of grazing.. 33

Figure 2.4. Arithmetic mean values for streambank elevation differences for three grazing treatments for the steep 1 m section of streambank adjacent to and above high water level... 34

Figure 2.5. Percentage of measurements that showed a measured change from surveys before and after treatment.. 35

Figure 3.1. Orientation of the pin-table to the streambank within a 5 x 5 m plot adjacent to Sheep Creek.. 67

Figure 3.2. The hoof simulator in operation, configured for hoof impression 68

Figure 3.3. Hoof simulator in configuration to perform shear tests on 10 cm diameter soil cores.. 69

Figure 3.4. Comparison of soil shear strength for three montane riparian communities.. 70

Figure 4.1. Servohydraulic biaxial mechanical testing machine used to determine root tensile strength, CSU Veterinary School............................... 104

Figure 4.2. Typical tensile failure for *Juncus arcticus* with applied force............ 105

Figure 4.3. Two-stage root tensile failure for *Juncus arcticus*; cortex failure at 12 Newtons, and stele failure at 7 Newtons, but 10 seconds later.......... 106

Figure 4.4. Example of root structure for *Juncus arcticus*............................ 107

Figure 4.5. Typical plot of force to failure for varying root diameters of *Carex aquatilis*. Regression line forced through the origin........................ 108

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

CHAPTER I

INTRODUCTION

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

BACKGROUND

Riparian areas are under scrutiny in the West as advocates for water quality, wildlife, and biodiversity point out the degraded state of many stream environments. Increasing numbers of laws, policies, and regulations now require changes in rangeland grazing practices to protect and enhance ecosystem diversity and water quality (Chaney et al. 1993). Streambanks are the transition zones between terrestrial and aquatic environments in these areas and can greatly affect both diversity and water quality (Platts 1991).

It is recognized that riparian streambanks have been altered by animal and human impacts. This has consequences for both water quality and aquatic life (Sidle and Sharma 1996). Duce (1918) noted the role that cattle played in affecting erosion of canyon bottoms. Naiman and Rogers (1997) indicated that large animals could significantly modify the structure and function of river corridors. Disturbances caused by movement and use by elk, moose, and domestic livestock are distinct from changes related to fluvial geomorphology and the action of streams. However, past research efforts have not conclusively shown how livestock use affects streambanks (Buckhouse et al. 1981, Kauffman and Krueger 1984).

Across a broad scale, Wohl (2001) noted changes in the form and function of streams along the Front Range of Colorado attributed to beaver and tree removal, and mining and road and railroad construction. She described profound alteration to mountainous river systems at the level of plants and animals, chemical and physical processes, and to the overall landscape. The intent of this research was to examine that portion of streambank stability directly affected by ungulate traffic, but above the waterline, in order that fluvial geomorphic complexities be avoided.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Skovlin (1984) stated that the importance of bank stability to fisheries habitat centered on the reduction of silt (sediment) production. Fishery biologists Platts and Raleigh (1984) agreed, but contended that of equal or greater importance was the loss of good channel and bank morphology that resulted from continued streambank instability. They indicated that specialized grazing systems should be studied over the next decade to determine if some systems could be used to protect and enhance riparian habitats.

Buckhouse et al. (1981) did not find a relationship between streambank erosion and various grazing treatments in northeastern Oregon. Kauffman et al. (1983) found significantly greater streambank losses (as measured by streambank recession) in grazed riparian pastures as compared with areas where grazing had been excluded, but they noted that more work was needed to identify thresholds of significance for that loss.

Kauffman and Krueger (1984) reviewed the effects of livestock grazing on streambank morphology. They concluded that streambanks were quite variable and that stability depended on several factors, in particular, the nature of the stream system studied. In other words, the susceptibility of a streambank to livestock grazing will vary by the inherent stream flow energy, degree of meanders, and composition of bed and bank material of a stream. Rhodes et al. (1995) found it very difficult to distinguish grazing impacts from natural streambank variability. Trimble and Mendel (1995) were frustrated by contradictory evidence in the literature, but concluded that cows were important agents of geomorphological change. Chambers and Miller (2004) noted that assignment of cause and effect to diffuse anthropogenic disturbances such as heavy grazing was difficult, and it might not be possible to distinguish the amount of channel incision caused by climate change from that resulting from anthropogenic disturbance.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Livestock can contribute to streambank instability in at least three ways: 1) they may leave insufficient vegetation on banks for protection (Platts 1991), 2) hoof action results in 'chiseling' and soil compaction (George et al. 1992, Platts 1991, Skovlin 1984), and 3) the removal of above-ground leaf tissue will reduce root length and mass over the long term, reducing the binding effects of roots on streambanks (Manning et al. 1989, Kleinfelder et al. 1992). Long-term browsing and trampling of riparian shrubs may cause the size and vigor of shrubs and associated roots to decline (Skovlin 1984). Livestock trailing adjacent to vertical banks can increase loading and lead to streambank failure (Platts 1993, personal communication).

Platts and Raleigh (1984) believed that hoof action (chiseling) was the predominant deleterious effect of livestock on streambank stability. Williamson et al. (1992) found undercutting of banks in New Zealand was largely unaffected by grazing streambanks, whereas channelizing streams led to severe streambank erosion. Selby (1982) discussed factors that contributed strength to soils in sloped situations, and concluded that mechanical reinforcement of the soil was provided by root networks, particularly by trees.

Kleinfelder et al. (1992) found that herbaceous roots appeared to supply most of the compressive strength and soil stability found in meadow streambanks, especially those dominated by Nebraska sedge (*Carex nebrascensis* Dewey). Dunaway et al. (1994) found that the interaction of plants and soil was important, and that knowledge of both vegetation and soil texture was necessary to predict streambank erodibility and to manage streambank stability. Manning et al. (1989) found that total root length density and root mass to a depth of 40 cm were positively correlated with the wetness of the site, (i.e., there were more roots at the wetter sites), thus reinforcing streambank soils.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Most geomorphic studies of streambank erosion have used techniques such as erosion pins in the streambanks to quantify erosion from the streambank as related to flow regime, and have ignored the contribution of roots (Goss 1973, Grissinger et al. 1981, Hooke 1980). For example, Wolman (1959) focused on soil characteristics that contributed to riverbank erosion and found 85% of erosion (measured by steel pins driven into the bank) occurred during winter months in Maryland. One of the factors implicated was the vulnerability of moist soil to disturbance. Marlow and Pogacnik (1985) found that streambank moisture explained 71 to 85% of bank susceptibility to change during a three-year study in Montana.

Geotechnical scientists have used analytical approaches in their investigation of soil-root interactions (Wu et al. 1988a, 1988b). Roots from 0.2 to 1.0 cm diameter were partly excavated and force applied to roots until they failed. Smith (1976) noted that bank sediment (silt) with a root volume of 16-18% offered 600 times more resistance to bank erosion and areas with an additional 5 cm of matted roots (i.e., roots concentrated at the surface) afforded 20,000 times more protection from erosion than comparable sediment with neither roots nor root mat. Laboratory and in-situ shear tests of barley (*Hordeum vulgare* L.), sunflower (*Helianthus annuus* L.), Ponderosa pine (*Pinus ponderosa* P. and C. Lawson), and alfalfa (*Medicago sativa* L.) roots were used to investigate soil-root interactions. These experiments have generally shown greater soil shear strength with greater root volume (Waldron and Dakessian, 1982). Physiological approaches have been used to examine the response of roots to differences in soil strength, but not the responses of the soil-root matrix to external forces (Atwell 1993). Unger and Kaspar (1994) in their review noted that plants could exert pressures on soil of 2500 kPa during root growth, and pointed toward complex interrelationships among soil compaction, density, strength, water content, aeration, root

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

growth, and plant growth and yield. Swanson and Kamyab (1996) found that many soil and root variables differed among plant community types, and their study suggested that a high level of erosional resistance was provided by roots of different riparian communities.

Much progress has been made in the analysis of forces at work on the streambanks of incised channels, where the driving forces of streambank instability were controlled by bank height and slope, the unit weight of the soil and the water in it, and the weight imposed by objects on top, on the side, or within the streambank (Simon and Collison 2002). While the montane riparian streambanks I studied were neither deeply incised nor wooded, I investigated the interaction of soils and vegetation to the weight and force of ungulate hooves above the waterline. The resistance and resilience of streambanks to animal traffic reflects the effects of compaction and shear imposed by an animal hoof (in the case of large ungulates) on a soil medium (Trimble and Mendel 1995) versus the inherent properties of that medium and its tendency to recover (Wheeler et al. 2002). The experiments I performed to test this resilience describe measures of streambank stability.

HYPOTHESIS AND OBJECTIVES

Hypotheses

1. Streambank morphology, soil physical properties, herbaceous plant communities, and root characteristics of streambank soils contribute to the resistance of streambanks to livestock traffic.
2. Streambank stability in grazed riparian areas is inversely related to intensity of livestock trampling.

Specific Objectives

1. Evaluate streambank morphology as affected by cattle trampling.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

2. Determine the importance of streambank soil physical properties, herbaceous plant cover, and root morphology on streambank soil strength and how these variables are affected by livestock use and trampling.
3. Relate artificial hoofprints to soil extension and soil and root physical properties as indicators to streambank stability.
4. Determine effects of riparian root tensile strength, root diameter and root density at the species level on soil-root matrix strength.
5. Determine resistance of the streambank soil-root matrix to imposed shear stress.

RESEARCH APPROACH

Grazing treatments at three intensities were imposed on small streambank paddocks of 0.0025 ha in size (5 m by 5 m) to determine if changes occurred in streambank morphology (Figure 1.1) (see Sheep Creek map in Appendix A). These changes were measured by repeated sag-tape survey measurements (Harrelson et al. 1994) before and after grazing during one growing season. Plot locations were selected to sample several plant community conditions typical of this montane riparian system. Plot size was constrained by the number of animals available for the experiment and by the use of straight stretches of stream of similar topographic morphology. Profiles of streambank elevations were compared before and after grazing to evaluate grazing treatment intensity on streambank shape. Comparisons were made by both graphical plots and by standard statistical methods. Results of this work are discussed in Chapter II.

A hoof impact simulator was constructed to simulate trampling effects but without the variability associated with live animals. Plot locations used as controls the previous year were utilized in this second season to impose artificial hoof imprints into the soil. Imprint

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

depth was associated with numerous variables measured on the streambank, both above and below the soil surface (Chapter III). Soil cores were also taken and subjected to a shear force to further measure this resistance (Chapter III).

In an effort to further investigate the components of soil matrix strength and integrity, more than 850 root samples of sedges (*Carex* spp.), willows (*Salix* spp.), bluejoint reedgrass (*Calamagrostis canadensis* (Michx.) Beauv.), tufted hairgrass (*Deschampsia caespitosa* (L.) Beauv.), Baltic rush (*Juncus arcticus* Willd.), Kentucky bluegrass (*Poa pratensis* L.), and Timothy (*Phleum pratense* L.) were taken from the streambank community. These root samples were subjected to a controlled uniaxial tension until failure, with tension, extensibility and time to failure all recorded. This experiment was used to describe intrinsic strength and resistance of root segments to one-dimensional stress, with biomechanical interpretations (Niklas 1992). Results for root strength of these species are discussed in Chapter IV.

The final chapter (V) summarizes the major conclusions of the study. An integration of soil and plant characteristics that affect streambank stability is included.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

LITERATURE CITED

Atwell, B. J. 1993. Response of roots to mechanical impedance. *Environmental Experimental* Botany 33:27-40.

Buckhouse, J.C., J.M. Skovlin, and R.W. Knight. 1981. Streambank erosion and ungulate grazing relationships. *Journal of Range Management* 34:339-340.

Chambers, J. C. and J. R. Miller [EDS.]. 2004. Great basin riparian ecosystems: ecology, management, and restoration. Covelo, CA: Island Press. 303 p.

Chaney, E., W. Elmore, and W. S. Platts. 1993. Managing change - livestock grazing on western riparian areas. Denver, CO: Environmental Protection Agency, Region 8. 31 p.

Duce, J. T. 1918. The effect of cattle on the erosion of canyon bottoms. *Science* 47:450-452.

Dunaway, D., S. R. Swanson, J. Wendel, and W. Clary. 1994. The effect of herbaceous plant communities and soil textures on particle erosion of alluvial streambanks. *Geomorphology* 9:47-56.

George, M., D. Lile, and N. McDougald. 1992. Monitoring livestock impacts in mountain meadows. Unpublished Report. Department of Agronomy and Range, University of California. Davis, CA. 42 p.

Goss, D. W. 1973. Relation of physical and mineralogical properties to streambank stability. *Water Resources Bulletin* 9:140-144.

Grissinger, E. H., W. C. Little, and J. B. Murphey. 1981. Erodibility of streambank materials of low cohesion. *Transactions of the ASAE* 24:624-630.

Harrelson, C. C., C. L. Rawlins, and J. P. Potyondy. 1994. Stream channel reference sites: an illustrated guide to field technique. *USDA Forest Service General Technical Report* RM-245. 61 p.

Hooke, J. M. 1980. Magnitude and distribution of rates of river bank erosion. *Earth Surface Processes* 5:143-157.

Kauffman, J. B., W. C. Krueger, and M. Vavra. 1983. Impacts of cattle grazing on streambanks in northeastern Oregon. *Journal of Range Management* 36:683-685.

Kauffman, J. B. and W. C. Krueger. 1984. Livestock impacts on riparian ecosystems and streamside management implications: a review. *Journal of Range Management* 37:430-438.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Kleinfelder, D., S. R. Swanson, G. Norris, and W. Clary. 1992. Unconfined compressive strength of some streambank soils with herbaceous roots. *Soil Science Society of America Journal* 56:1920-1925.

Manning, M. E., S. R. Swanson, T. Svejcar, and J. Trent. 1989. Rooting characteristics of four Intermountain meadow community types. *Journal of Range Management* 42:309-312.

Marlow, C. B. and T. M. Pogacnik. 1985. Time of grazing and cattle-induced damage to streambanks. *In:* R. Johnson [ED.]. Proceedings of the North American Riparian Conference: April 15-19; Tucson, AZ. Washington, DC: USDA Forest Service. p. 279-284.

Naiman, R. J. and K. H. Rogers. 1997. Large animals and system-level characteristics in river corridors: implications for river management. *Bioscience* 47:521-529.

Niklas, K. J. 1992. Plant biomechanics: an engineering approach to plant form and function. Chicago, IL: The University of Chicago Press. 607 p.

Platts, W. S. 1991. Livestock grazing. *In:* William R. Meehan [ED.]. Influences of forest and rangeland management on salmonid fishes and their habitats. Bethesda, MD: American Fisheries Society Special Publication #19. p. 389-423

Platts, W. S. and R. F. Raleigh. 1984. Critique - impacts of grazing on wetlands and riparian habitat. *In*: Developing strategies for rangeland management. Boulder, CO: Westview Press. p. 1105-1118.

Rhodes, B. J., C. B. Marlow, and H. W. Sherwood. 1995. Monitoring streambank stability: Grazing impacts or stream variability? *Montana AgResearch* 12:3-8.

Selby, R. 1982. Hillslope materials and processes. New York, NY: Oxford University Press. 264 p.

Sidle, R. C. and A. Sharma. 1996. Stream channel changes associated with mining and grazing in the Great Basin. *Journal of Environmental Quality* 25:1111-1121.

Simon, A, and A.J.C. Collison. 2002. Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. *Earth Surface Processes and Landforms* 27:527-546.

Skovlin, J. M. 1984. Impacts of grazing on wetlands and riparian habitat: a review of our knowledge. *In*: Developing strategies for range management, Boulder, CO: Westview Press. p. 1001-1102.

Smith, D. G. 1976. Effect of vegetation on lateral migration of anastomosed channels of a glacier meltwater river. *Bulletin of the Geological Society of America* 87:857-860.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Swanson, S. and I. Kamyab. 1996. Simulated streambank erosion of surface and subsurface samples from three meadow plant communities. Proc. of the 6th Federal Interagency Sedimentation Conference. March 10-14, 1996. Las Vegas, NV. Volume III. p. 100-107.

Trimble, S. W. and A. C. Mendel. 1995. The cow as a geomorphic agent - a critical review. *Geomorphology* 13:233-253.

Unger, P. W. and T. C. Kaspar. 1994. Soil compaction and root growth: a review. *Agronomy Journal* 86:759-766.

Waldron, L. J. and S. Dakessian. 1982. Effect of grass, legume, and tree roots on soil shearing resistance. *Journal of the Soil Science Society of America* 46:894-899.

Wheeler, M. A., M. J. Trlica, G. W. Frasier, and J. D. Reeder. 2002. Seasonal grazing affects soil physical properties of a montane riparian community. *Journal of Range Management* 55:49-56.

Williamson, R. B., R. K. Smith, and J. M. Quinn. 1992. Effects of riparian grazing and channelisation on streams in Southland, New Zealand. 1. Channel form and stability. *New Zealand Journal of Marine and Freshwater Resources* 26:241-258.

Wohl, E. E. 2001. Virtual rivers. New Haven, CT: Yale University Press. 210 p.

Wolman, M. G. 1959. Factors affecting erosion of a cohesive riverbank. *American Journal of Science* 257:204-216.

Wu, T. H., P. E. Beal, and C. Lan. 1988a. In-situ shear test of soil-root systems. *Journal of Geotechnical Engineering* 114:1376-1394.

Wu, T. H., R. M. McOmber, R. T. Erb, and P. E. Beal. 1988b. Study of soil-root interaction. *Journal of Geotechnical Engineering* 114:1351-1375.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Figure 1.1. Exclosure and pin table adjacent to Sheep Creek, 1996.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

CHAPTER II

LIVESTOCK GRAZING AND HOOF IMPACT ON A MONTANE RIPARIAN STREAMBANK

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

INTRODUCTION

Livestock can contribute to streambank instability in at least three ways: 1) they may leave insufficient vegetation on streambanks for protection from hooves (Duce 1918), 2) the direct effect of 'chiseling' and soil compaction by hoof action (George et al. 1992, Platts 1991, Skovlin 1984), and 3) removal of phytomass could result in reduced root length and mass, thus reducing the binding effects of roots on streambank soil (Manning et al. 1989, Kleinfelder et al. 1992). McDowell and Magilligan (1997) found that cattle grazing has often been associated with loss of riparian vegetation, destabilization of banks, channel widening, and decrease in pool area. Binkley et al. (2002) found that grazing and hoof action by elk significantly increased bulk density of soil, with greater effects on soils with fewer rocks.

Long-term browsing and trampling of riparian shrubs may cause the most deleterious effect as the shrubs may become weak and die (Skovlin 1984). However, Platts and Raleigh (1984) believed that hoof action (chiseling) was the predominant deleterious effect of livestock on streambank stability. Streams are dynamic systems (Knighton 1984); streambank stability in this study refers to the resistance to change in streambank morphology mediated by livestock and other large animal impacts. Williamson et al. (1992) found that undercutting of banks in New Zealand was largely unaffected by grazing stream margins.

Selby (1982) discussed factors that contributed strength to soils on slopes and concluded that mechanical reinforcement of the soil was provided by root networks, particularly by trees. Kleinfelder et al. (1992) found that herbaceous roots appeared to supply most of the compressive strength and soil stability found in meadow streambanks, especially those dominated by Nebraska sedge (*Carex nebrascensis* Dewey). Dunaway et

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

al. (1994) found that the interactions of plants and soil were important, and that knowledge of both vegetation and soil texture were necessary to predict streambank erodibility and to manage streambank stability. Manning et al. (1989) found that total root length density and root mass were correlated with the wetness of a site (i.e., there were more roots in wetter sites).

Most geomorphic studies of streambank erosion have used techniques such as erosion pins in the streambanks to quantify erosion from the streambank as related to flow regime, but have ignored the contribution of roots (Goss 1973, Grissinger et al. 1981, Hooke 1980). Smith (1976) noted that bank sediment with a root volume of 16-18% and a root mat 0.5 m thick afforded 20,000 times more protection from erosion than did comparable sediment without vegetation.

Several plant and soil features of streambanks may affect their resistance to trampling effects. The purpose of this study was to determine the cumulative impacts of cattle grazing and trampling on streambank morphology for a montane riparian area as related to soil texture, soil organic matter, past grazing history, and plant species composition.

Hypotheses

1. Streambank morphology, soil physical properties, herbaceous plant communities, and root characteristics of streambank soils contribute to the resistance of streambanks to livestock traffic.
2. Streambank stability in grazed riparian areas is inversely related to intensity of livestock trampling.

Specific objectives were to:

1. evaluate streambank morphology as affected by cattle trampling;

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

2. determine the importance of streambank soil physical properties and herbaceous plant cover and communities for streambank stability and how these variables are affected by livestock use and trampling.

STUDY AREA

The study was conducted during the summer of 1995 at 40^0 38' latitude and 105^0 38' longitude in the riparian community along Sheep Creek in the Roosevelt National Forest of north-central Colorado. The research site was located along 2.4 km of Sheep Creek. The site is approximately 80 km northwest of Fort Collins, Colorado at an elevation of about 2500 to 2550 m. Historical land ownership was primarily the Union Pacific Railroad and the U.S. Forest Service (USFS), but is now under USFS management. The area is open to recreation (such as fishing, hunting, and camping), and is used for livestock grazing, timber harvesting, and as a water catchment for downstream irrigation.

The vegetation of the montane riparian community along Sheep Creek consists of mixtures of willows (*Salix* spp.), sedges (*Carex* spp.), rushes (*Juncus* spp.), Kentucky bluegrass (*Poa pratensis* L.), tufted hairgrass (*Deschampsia caespitosa* (L.) Beauv.), Canada reedgrass (*Calamagrostis canadensis* (Michx.) P. Beauv.), and other minor species. (All species are described according to: USDA, NRCS. 2006. The PLANTS Database. National Plant Data Center, Baton Rouge, LA 70874-4490 USA.)

Soils in the study area were derived from granitic parent material and are deep, coarse, sandy to clay loam family of pachic cryoborolls (USDA 1980), with inclusions of fluvaquents in what is described as a 'mountain meadow' range site. Mean annual precipitation for the study site is approximately 400 mm (NOAA 1995). Growing season

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

precipitation averages about 240 mm (NOAA 1995). Sheep Creek is a small headwaters stream and is classified as a C-4 stream according to Rosgen (1996).

The USFS and Colorado Division of Wildlife (DOW) constructed two livestock exclosures in 1956 and a third in 1959 along Sheep Creek to evaluate recovery from historic heavy grazing by livestock. Collectively, these exclosures protect a total of 40 ha along 2.5 km of stream (Schultz and Leininger 1990). Three additional exclosures were built in 1988 encompassing approximately 1.3 ha. In 1988 three areas totaling 1.8 ha, which had been protected from livestock grazing since 1956 or 1959, were opened to grazing (Popolizio et al. 1994).

MATERIALS AND METHODS

Small paddocks 0.0025 ha in size (5 m by 5 m) were located along reaches of Sheep Creek. They were fenced for confinement of steers that were used to apply a controlled grazing treatment. Fencing was positioned to allow cattle to enter the stream from the bank, but they could not cross the stream (Figure 2.1). Access to water depended on access to the creek, and banks were navigable by livestock. Study sites included areas excluded from grazing since 1956; sites excluded from grazing from 1956-1988, but opened in 1988 to grazing; and sites grazed each summer grazing season for many years. Sites were located to represent both grass (*Poa* spp., *Calamagrostis* spp.) and grass-like (*Carex* spp., *Juncus arcticus* Willd. ssp. *littoralis* (Engelm.) Hultén) riparian communities.

Three to five Holstein steers (approximately 450 kg each) were penned into each paddock (from 1 to 4 hours) to achieve moderate or heavy levels of grazing impact. Animals were confined on the plots during the afternoon following their morning activities in another experiment, and their appetites were variable during the period of confinement. Therefore,

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

assignment of grazing treatments reflects actual plant utilization achieved for comparison of grazing treatments in the statistical analyses. Treatments included three levels of grazing: control, moderately grazed, and heavily grazed, for each of the two plant communities. Little ungrazed and non-fouled vegetation remained at the end of the grazing period at the heavier level of utilization (60% utilization on average). Moderately grazed paddocks were grazed until an intermediate level of vegetation remained (35% utilization on average). Utilization of key species was determined by comparison with the photographic utilization guide for riparian species developed by Kinney and Clary (1994). Livestock were excluded from the ungrazed control paddocks. Treated paddocks were grazed once during the 1995 growing season.

Two vegetation types (1. grass-like (*Carex* spp., *Juncus arcticus*) and 2. grass (*Calamagrostis canadensis* and *Poa pratensis*)) were the dominant plant communities and these community assignments were based on canopy cover by species. Table 2.1 describes treatment specifics.

Soil physical properties collected in 1995 were used in the analyses and explanation of the treatment effects. Soil texture and organic matter were sampled at 0-10, 10-20, and 20-30 cm (if possible) depths in each paddock in 1995. The deepest samples were sometimes impossible to obtain because of large cobbles in the soil profile. Three soil cores of dimensions 7 cm x 10 cm were taken within each paddock and for each depth using a Giddings soil sampler (Giddings, Ft. Collins, Colo.). Soil texture was determined using hydrometer analysis (Bouyoucos 1962, Allen 1990). Soil samples were weighed, ashed at 550^{0}C for 5 hours (Storer 1984, Klute 1986, Pearce 1995), and re-weighed for organic matter determination.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Soil physical properties collected in 1995 were used in the analyses of grazing histories, but soil characteristics in 1996 (a year following experiments) were also summarized and used to help explain relationships among the three grazing histories. Three soil cores of dimensions 7 cm x 10 cm were taken within each plot and for each depth using a Giddings soil sampler (Giddings, Ft. Collins, Colo.). This resulted in 9 soil samples for each sample plot (3 depths at 3 locations). Soil texture, soil bulk density, and organic matter were sampled at 0-10, 10-20, and 20-30 cm depths and at three locations along a 2 m length of the streambank perpendicular to the stream channel. The 1996 soil bulk density and soil organic matter data came from samples nearest the stream, at the break point of the streambank topography, and only the 0-10 cm depth was sampled. This was used because it was the portion of the soil profile most impacted by the grazing animals (Wheeler et al. 2002).

Plant canopy cover and production were determined just prior to grazing within 1 m of the streambank edge for each paddock using both a point frame and a quadrat. Plant cover was measured along the 5 m streambank parallel to the stream with 10 replications of a 10-point frame on the streambank (Devaurs and Gifford 1984). One 0.25 m^2 plot within 1 m of the streambank in each paddock was randomly located and clipped to determine aboveground biomass by species (Bonham 1989). Clipped samples of each individual species from this plot were put in paper bags, dried for 72 hours at 50^0 C in a forced draft oven, and then weighed. Results were expressed as species composition by weight.

Streambank Morphology

Two permanent transects were established to describe the streambank profile at 1/3 and 2/3 of the distance along a 5 m reach of streambank frontage within each treatment plot. A 'sag tape' was used to determine vertical elevations and horizontal bank measurements

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

following the methodology of Platts et al. (1987) and Harrelson et al. (1994). A survey level and rod were used with the sag tape to measure streambank profiles. Measurements were taken horizontally at decimeter increments and by millimeters vertically. Bank morphology along these measured transects was determined before grazing and after grazing treatments.

The change in streambank morphology was described by comparing streambank elevations at decimeter 'sag tape' points taken before and after livestock grazing. The entire streambank to the channel bottom (invert) was measured with use of the tape, survey rod, and survey instrument. The streambank was divided into an upper section (farthest from water's edge) and the lower section that was above high water level. This lower section of streambank was above high water (during the survey period) to the natural slope break that was approximately 1 m horizontally from the edge of the water. Elevation changes between survey dates were analyzed by grazing treatments for the entire sag tape length, the upper length, and the lower (usually steeper) section. Both the arithmetic (by subtraction) difference and absolute difference between bank heights before and after grazing treatment were analyzed. Absolute differences were used because they allowed the fullest expression of both positive and negative elevation changes attributable to animal hoof action.

Experimental Design and Data Analysis

Grazing intensities (none, moderate, and heavy) and grazing histories (grazing excluded since 1956, grazing excluded 32 years [1956-1988], and long-term grazing) were examined to determine influence of grazing on streambank morphology. Absolute differences and arithmetic differences were used as dependent variables in these analyses.

The experimental design was initially established to conduct a two-way analysis of variance using grazing treatments and plant community as the independent variables.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

However, the actual field design was unbalanced, so a general linear model (GLM) was used instead (Ott 1988). Least significant difference tests (LSD) were used to separate significant ($P < 0.10$) means (SAS 1994). This analysis was performed on the entire section of streambank measured and two sections of the streambank that were measured (1/ the upper flatter portion of streambank and 2/ closest to the water's edge).

Treatments (grazing intensities) and grazing histories were both considered populations of interest and a general linear model (GLM) one-way analysis of variance (ANOVA) was performed on streambank elevation changes to test for differences ($P \leq 0.10$) among grazing treatments and histories (Ott 1988). Least significant difference tests (LSD) were used to separate significant ($P \leq 0.10$) means (SAS 1994).

Stepwise linear regression was run using the arithmetic difference as the dependent variable for only the steep section of the streambank when analyzing grazing treatments, intensities of grazing, and grazing history. Correlation analysis was also conducted for arithmetic mean and canopy cover variables, and stratified by treatment.

Principal components analysis was performed on plant species data to simplify the description of a set of interrelated site variables. The analysis was used to transform original site and vegetation variables into new, uncorrelated variables (Affifi and Clark 1996).

Cluster analysis was used to quantitatively group the many species recorded into new groups. This multivariate procedure was used to separate a single data set into plant community groups which were not recognized before the analysis was performed (Affifi and Clark 1996). Cluster analysis was performed on canopy cover data for seven cover classes (litter, miscellaneous forbs, grass spp., Baltic rush, sedge spp., willow spp., and all grass-like plants). Data were analyzed using a nonhierarchical procedure (ISODATA) to form

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

vegetation groups based on within group similarities and between group differences (Hall and Khanna 1977).

RESULTS AND DISCUSSION

Plant Communities

Results of the general linear model (GLM) one-way analysis of variance for grazing treatment and plant community responses showed a grazing treatment effect ($p = 0.09$), for arithmetic mean differences only. Some of the grazed streambank paddocks showed surface morphological changes that were associated with and characteristic of heavy grazing use, but measurements and analyses failed to detect significant differences ($p \leq 0.10$).

Variability in measurements using the sag-tape methodology (Harrelson et al. 1994) was substantial, and significant differences in elevation changes were difficult to detect. Differences among arithmetic means and absolute mean difference were not detected for any grazing histories or any section of the sag-tape that was analyzed (complete section, upper section, section about 1 m from waters edge). No differences were found ($p \leq 0.10$) in absolute difference in streambank changes among grazing intensities for any section of the sag-tape.

The ungrazed control plot illustrated in Figure 2.2 exhibited the expected unchanged streambank morphology, whereas other control plots exhibited greater variability. I speculate that this was associated with errors intrinsic to placing the survey rod vertically at exactly the same decimeter increment along a less-than-rigid sag tape over irregular terrain. In addition, more than one student acted as a rod person during measurements of several transects, which also may have increased variability. Figure 2.3 illustrates typical changes to streambank morphology associated with heavy grazing.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Results among the three grazing intensities for the section of streambank immediately above high water (steep section) indicated a significantly greater difference using the arithmetic mean ($p < 0.09$) (Figure 2.4) (Appendix B Table 1). Results of an LSD test showed that the heavy grazing treatment resulted in significantly greater alteration in bank height after grazing as compared with control and moderately grazed streambanks. This indicated that differences in bank height within about 1 m of the water's edge with heavy grazing could be detected along the section of the streambank above the high water level compared to no grazing or moderate grazing using the sag-tape method.

Fifty percent of the repeated measurements showed a decrease in bank height, 13% a gain, and 37% showed no difference within the heavy grazing treatment, whereas 85% and 78% of the measurements showed no significant change in bank height differences between the control and moderate grazing treatments, respectively (Figure 2.5). (A gain in bank height can result from the uplifted edge of a hoofprint.) Changes in elevation were detected in about 40% more measurements in the heavy grazing treatment than were detected with no grazing or moderate grazing. It was expected that the control, as shown in Figure 2.2, would have very few changes in elevation measurements because no cattle were allowed within the control paddocks.

Stepwise linear regression analyses for the steep section of streambank identified important variables that accounted for some of the variation in arithmetic differences in bank elevations measured within the treatments. Soil organic matter was most important the variable in all treatment regression equations and the only variable selected for no grazing and heavy grazing treatments. Soil organic matter for the no grazing treatment resulted in an $r^2 = 0.26$ and was positively correlated with bank elevations (0.51, $p = 0.08$). It was expected

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

there would be little or no change in the sag-tape data from the two control treatment measurements at different dates at the same location (Figure 2.2), but as seen in Figure 2.5, there were 15% of the measurements at the same location where a difference was found, and most of these differences in streambank height were attributed to sampling error (lack of reproducibility) in rod placement when streambank height was re-measured. Variable selection in the moderate grazing treatment included total plant cover, soil organic matter, sand percentage, and the biomass of grass and explained 40, 23, 16, and 10% of the variation in streambank elevation differences, respectively ($r^2 = 0.89$). Again, for the heavy grazing treatment, soil organic matter was found to be the most important variable and resulted in an $r^2 = 0.89$, and was negatively correlated with streambank changes (-0.83, $p = 0.01$). Therefore as soil organic matter declined, a greater change in streambank height was noted.

Soil organic matter was the most frequent soil or plant variable selected during the stepwise multiple regressions analyses among treatments for changes in bank elevation for the steep section of the streambank. Total plant cover was also an important variable within the moderate grazing treatment. Overall, soil variables that were analyzed for this experiment (organic matter and texture) were important to help explain streambank stability as measured by differences in streambank height with grazing. Total plant cover also indicated that plant cover, or perhaps roots associated with plant cover, may also be important for streambank stability.

Principal Component Analysis

Principal component analysis (PCA) was used to condense the large data set of individual species cover and through ordination expose underlying community patterns. Three principal component groups were formed that explained 84% of the variability in

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

canopy cover. A negative correlation between sites where the *Carex* group dominated and the *Juncus arcticus* group dominated sites was found (-0.63) (Table 2.2). The correlation matrix exhibited a negative correlation between surface elevation differences measured before and after grazing and canopy cover of *Carex* spp. (- 0.11), *Juncus arcticus* (- 0.27), and more so for all grass-like plants (- 0.47). This indicated that an increased composition of both *Carex* spp. and *Juncus arcticus* resulted in increased resistance of the streambank to trampling-induced elevation changes.

This finding was confirmed by PCA in a correlation matrix with a strong negative correlation (- 0.63) between cover of *Juncus arcticus* and cover of *Carex* spp. Negative correlations were also evident between cover of *Carex* spp. and canopy cover of willows (- 0.3), and between canopy of *Carex* spp. and miscellaneous forbs (- 0.49). Cover of *Juncus arcticus* was also negatively correlated with grass cover (- 0.45) (Table 2.2).

CONCLUSIONS

Results of the analyses of streambank morphology for different grazing intensities and grazing histories showed the sag-tape methodology was variable and produced up to 15% error when trying to re-measure the same locations on two different dates. Change in streambank morphology could not be detected when the entire sag-tape profile or the upper profile section were analyzed. Regardless of the error associated with this technique, significant differences in grazing treatments could be detected for the steep bank section when the sag-tape profile was divided into two sections. The change in profile could only be detected within 1 m of the stream. A significant ($p = 0.09$) change in elevation was identified with changes in an arithmetic means with grazing intensity, but only for the section of

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

streambank adjacent to the stream. Grazing cattle does impact streambank channels, most noticeably within 1m of the water's edge.

The use of the sag-tape methodology is variable and changes in streambank morphology may fail to be detected with this method unless sections where greater change occurs are isolated. In this study, morphological change could only be detected within 1 m of the high water level. This typically steeper 1 m region of streambank is most susceptible to change from cattle hoof action and could be most damaging to water quality as this section is adjacent to the stream. This implies that the section of streambank just above high water is more prone to deformation and impact by grazing and trampling animals. This may reflect, in part, the impact of both water table and capillarity enhancing the soil moisture and rendering the soil near the stream more plastic.

MANAGEMENT IMPLICATIONS

Although this experiment was constrained by the sag-tape methodology, which limited the precision of data collected, insights with predictive value into the relative resilience of streambanks with past grazing history have real value for owners and managers of riparian rangeland grazed by either domestic or wild ungulates. The sag-tape methodology was just accurate enough to adequately describe significant differences in streambank morphology just above the high water level after heavy grazing, a finding Allen-Diaz et al. (1998) also noted. However, hoof impacts effects on the total streambank adjacent to the stream were not detected with this method. Unless greater precision in measurements are used (like survey grade survey equipment instead of sag-tape and rod) managers may fail to detect changes in streambank morphology using sag-tape method.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

LITERATURE CITED

Affifi, A. A. and V. Clark. 1996. Computer-aided multivariate analysis. 3rd Ed. New York, NY: Chapman and Hall. 455 p.

Allen, T. 1990. Particle size measurement. 4th Ed. New York, NY: Chapman and Hall. 806 p.

Allen-Diaz, B. H., R. D. Jackson, and J. S. Fehmi. 1998. Detecting channel morphology change in California's hard-wood rangeland spring ecosystems. *Journal of Range Management* 51:514-518.

Binkley, D., F. J. Singer, M. Kaye, and R. Rochelle. 2002. Influence of elk grazing on soil and nutrients in Rocky Mountain National Park. *In:* Singer, F.J. and L.C. Zeigenfuss [EDS.]. Ecological evaluation of the abundance and effects of elk herbivory in Rocky Mountain National Park, 1994-1999. Fort Collins, CO: U.S. Geological Survey Open Report 02-208.

Bonham, C. D. 1989. Measurements for terrestrial vegetation. New York, NY: John Wiley. 339 p.

Bouyoucos, G. J. 1962. Hydrometer method improved for making particle size analysis of soils. *Agronomy Journal* 54:464-465.

Devaurs, M. and G. F. Gifford. 1984. Variability of infiltration within large runoff plots on rangelands. *Journal of Range Management* 37:523-528.

Duce, J. T. 1918. The effect of cattle on the erosion of canyon bottoms. *Science* 47:450-452.

Dunaway, D., S. R. Swanson, J. Wendel, and W. Clary. 1994. The effect of herbaceous plant communities and soil textures on particle erosion of alluvial streambanks. *Geomorphology* 9:47-56.

George, M. R., D. Lile, and N. McDougald. 1992. Monitoring livestock impacts in mountain meadows. Unpublished Report. Department of Agronomy and Range, University of California, Davis, CA. 42 p.

Goss, D. W. 1973. Relation of physical and mineralogical properties to streambank stability. *Water Resource Bulletin* 9:140-144.

Greenwood, K. L. and B. M. McKenzie. 2001. Grazing effects on soil physical properties and the consequences for pastures: a review. *Australian Journal of Experimental Agriculture* 41:1231-1250.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Grissinger, E. H., W. C. Little, and J. B. Murphey. 1981. Erodibility of streambank materials of low cohesion. *Transactions of the American Society of Agricultural Engineering* 24:624-630.

Hall, D. J. and D. Khanna. 1977. The ISODATA method of computation for the relative perceptions of similarities and differences in complex and real data. *In*: K. Enslein, A. Ralston, and H.W. Wilf [EDS.]. Statistical methods for digital computers, Vol. 3, New York, NY: John Wiley and Son. p. 340-373.

Harrelson, C. C., C. L. Rawlins, and J. P. Potyondy. 1994. Stream channel reference sites: An illustrated guide to field technique. USDA Forest Service Gen. Tech. Rep. RM-245.

Hooke, J. M. 1980. Magnitude and distribution of rates of river bank erosion. *Earth Surface Processes* 5:143-157.

Kauffman, J. B., A. S. Thorpe, and E. N. J. Brookshire. 2004. Livestock exclusion and belowground ecosystem responses in riparian meadows of eastern Oregon. *Ecological Applications* 14:1671-1679.

Kinney, J. W. and W. P. Clary. 1994. A photographic utilization guide for key riparian graminoids. USDA Forest Service Gen. Tech. Rep. INT GTR 308.

Kleinfelder, D., S. R. Swanson, G. Norris, and W. Clary. 1992. Unconfined compressive strength of some streambank soils with herbaceous roots. *Soil Science Society of America Journal* 56:1920-1925.

Klute, A. 1986. Methods of soil analysis. Part I. Physical and mineralogical methods. Madison, WI: American Society of Agronomy & Soil Science Society of America. 1188 p.

Knighton, D. 1984. Fluvial forms and processes. New York, NY: Edward Arnold. 218 p.

Manning, M. E., S. R. Swanson, T. Svejcar, and J. Trent. 1989. Rooting characteristics of four intermountain meadow community types. *Journal of Range Management* 42:309-312.

McDowell, P. F. and F. J. Magilligan. 1997. Response of stream channels to removal of cattle grazing disturbance: overview of western U.S. exclosure studies. *In*: Wang, S.Y. et al. [EDS.]. Management of landscapes disturbed by channel incision. Proc. of the Conference on Management of Landscapes Disturbed by Channel Incision, University of Mississippi, Oxford, MS., May 19-23, 1997. University of Mississippi, Oxford, MS. p. 469-475

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

NOAA (National Oceanic and Atmospheric Administration). 1995. Climatological data. Red Feather Lakes, Colorado, USA. Asherville, NC: U.S. Department of Commerce, ISSN 0145-0506.

Ott, L. 1988. An introduction to statistical methods and data analysis. 3rd Ed. Boston, MA: PWS-Kent Publishing Co.

Parker, D. B., T. G. Michel, and J. L. Smith. 1995. Compaction and water velocity effects on soil erosion in shallow flow. *Journal of Irrigation Drainage Engineering* 121:170-178.

Pearce, R. A. 1995. Sediment movement and filtration within laboratory and riparian vegetation buffer strips (dissertation). Fort Collins, CO: Colorado State University.

Platts, W. S. and R. F. Raleigh. 1984. Critique - impacts of grazing on wetlands and riparian habitat. *In*: Developing Strategies for Rangeland Management. Boulder, CO: Westview Press. p. 1105-1118.

Platts, W. S., C. Armour, G. D. Booth, M. Bryant, J. L. Bufford, P. Cuplin, S. Jensen, G. W. Lienkaemper, G. W. Minshall, S. B. Monsen, R. L. Nelson, J. R. Sedell, and J. S. Tuhy. 1987. Methods for evaluating riparian habitats with applications to management. USDA Forest Service Gen. Tech. Rep. INT-221.

Platts, W. S. 1991. Livestock grazing. *In:* William R. Meehan [ED.]. Influences of forest and rangeland management on salmonid fishes and their habitats. Bethesda, MD: American Fisheries Soc Special Pub 19. p. 389-423

Popolizio, C. A., H. Goetz, and P. L. Chapman. 1994. Short-term response of riparian vegetation to 4 grazing treatments. *Journal of Range Management* 47:48-53.

Rosgen, D. L. 1996. Applied river morphology. Pagosa Springs, CO: Wildland Hydrology.

SAS Institute Inc. 1994. Cary, NC: SAS Release 6.10 for Windows.

Schultz, T. and W. C. Leininger. 1990. Differences in riparian vegetation structure between grazing areas and exclosures. *Journal of Range Management* 43:295-299.

Selby, R. 1982. Hillslope materials and processes. New York, NY: Oxford University Press. 264 p.

Skovlin, J. M. 1984. Impacts of grazing on wetlands and riparian habitat: a review of our knowledge. *In*: Developing Strategies for Range Management. Boulder, CO: Westview Press. p. 1001-1102.

Smith, D. G. 1976. Effect of vegetation on lateral migration of anastomosed channels of a glacier meltwater river. *Bulletin of the Geological Society America* 87:857-860.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Storer, D. A. 1984. A simple high volume ashing procedure for determining soil organic matter. *Commercial Soil Science Plant Analysis* 15:759-772.

USDA, Soil Conservation Service and Forest Service. 1980. Soil survey report. Larimer County, CO. Washington, DC: U.S. Government Printing Office. 239-812/48.

Wheeler, M. A., M. J. Trlica, G. W. Frasier, and J. D. Reeder. 2002. Seasonal grazing affects soil physical properties of a montane riparian community. *Journal of Range Management* 55:49-56.

Williamson, R. B., R. K. Smith, and J. M. Quinn. 1992. Effects of riparian grazing and channelisation on streams in Southland, New Zealand. 1. Channel form and stability. *New Zealand Journal of Marine Freshwater Resources* 26:241-258.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

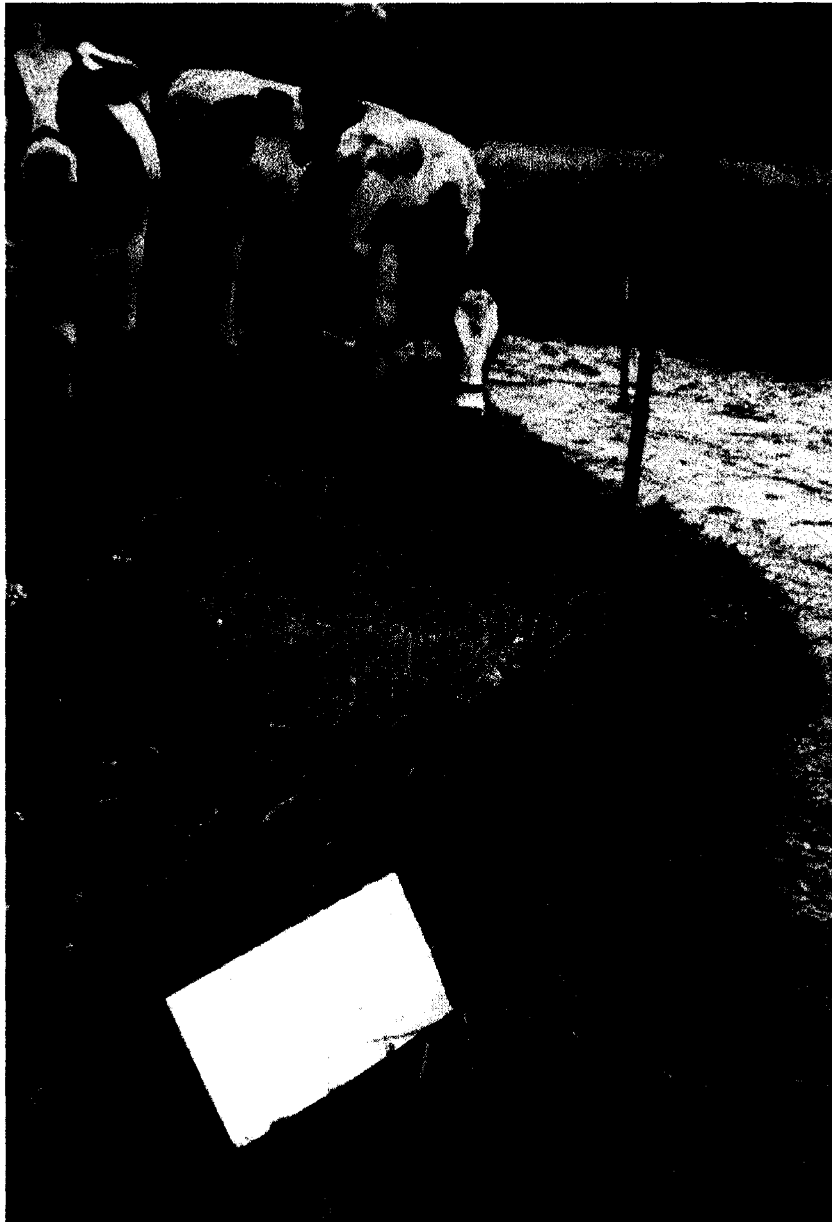


Figure 2.1. Cattle grazing on a moderately grazed and trampled grass-like plant community paddock on the streambank of Sheep Creek.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

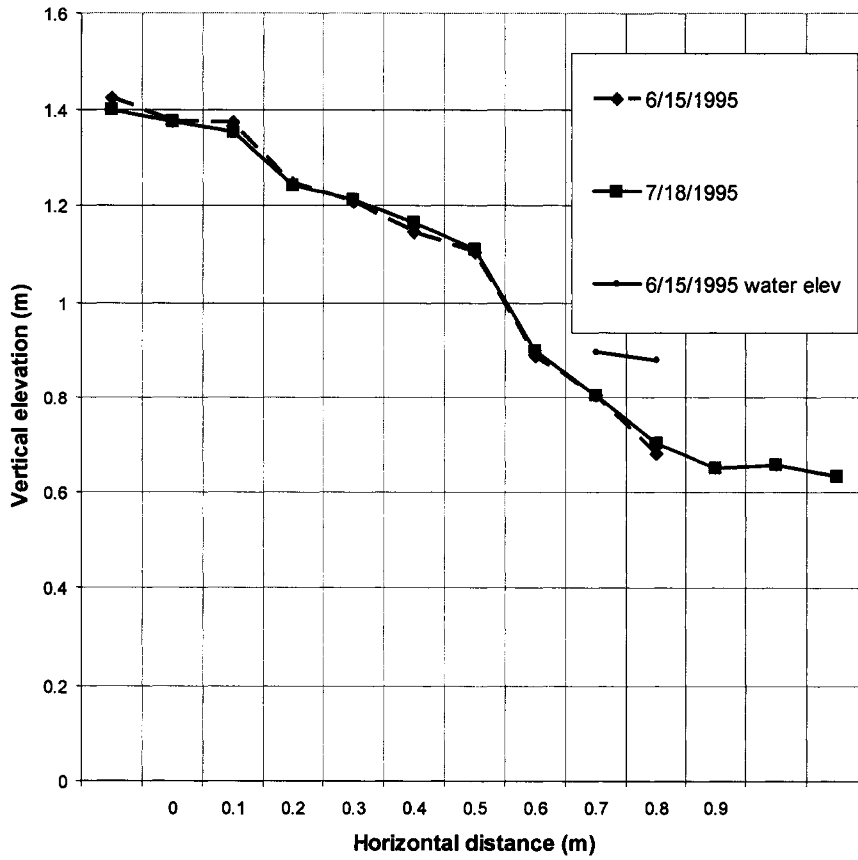


Figure 2.2. A streambank profile for Sheep Creek on two dates of measurement for paddocks with no grazing.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

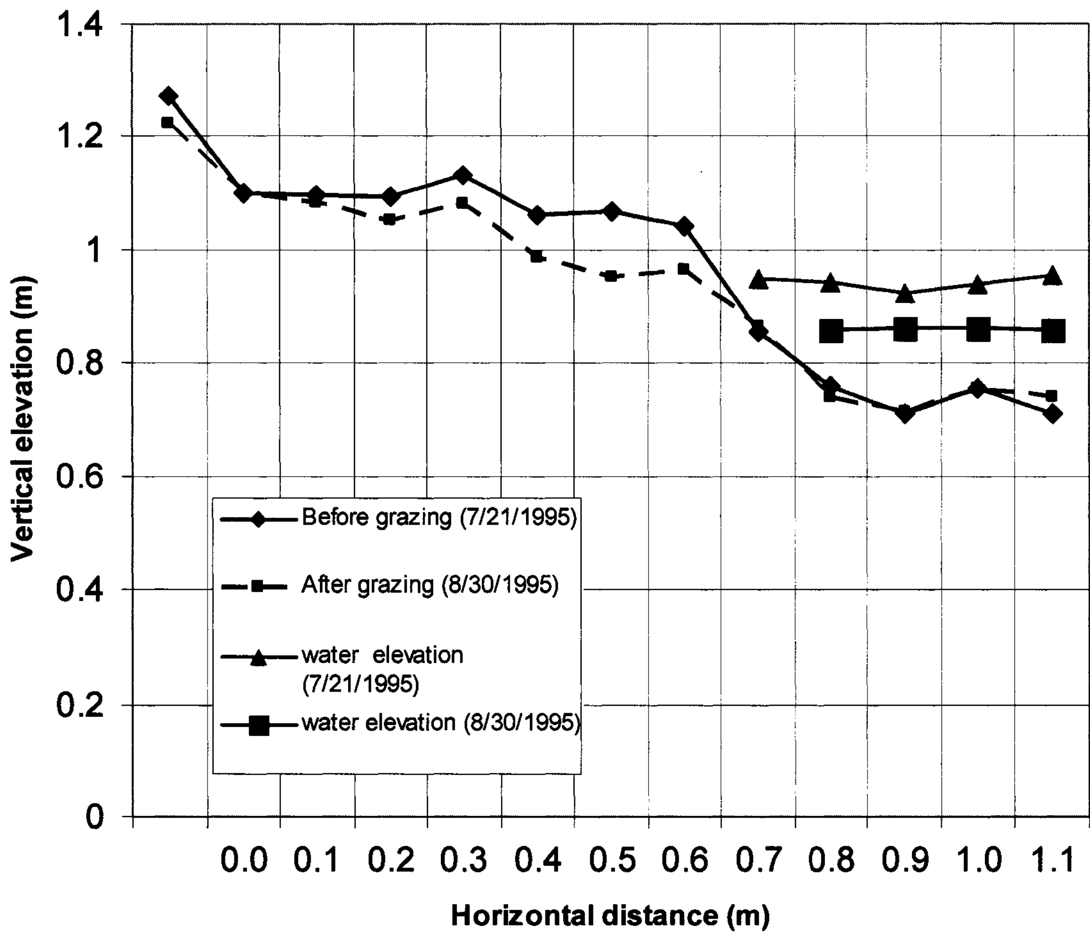


Figure 2.3 An example of streambank profile for Sheep Creek before and after a heavy intensity of grazing.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

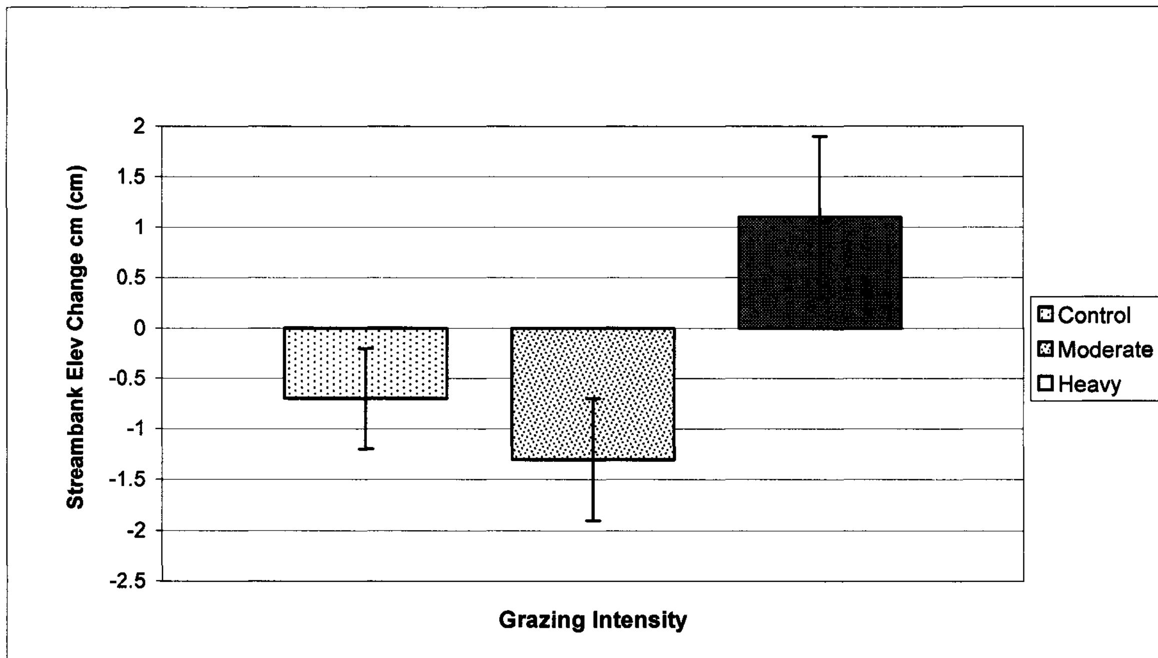


Figure 2.4. Arithmetic mean values for streambank elevation differences for three grazing treatments for the steep 1 m section of streambank adjacent to and above high water level, ($p \leq 10$). Error bars represent ± one standard error.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

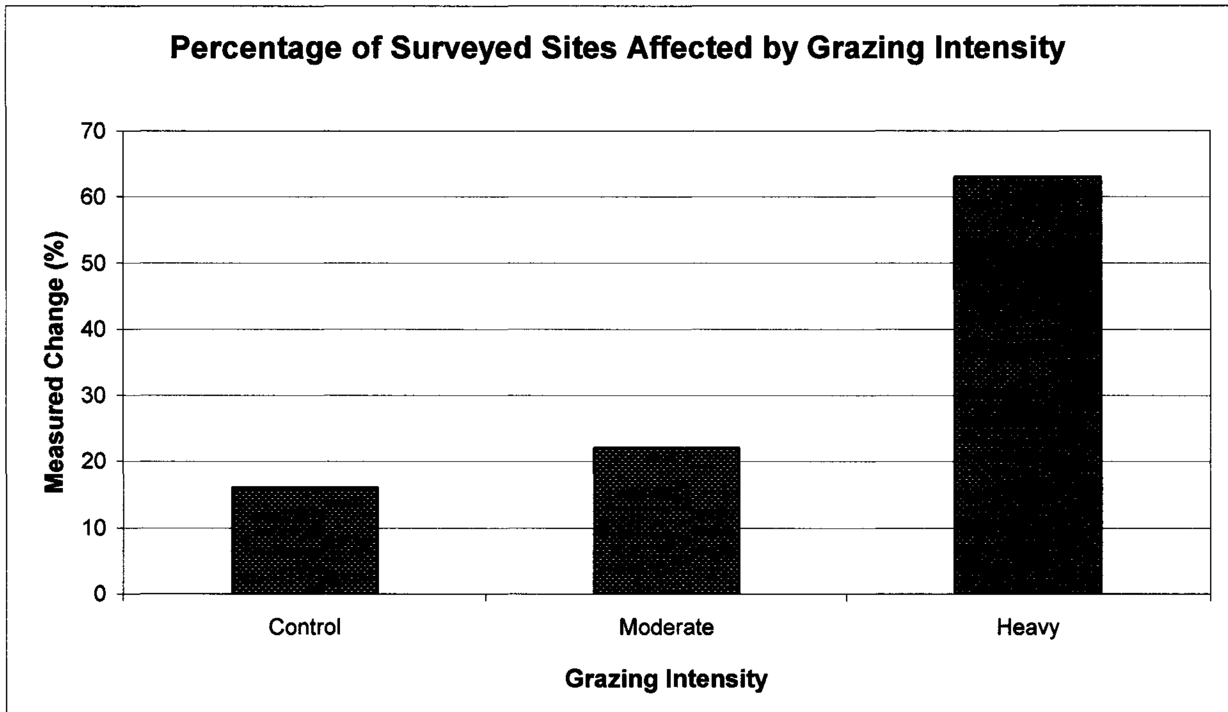


Figure 2.5. Percentage of measurements that showed a measured change from surveys before and after grazing treatments.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 2.1. Means for plant and soil variables for streambank paddocks that were grazed at three intensities in 1995.

Plot	Grazing intensity	Soil organic matter (%)	Dominant plant cover type (%)	Plant utilization (%)	Treatment date	Grazing treatment specifics
1	None	11.3	grass-like	0	na	None
2	None	12.8	grass-like	0	na	None
3	None	9.8	grass-like	0	na	None
4	None	13.2	grass-like	0	na	None
5	None	10.4	grass	0	na	None
6	None	8.0	grass	0	na	None
7	None	7.4	grass-like	0	na	None
8	None	9.7	grass-like	0	na	None
9	None	7.1	grass-like	0	na	None
10	None	13.1	grass-like	0	na	None
11	None	8.0	misc. forbs	0	na	None
12	None	5.0	grass	0	na	None
13	None	6.9	grass-like	0	na	None
14	Moderate	5.2	grass-like	27	9/12/1995	4 steers 90 min
15	Moderate	5.9	grass-like	52	8/21/1995	4 steers 70 min
16	Moderate	8.3	grass	38	8/26/1995	3 steers 75 min
17	Moderate	8.7	grass-like	50	8/19/1995	5 steers 60 min
18	Moderate	8.5	grass-like	33	8/16/1995	4 steers 120 min
19	Moderate	8.3	grass	36	8/12/1995	3 steers 90 min
20	Moderate	5.0	grass	8	8/10/1995	2 steers 120 min
21	Heavy	7.5	grass-like	80	9/24/1995	4 steers 75 min
22	Heavy	9.7	grass-like	82	9/24/1995	4 steers 45 min
23	Heavy	8.3	grass-like	64	8/17/1995	3 steers 90 min
24	Heavy	6.0	grass	56	8/22/1995	3 steers 150 min
25	Heavy	10.0	grass-like	69	8/21/1995	4 steers 135 min
26	Heavy	6.3	grass-like	69	9/26/1995	3 steers 80 min
27	Heavy	7.2	grass-like	53	9/26/1995	3 steers 60 min
28	Heavy	7.8	grass-like	62	8/19/1995	5 steers 90 min
29	Heavy	10.1	grass-like	35	8/14/1995	3 steers 120 min
30	Heavy	4.9	grass-like	30	8/11/1995	4 steers 105 min

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 2.2. Correlation matrix resulting from a reduced set of variables using Principal Components Analysis (PCA).

	CLITT	CMISF	CGRASS	CJUBA	CCAREX	CWILLOW	TGRASLIK	TOTSHRUB	CMADIFFA
CLITT[1]	1.00	0.39	0.52	-0.24	-0.36	0.36	-0.54	0.39	0.10
CMISF	0.39	1.00	0.27	-0.14	-0,49	0.19	-0.79	0.22	0.31
CGRASS	0.52	0.27	1.00	-0.45	-0.13	-0.11	-0.12	-0.06	0.16
CJUBA	-0.24	-0.14	-0.45	1.00	-0.63	0.05	0.07	0.03	-0.11
CCAREX	-0.36	-0.49	-0.13	-0.63	1.00	-0.34	0.62	-0.37	-0.27
CWILLOW	0.36	-0.79	-0.11	0.05	-0.34	1.00	-0.56	0.99	0.13
TGRASLIK	-0.54	0.19	-0.12	0.07	0.62	-0.56	1.00	-0.60	-0.46
TOTSHRUB	0.39	0.22	-0.06	0.03	-0.37	0.99	-0.60	1.00	0.17
CMADIFFA	0.10	0.31	0.16	-0.11	-0.27	0.13	-0.46	0.17	1.00

[1] CLITT = litter canopy, CMISF = miscellaneous forbs canopy, CGRASS = grass canopy, CJUBA = *Juncus arcticus* canopy, CCAREX = *Carex* canopy, CWILLOW = *Salix* canopy, TGRASLIK = total grass-like canopy, TOTSHRUB = total shrub canopy, CMADIFFA = cm of elevation difference between first and second streambank surveys.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

CHAPTER III

HOOF SIMULATOR EFFECTS ON A MONTANE RIPARIAN STREAMBANK AS AFFECTED BY GRAZING HISTORY

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

INTRODUCTION

Riparian areas in the western United States represent 2% or less of the available public and private lands historically used for grazing (Kauffman and Krueger 1984). The riparian zones are frequently used by grazing livestock (Heady and Child 1994) and by many wildlife species (Skovlin 1984). Riparian vegetation also influences streambank stability, water quality (Corley et. al. 1999), and sediment filtration (Pearce et al. 1998), and are often the most productive communities with deeper and more fertile soils compared with the surrounding upland communities (Platts 1991, Naiman and Décamps 1997). Understanding the effects of past grazing use on riparian zones and how past use has influenced soil and plant characteristics may help managers better understand how grazing may influence streambank stability, root and soil characteristics (Kauffman et al. 2004).

As cattle graze, their hooves exert pressure on the soil surface. This pressure was estimated by Abdel-Magid et al. (1987) at 120 kPa, by Lull (1959) at 168 kPa, by Scholefield and Hall (1986) at 133 kPa, and by Di et al. (2001) at 130-400 kPa. This pressure usually results in soil compaction, increased bulk density, and decreased porosity (Blackburn 1984, Gifford and Hawkins 1978, Warren et al. 1986a,1986b), and in wet soils alters soil structure and carves pits. These effects may be ameliorated by high organic matter content of the soil and accentuated by high soil moisture conditions and heavy soil textures (Brady 1974, Wheeler et al. 2002). Treading can affect soil physical properties and soil strength (Di et al. 2001) and soil damage is particularly great when soil moisture is high (Greenwood and McKenzie 2001).

Gifford and Hawkins (1978) summarized results of animal traffic on soils and watersheds. They focused on hydrologic aspects and found no evidence to show that any

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

single grazing system consistently or significantly increased plant and litter cover on watersheds that might then affect trampling damage. Tanner and Mameril (1959) found that grazing animals increased bulk density from 1.22 to 1.43 g/cm^3, decreased porosity from 17 to 7%, and increased penetrometer resistance from 3.2 to 19.5 bars. Greenwood and McKenzie (2001) reviewed the impacts of grazing for many different species of grazing animals, and described average values of force applied and elements of soil strength and resilience. They concluded that grazing animals exert pressures on the ground comparable to agricultural machinery.

Trampling can affect plants directly as hooves cut and tear leaf and stem tissue during the action of grazing. Losses of herbage from trampling have been reported as low as 1 to 5% in the sand hills of Eastern Colorado (Quinn and Hervey 1970) to 23% on sheep ranges in Utah (Laycock et al. 1972). Roots anchor plants against trampling damage (Jackson et al. 1999).

Livestock can contribute to streambank instability in at least three ways: 1) they may leave insufficient vegetation on banks (Duce 1918), 2) soil disturbance by 'chiseling' and soil compaction from hoof action (George et al. 1992, Platts 1991, Skovlin 1984), and 3) the removal of aboveground phytomass over long periods will reduce root length and mass, thus reducing the binding effects of roots on streambanks (Weaver 1954, Manning et al. 1989, Kleinfelder et al. 1992). Long-term browsing and trampling of riparian shrubs may cause the most deleterious effect (Skovlin 1984). Platts and Raleigh (1984) believed that hoof action (chiseling) was the predominant deleterious effect of livestock on streambank stability. However, Williamson et al. (1992) found undercutting of banks in New Zealand was largely unaffected by grazing of stream margins, whereas channelizing streams (straightening or

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

increasing capacity) led to severe streambank erosion. Selby (1982) discussed factors that contributed to strength of soils in sloped situations, and concluded that mechanical reinforcement of the soil was provided by root networks, particularly by trees.

Ziemer (1978) investigated the relationship between soil shear strength and tensile strength in live tree roots, and developed a regression equation that related the two with an r^2 value of 0.97. His purpose was to examine the deterioration in root strength following logging, and the contribution that root deterioration made to slope failure.

Kleinfelder et al. (1992) found that herbaceous roots appeared to supply most of the compressive strength and soil stability found in meadow streambanks, especially those dominated by Nebraska sedge (*Carex nebrascensis* Dewey). Dunaway et al. (1994) found that the interactions of plants with soils were important, and that knowledge of both vegetation composition and soil texture were necessary to predict streambank erodibility and to manage streambank stability. Manning et al. (1989) found that total root length density and root mass to a depth of 40 cm were correlated with the wetness of the site, with greater root mass and density at wetter sites, which they suggested meant that wetter sites had superior site stabilizing characteristics.

Most geomorphic studies of streambank erosion have used techniques such as erosion pins in the streambanks to quantify erosion from the streambank as related to flow regime, and have ignored the contribution of roots (Goss 1973, Grissinger et al. 1981, Hooke 1980). Smith (1976) noted that bank sediment with a root volume of 16 to18 % and a 0.5 m thick root mat afforded 20,000 times more protection from erosion than comparable bank sediment without vegetation. Micheli and Kirchner (2002) found that streambank strength was correlated with vegetation density indicators, including stem counts, standing biomass per

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

unit area, and the ratio of root mass to soil mass. Easson and Yarbrough (2002) modeled root reinforcement of riparian soils and noted that deformation of the soil was resisted by tangential forces that develop along the root, which in turn mobilized the tensile resistance of the root.

This study was conducted with a mechanical hoof simulator to measure the direct chiseling impact of hoofprints on streambanks. As Scholefield and Hall (1986) noted, such a hoof simulator could function as a penetrometer, and was a desirable test because classical theories of soil mechanics are inapplicable to unsaturated agricultural topsoils. Hillel (1980) noted that a penetrometer does not measure soil strength per se, but instead measures a composite parameter that should be related to soil strength.

The objective of the first part of this study was to relate the imprints from a hoof simulator on a streambank with variables such as soil texture, soil organic matter, plant community composition, root biomass, and root length density as influenced by grazing history. This information might then be used to quantify streambank susceptibility to trampling. The mechanical hoof was chosen to minimize imprint variability. Scholefield and Hall (1986) described total vertical displacement as the most appropriate index of soil strength, because it was the result of both vertical compression and shear. Hoof extension was intended to represent a measure of soil-root matrix strength within each one of three previous grazing histories.

A second experiment on soil matrix shearing was conducted to further characterize resilience of streambank soils based on past grazing use. The objective of this experiment was to measure the shear strength of soil cores and evaluate soil and vegetation characteristics that could be used to predict shear strength. Soil strength was defined by

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Hillel (1980) as the capacity of soil to withstand forces without experiencing failure, but he described it as a highly variable property that was difficult to measure.

Hypotheses

1. Streambank morphology, soil physical properties, herbaceous plant communities, and root characteristics of streambank soils contribute to the resistance of streambanks to livestock traffic.
2. Streambank stability in grazed riparian areas is inversely related to intensity of livestock trampling.

STUDY AREA

The study took place during the summer of 1996 at 40^0 38'N latitude and 105^0 38'W longitude in the riparian zone along 2.4 km of Sheep Creek in the Roosevelt National Forest of North Central Colorado. The site is approximately 80 km northwest of Fort Collins, Colorado at an elevation of 2500 to 2550 m. The ownership of the area was historically 'checkerboarded' between the Union Pacific Railroad and the U. S. Forest Service (USFS), but is now under USFS ownership. The area is open to recreation (such as fishing, hunting, and camping), and is used for livestock grazing, timber harvesting, and as a water catchment for downstream irrigation.

The general vegetation of the riparian zone along Sheep Creek consists of mixtures of willows (*Salix* spp.), sedges (*Carex* spp.), rushes (*Juncus* spp.), Kentucky bluegrass (*Poa pratensis* L.), tufted hairgrass (*Deschampsia caespitosa* (L.) Beauv.), Canadian reedgrass (*Calamagrostis canadensis* (Michx.) P. Beauv.), and other minor plant species (Schultz and Leininger 1990).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Soils in the study area were derived from granitic parent material and are deep, coarse, sandy to clay loam family of pachic cryoborolls (USDA 1980). Mean annual precipitation for the study site is approximately 400 mm. Growing season precipitation averages about 240 mm (NOAA 1995). Sheep Creek is classified as a C-4 stream according to Rosgen (1996).

The USFS and Colorado Division of Wildlife (DOW) constructed three livestock exclosures in 1956 along Sheep Creek to remedy past heavy grazing by livestock. Collectively, these exclosures protect a total of 40 ha along 2.5 km of stream (Schultz and Leininger 1990). Three additional exclosures were built in 1988 to eliminate livestock grazing, and encompassed approximately 1.3 ha. Three other areas totaling 1.8 ha, which had been protected from livestock grazing since 1956, were opened to grazing in 1988 (Popolizio et al. 1994).

MATERIALS AND METHODS

Thirteen plots were located on the banks of Sheep Creek and included areas excluded from grazing since 1956 (2 plots), areas opened from this protection in 1988 (4 plots), and areas that had been grazed seasonally since before the turn of the century (7 plots). Sites were selected to represent grass (*Poa* spp., *Calamagrostis* spp.), grass-like (*Carex* spp., *Juncus arcticus* Willd. ssp. *littoralis* (Engelm.) Hultén), and willow (*Salix* spp.) riparian communities. Four subplots were located within each 5 x 5 m plot.

A combination elevation table and point frame (pin-table) of dimensions 0.6 m x 2 m (corresponding to the subplot) was used to characterize vegetation canopy and soil surface cover and include species composition, litter, and bare soil of each subplot (Mergen 1998). The point frame was also used to describe surface elevations (micro-topography) before and

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

after a hoof simulator treatment. Each plant community was characterized by several 100-point pin-table samples, and species canopy cover values were calculated as percent frequency of the 100 points.

Four (1.2 m^2) subplots within each 5 x 5 m plot were oriented at right angles to the streambank (Figure 3.1). Two subplots were controls, and two were treated with a hoof imprint simulator. Selection of treated or control plots was randomized by the method of Inouye (1996). Soil core samples were collected for shear strength determinations at these same sites after hoof simulation experiments were completed.

Soil physical properties within each plot were determined. Three soil cores of dimensions 7 x 10 cm were taken within each subplot for each depth 0-10, 10-20, and 20-30 cm (if possible), and at even intervals beneath the 2 m long pin-table. Soil texture, soil moisture and organic matter were determined. Soil texture was determined using hydrometer analysis (Allen 1990). Soil samples were dried at 105^0C for 40 hours to determine soil moisture and then the samples were ashed at 550^0C for 5 hours (Storer 1984, Klute 1986, Pearce 1995) for organic matter determination. Bulk density was also obtained for these depths following the NRCS methodology of Grossman and Reinsch (2002).

Hoof Simulator

The pin-table frame was leveled for each transect perpendicular to the upstream/downstream direction and soil surface elevation measurements were collected. The pin-table was removed and hoofprints were simulated in the center of these subplots, and spaced 25 cm apart within a linear belt transect to provide seven replications of hoof imprints in each subplot. Then the supports of the pin-table were precisely replaced into locations marked by wire flags and paint, allowing re-measurement of the surface elevations after hoof

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

imprints had been applied. The use of a pin-table constructed of rigid aluminum to measure soil extension and micro-topography reduced variability of measurement. The use of a hoof simulator similarly reduced the imprecision associated with individual steps of grazing animals.

The force applied and spacing selected for hoof imprinting (trampling) were designed from criteria resulting from related experiments conducted by Abdel-Magid et al. (1987) and Scholefield and Hall (1986). An artificial hoof apparatus constructed at the University of Wyoming, Department of Civil Engineering was used to apply hoof imprints to streambanks in transects from the stream edge and oriented perpendicular to the stream (Figure 3.1). The hoof was constructed of natural cattle hoof material with dimensions and density consistent with sample steer hooves obtained from the Monfort cattle feeding operation in Greeley, Colorado. This hoof material was mounted into a machined steel frame. The hoof simulator consisted of a square tubular frame that contained this artificial hoof connected to a hydraulic cylinder (Fig 3.2). The artificial hoof was driven by a pressure of 300 kPa to emulate the vertical stress of a representative hoofprint for a steer (Scholefield and Hall 1986). The cylinder was connected to a pressure gauge and pumped by hand to thrust the artificial hoof into the ground. The pressure was further regulated by the installation of a pressure accumulator in the system to hold a charge of 6.9 MPa (1000 psi). This allowed the application of force to be made smoothly and consistently. It was used to simulate cattle hoofprints, but at a specific pressure level. Pressures used were 0 and 300 kPa to simulate no hoof impact or vertical extension of the soil-root matrix by cattle. The dimensions of the hoof were approximately 10 by 11.4 cm, resulting in an area of 84.1 cm^2. This resulted in

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

pressures of 3.5 MPa (500 psi)/84.1cm^2, or 0.042 MPa/cm^2. This compares with a range of 98 to 192 kPa cited by Greenwood and McKenzie (2001) for cattle trampling.

Hoof simulations were conducted at two times during the growing season. The early treatment occurred on soil still moist from spring runoff. The later treatment occurred on drier soils which had been wetted (by means of pump and sprinkler) to increase the surface soil moisture level to field capacity. These data were then compared to determine if soil moisture had any effect on hoof simulator impressions. Data for both the early and late sample periods were combined because surface soil moistures were found to be similar ($p \leq 0.96$). Conceptually, as the hoof simulator drives the hoof into the moist soil, it may reach a horizon of greater or lesser soil moisture and therefore inherent strength.

Shear Strength

After hoof imprint simulations were conducted, 3 to 5 soil cores were collected by driving a soil core sampler of dimensions 7 x 10 cm horizontally into the streambank along the edge of the subplot within the 0-10 cm range of depth. Samples were collected horizontally to better represent a single surface soil horizon. These cores were then placed into the vertical shear column of the modified hoof simulator, and pressure was applied to the upper (mobile) portion of the column with the lower portion immobile until the sample was completely sheared (Figure 3.3). This was considered equivalent to a shear force directed vertically downward into the surface soil horizon. It is also possible this protocol accessed more compacted soil material. Maximum pressure to shear the soil core was measured and recorded. A portion of the maximum pressure reading obtained was derived from overcoming friction in the device, therefore a value related to friction was subtracted from the maximum pressure to yield applied pressure. The friction value was determined by

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

readings of several runs of the unloaded device. Applied pressure was multiplied by the diameter of the piston in the hydraulic cylinder (2.54 cm) to arrive at the final shear value in kN/m^2. This part of the study was used to determine shear strength of soil cores obtained in each plot within the surface (0-10 cm) soil horizon and within 2 m of the stream, from the two plant communities identified. As the soil cores were sheared, the roots imbedded within were pulled in tension.

Root Tensile Strength

Clumps of roots 15-30 cm in diameter were obtained from herbaceous riparian species located within plots. Larger individual roots and root clumps of *Salix* species were excavated from plots where they occurred. Root samples were placed in coolers and transported to a lab in Fort Collins, Colorado. Root clumps were carefully rinsed with a jet of water, separated into similar-sized root diameters, and cut into sub-samples 10-20 cm long. Once cleaned and cut to length, root samples were placed into re-sealable plastic bags in a solution of approximately 50% isopropyl alcohol, and refrigerated at 5^0 C.

Testing equipment at CSU Orthopaedic Research Group (CSU OIRP) located in the Colorado State University Veterinary Medicine facility was used to measure root tensile strength. A servohydraulic biaxial mechanical testing machine (MTS) (model 809), with a low force load cell (model 662.20C-01)(MTS Systems Corporation, Eden Prairie, Minnesota, USA) was used to measure root tensile strength. Instron grips were used to hold root segments to be tested. The MTS hydraulics were computer mediated, and test results were generated as digital ASCII files that were transferred into spreadsheets.

The low-force load cell and low-pressure system settings were used, and force was applied at a constant 6.35 cm/minute rate until each root failed. Hydraulic system pressures

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

were 150 Mpa. Data generated included time elapsed in half-second intervals, distance traveled, and force. These values were converted to metric units. Root sample diameters were obtained by measuring images scanned at an optical resolution of 236 dots per cm (600 dots per inch; equivalent to resolution of 23.6 pixels/mm). The dimension (length and width) of a scanned pixel at this resolution is 0.042 mm. The average diameter for a human hair is 0.13 mm. Therefore, the cut off chosen in recognizing root versus non-root material was 0.1 mm. At values less than 0.1 mm there exists the potential for great lengths of root, and also great potential for misidentification. The minimum root diameter that Kaspar and Ewing (1997) measured with their system was 0.15 mm. For perspective, the inevitable contribution of fungal hyphae represented diameters in the range of approximately 1-3 μm (micrometers) Polomski and Kuhn (2002). The same source described average minimum diameters of root hairs at 1 μm and of fine roots as 50 μm.

An average diameter value for three measurements along the root segment was used to relate root diameter to force applied at root tensile failure. Force variability averaged 0.91 Newton in the hydraulic measurement system, and was measured by collecting at least three 'unloaded' samples for each run of samples.

Data Analyses

Data for soil shear strength were collected from a total of 52 sub-plots within the riparian ecosystem. Data were examined to determine treatments tested for hoof impact on soils that were wet compared to non-wetted soils (control) before being stratified by grazing histories. Correlation and stepwise regression analyses were conducted on the complete data set (n = 52) before stratifying data by grazing history.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Data within the three grazing histories were then compared to assess differences in hoof simulator impacts and soil shear strength. Data were organized into three grazing history groupings that were described as exclosures (since 1956), opened to grazing (grazing started in 1988 in previous exclosures), and continuous grazing (long-term grazing that has been continuous since before 1956).

Stepwise multiple linear regression and correlation analyses (Steel and Torrie 1976) were performed to determine hoof simulator impact and for soil shear strength relationships for each grazing history. This process was used to select a set of independent variables based on plant cover, root characteristics, and soil characteristics to be included in regression models (SAS 1988). The analyses contained independent variables that included means for percentage cover of grasses, *Carex spp., Juncus arcticus*, forbs, shrubs, root biomass, root-length density, and soil characteristics. Soil characteristics included were soil moisture, soil organic matter, soil bulk density, and texture. Probability for variable selection was set at 0.10. Hoof simulator impact and soil shear strength were dependent variables.

Grazing histories were considered a population of interest (Wester 1992) and a general linear model (GLM) one-way analysis of variance (ANOVA) was performed to test for differences among the past grazing histories (Ott 1988). Least significant difference tests (LSD) were used to separate significant ($p \leq 0.10$) means (SAS 1988).

Stepwise multiple regression was employed to examine shear strength results among the three past grazing histories. Because so many variables were measured, principal component analysis (PCA) was used to reduce the number of important variables (McGarigal et al. 2000), and to separate plant communities into those dominated by *Salix spp.*, *Juncus arcticus*, and *Carex spp.* An analysis of variance with the General Linear Model procedure

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

was performed where differences in streambank elevation in each plot were used as the dependent variable.

RESULTS AND DISCUSSION

Grazing Histories

Table 3.1 shows a summary of the significant differences observed among the three grazing histories for soil and plant characteristics. Soil organic matter content decreased from the long-term exclosures, to the exclosures opened to grazing in 1988, and to the continuously grazed areas. Soil bulk density was lowest in the exclosures and showed an increasing trend in the exclosures opened to grazing in 1988 and bulk density observed in areas that were continuously grazed. These results were not surprising (Kauffman et al. 2004), and showed that exclosures opened to grazing can have similar soil organic matter contents and soil bulk densities as long-term grazed areas, and approach these similarities in eight years or less in this montane riparian study area in Colorado.

Following this same trend, the long-term exclosures had significantly greater canopy cover of grasses compared to grass cover in the continuously grazed area (Table 3.1). Table 3.2 shows that grasses had significantly smaller roots compared with sedges, rushes, and *Salix* roots. The greater grass canopy and smaller average root diameters probably contributed greatly to the greater soil organic matter content observed in the exclosures. Root biomass was significantly ($p \leq 0.10$) greater in the exclosures opened in 1988 compared to the exclosures not opened to grazing. Root length for root diameters between 0.1 and 0.5 mm was significantly greater in exclosures than for the other two grazing histories (Table 3.1). The last observed significant difference among grazing histories was for canopy cover of water sedge (*Carex utriculata* Boott). Greater canopy of this species was recorded in the

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

continuously grazed areas compared with the other two areas. However, differences in the combined canopy of *Carex* species among grazing histories were found to be insignificant.

Hoof impressions created by the hoof simulator, although not significantly different ($p > 0.10$) among grazing histories, did show an increasing trend in soil deformation from long-term exclosures, to exclosures opened in 1988, and to continuously grazed plots (2.8 cm to 4.5 cm and 5 cm respectively) (Table 3.1). Soil shear strength showed an increasing trend, (although not significant ($p > 0.10$)), from the long-term exclosures, to the exclosures opened to grazing in 1988, and strongest in the continuously grazed areas. This non-significant trend followed the trend in soil bulk density, and is worthy of further research.

Hoof Simulator

The application of the hoof simulator was found to create a significantly ($p = 0.01$) greater impact when soils were wetted to create a soil surface commonly found in the spring following snowmelt or following intense rainfall events, when compared to a non-wetted soil surface. Grazing history did show a trend in hoof simulator treatment (with deeper impressions with longer grazing), but no statistically significant differences were found among the three grazing histories (Table 3.1). It is believed that a one-time hoof impression may not be sufficient to cause deformation unless impressed on wet soils.

Stepwise regression analyses were used with the hoof simulated impact (depth of impression) as the dependent variable (Table 3.3). The complete model (before stratifying) yielded hoof impact (impression) = -2.57 + 0.16 (surface soil moisture), but had a very low $r^2 = 0.08$. The surface soil moisture would be expected to be an important variable for depth of hoof impact. The hoof simulator impressions were slightly correlated ($r^2 = 0.29$, $p = 0.04$)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

with surface soil moisture. This suggested that with greater soil moisture content of the soil surface, the depth of imprint caused by the hoof simulator was greater.

Stratifying the hoof simulator data among the three grazing histories did help explain a greater percentage of the variability in hoof simulator depth, but only within the area opened to grazing in 1988. Results of the stepwise regression analyses for the exclosure and long-term grazing models failed to produce significant regression equations because variable selection failed to meet the $p \leq 0.10$ significance criteria. This indicated that the hoof impact was not well explained by vegetation canopy and soil variables collected in this study for long-term exclosures and continuously grazed areas.

The area opened to grazing in 1988 did produce a significant regression equation ($p \leq 0.05$) and indicated that sand in the soil was the most important variable, followed by root length density. Both sand and total root length density were moderately correlated ($r^2 = -0.43$ and -0.48, $p \leq 0.10$) with the hoof simulator impression in the area opened to grazing in 1988. These negative correlations may indicate that the greater the content of sand and quantity of roots within the soil profile, the less the hoof impact on soils. Sand may indicate better soil drainage and decreased soil moisture. Soil moisture was positively correlated with the hoof impact in these opened areas, indicating that wetter soils resulted in greater hoof impact.

As expected, greater hoof imprint depths were found on wet soils compared to dry soils. Past grazing histories showed an increasing trend in hoof impact from exclosures to continuous grazed areas, but were not found to be significantly different. The significant results of the stepwise regression procedure did indicate that areas opened to grazing in 1988 had greater root length density, and the hoof impact decreased. Results also indicated that a

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

one-time hoof impact may not be sufficient to detect a significant soil extension unless soils were wet. The greater amount of roots, measured as root length density, may help to decrease hoof impact. As soil organic matter increased, hoof impact decreased. This would suggest that greater organic matter in the soil helps to reduce impacts of a one-time hoof impression on intact soils.

Shear Test Study

Soil shear strength

Soil shear strength showed an increased trend in strength from exclosures to continuously grazed sites, somewhat similar to depth of hoof impressions. A GLM one-way analysis of variance on soil shear strength did not show a significant difference for soil shear strength among grazing histories, even though shear strength in continuously grazed plots was more than twice that observed within long-term exclosures (Table 3.1). Tanner and Mameril (1959) reported that grazing animals increased bulk density, decreased porosity, and increased penetrometer resistance. Trends observed from this study would suggest further research to verify that a history of grazing animal use may also increase soil shear strength.

Soil shear strength as a dependent variable was expected to help explain factors that lead to soil extension by the artificial hoof. Stepwise multiple regression was used to examine shear stress results stratified by past grazing history and explained more variability than the hoof imprint analyses. Results of stepwise regression analyses resulted in r^2 of 0.34 for the complete model and between 0.32 and 0.81 when stratified by grazing history (Table 3.3).

Canopy cover of *Carex* spp. and surface soil moisture (0-10 cm) were the most important variables in explaining the variability in soil shear strength for the complete data

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

set (Table 3.3). *Carex* spp. roots are often described as important to streambank stability in riparian literature (Winward 2000), but it may be their properties of greater extensibility until tensile failure that help knit together streambanks in which they are dominant. Soil moisture was positively correlated ($r^2 = 0.43$, $p \leq 0.01$) with soil shear strength, which indicated that with greater soil moisture there was greater soil shear strength. Manning et al. (1989) found that root length density and mass were correlated with the wetness of the site (i.e., there were more roots at the wetter sites), and thus wetter sites had superior site stabilizing characteristics.

When data were analyzed for each of the grazing history areas, different variables were useful to help explain soil shear strength for areas that had been grazed by cattle or excluded. Sand and soil moisture were the important variables to help explain soil shear strength in areas recently opened to grazing. Sand was strongly negatively correlated (0.83, $p \leq 0.01$) with shear strength, indicating the greater percentage of sand in soil texture the weaker the shear strength. An increase in sand content helped explain diminished soil strength and fit classical soil mechanics (Brady 1974, Hillel 1980). Soil moisture was positively correlated with soil shear strength and would indicate that shear strength increased with increasing soil moisture (Table 3.1). This finding differed from the hoof simulator study where increasing soil moisture increased impression depth, but might be attributed to the greater strength of *Carex* roots.

Analysis of soil shear strength for long-term continuous grazing showed that the percentage of *Carex* cover was an important variable to help explain soil shear strength. The roots of *Carex* may give extra strength to the soil, at least twice the strength and extension of grasses (Table 3.2). Grouping of plant communities determined by Principal Component

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Analysis (PCA) exhibited greater soil shear strength for *Carex* dominated communities than for the other two communities (*Juncus*/grass, *Salix*/grass/forb) (Figure 3.4).

Soils data also indicated that after eight years of grazing of previous exclosures (the ones opened in 1988), soil shear strength nearly doubled, soil organic matter decreased 3% while soil bulk density significantly increased from 0.70 g cm^{-3} to 0.83 g cm^{-3} in the same period. Cruse and Larson (1977), using soil shear strength parameters from unconfined compression tests, determined that greater soil bulk density increased soil shear strength. Binkley et al. (2003) found grazing and hoof action by elk significantly increased soil bulk density at Rocky Mountain National Park. Blackburn (1984) noted that bulk density of topsoil was higher in heavily grazed pastures in 38 of 43 instances mentioned in his review. Soil strength is a function of physical texture, bulk density, moisture content, and type and amount of roots. Parker et al. (1995) used soil of very similar textural properties (87% sand, 4% silt, and 9% clay) in a laboratory experiment where samples were artificially compacted to derive soil shear strength values of 7.0, 7.6, 8.2, and 9.2 kN/m^2 at bulk densities of 1.28, 1.36, 1.44, and 1.52 Mg/m^3, respectively. Soil shear strengths as measured by a Swedish fall-cone penetrometer were found to be linearly correlated with soil compaction, and a penetrometer would not measure the root contribution to soil strength.

As we consider the relative contribution of root tensile strength to these soils, contrasting an exclosure with low bulk density with other areas outside the exclosures that were grazed for decades, it is likely that the contribution of root tensile strength was less important in compacted soil than in untrampled soil. In a literature review, Milchunas and Lauenroth (1993) reported approximately equal numbers of positive and negative responses

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

of root mass to previous grazing. Root biomass was found to be significantly different ($p = 0.08$) among land use histories in the present study (Table 3.1).

These results reflect the not surprising reality that just as soil engineers use a 'sheep's foot' roller to achieve maximum soil compaction and bulk density for design purposes (USDA NRCS Field Office Technical Guide, National Engineering Handbook, 2004), the hooves of grazing ungulates on soils of varying moisture conditions, especially near the water table of a riparian area, are ideally suited to deform and compact riparian soils. Hillel (1980) quoted Gill and Vanden Berg (1967) who found that a combination of pressure and shear stress accentuated compaction, perfectly describing the action of an ungulate hoof on soil of adequate moisture for plant growth. However, with freezing and thawing that occur over the winter period, much hoof compaction disappears (Clary and Kinney 2002, Wheeler et al. 2002). The results of the present study, reflecting land use differences over many years, showed a cumulative effect from hoof compaction.

Plant litter, stems, and other foliage may cushion the riparian soil surface from hoof impact. This was noted in Abdel-Magid et al. (1987), who described a cumulative effect of trampling on plant litter and live tissue detachment, as trampling intensity (number of footfalls/sod) was more influential in causing a reduction of shoot biomass and detachment of either living or dead shoot material than was the timing of this trampling. The single application of a hoof imprint in the present experiment did not cause a cumulative effect. A soil rebound effect, following a single hoof imprint, was perceived but the effect could not be measured. This probably resulted from the soil rebound effect that Greenwood and McKenzie (2001) cited from McBride and Watson (1990) that was related to high organic matter content, wet soils, low initial bulk density, and high clay content. Both high organic

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

matter and low bulk density were evident in the present study, especially in the exclosure. A cumulative effect was not tested in the present study. Future research into streambank resilience should investigate effects that act to defeat the rebound effect, and determine where the resilience threshold may be.

CONCLUSIONS

Hoof impression was found to be significantly greater when the soil surface was wet, similar to spring snow melt or rainfall events. Neither hoof impressions nor shear strength of surface soil showed significant statistical differences ($p \leq 0.10$) for areas with different grazing histories, though trends were apparent. Significantly different ($p \leq 0.10$) trends among the grazing histories were found: long-term exclosures had lower bulk density than exclosures opened in 1988 and continuously grazed exclosures; they had greater soil organic matter than exclosures opened in 1988 and continuously grazed exclosures; and root biomass was lower in exclosures and higher in exclosures opened to grazing in 1988. Therefore, soil bulk density for the 0-10 cm depth increased as long-term grazing history increased from exclosures, to 8 years grazing, to long-term (> 40 years) grazing.

Soil texture, particularly sand, was also important; as the percentage of sand increased in the soil profile, streambank stability (measured as shear stress) decreased. However, as sand percentage increases, streambank stability may increase if hoof impression depth is the variable measured. This contradictory finding can be explained because the greater sand percentage in an intact soil profile near the surface may increase drainage, causing a decrease in soil moisture at the surface where the hoof print is located. A sandy texture in a soil sample used for the shear stress test would decrease the shear strength of the sample. Hillel (1980) noted that 'soil consistency' was used to describe how a soil reacted to externally

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

imposed forces, and to what extent soil could maintain its shape when subjected to forces that might cause deformation. He reported that soil wetness was the major determinant of soil consistency. This is recognized by the often described 'Atterburg limits' for soils (Atterburg 1912) which illustrates changing soil consistency with increasing water content (from hard → friable → plastic → liquid).

For more than half a century, the Field Office Technical Guides of the USDA Soil Conservation Service (now known as the Natural Resources Conservation Service) have contained standards and specifications for grazing that include the counsel to avoid grazing when soils are wet. This current field research supports the recommendation that, all other things being equal, grazing to achieve less soil surface disturbance should occupy time periods when the soil is drier. This can be achieved by limiting use to later periods in the year or reducing time on moist or saturated soils. This research also supports the long-term relationship between grazing, soil bulk density, soil organic matter, and root biomass. Measuring streambank stability using different variables may give conflicting results. The *Carex* dominated plant community, with stronger roots, appeared to have greater shear strength than grasses and forbs. Therefore, plant community classifications can help managers determine time periods and areas where grazing may pose less disturbance.

Further research should be conducted to determine whether soil compaction can serve as a streambank degradation indicator or if the streambank is nearing a threshold. Compaction and soil bulk density can indicate early stages of species replacement and diminished root growth. Grazing systems that can ameliorate compaction short of a threshold should be pursued. Although livestock removal has been advocated (Kauffman et al. 2004) as an approach to streambank restoration, increased understanding of plant

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

succession and dynamics related to soil and hydrological properties (Stringham et al. 2001) can yield models that guide pragmatic and effective management prescriptions for both livestock and wildlife.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

LITERATURE CITED

Abdel-Magid, A. H., M. J. Trlica, and R. H. Hart. 1987. Soil and vegetation responses to simulated trampling. *Journal of Range Management* 40:303-306.

Atterburg, A. 1912. Die mechanische Bodenanalyse und die Klassification der Mineralöboden Schwedens. *Intern. Mitt. Bodenk* 2:312-342.

Allen, T. 1990. Particle size measurement. 4th Ed. New York, NY: Chapman and Hall. 806 p.

Binkley, D., F. Singer, M. Kaye, and R. Rochelle. 2003. Influence of elk grazing on soil properties in Rocky Mountain National Park. *Forest Ecology and Management* 185:239-247.

Blackburn, W. H. 1984. Impacts of grazing intensity and specialized grazing systems on watershed characteristics and responses. *In:* Developing strategies for rangeland management. Boulder, CO: Natural Research Council/National Academy of Sciences, Westview Press. p. 927-983.

Brady, N. C. 1974. The nature and properties of soils. 8th Ed. New York, NY: MacMillan Publishing. 639 p.

Clary, W. P. and J. W. Kinney. 2002. Streambank and vegetation response to simulated cattle grazing. *Wetlands* 22:139-148.

Corley, C. J., G. W. Frasier, M. J. Trlica, F. M. Smith, and E. M. Taylor Jr. 1999. Technical note: nitrogen and phosphorus in runoff from 2 montane riparian communities. *Journal of Range Management* 52:600-605.

Cruse, R. M. and W. E. Larson. 1977. Effect of soil shear strength on soil detachment due to raindrop impact. *Soil Science Society of America Journal* 41:777-781.

Di, H. J., K. C. Cameron, and Reijnen. 2001. A mechanical hoof for simulating animal treading under controlled conditions. *New Zealand Journal of Agricultural Research* 44:111-116.

Duce, J. T. 1918. The effect of cattle on the erosion of canyon bottoms. *Science* 47:450-452.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Dunaway, D., S. R. Swanson, J. Wendel, and W. Clary. 1994. The effect of herbaceous plant communities and soil textures on particle erosion of alluvial streambanks. *Geomorphology* 9:47-56.

Easson, G. and L. D. Yarbrough. 2002. The effects of riparian vegetation on bank stability. *Environmental and Engineering Geoscience* 8:247-260.

George, M. R., D. Lile, and N. McDougald. 1992. Monitoring livestock impacts in mountain meadows. Unpublished Report. Department of Agronomy and Range, University of California, Davis, CA. 42 p.

Gifford, G. F. and R. H. Hawkins. 1978. Hydrologic impact of grazing on infiltration: a critical review. *Water Resources Research* 14:305-315.

Gill, W. R. and G. E. Vanden Berg. 1967. Soil dynamics in tillage and traction. U.S. Department of Agriculture. Handbook No. 316. p. 22.

Goss, D. W. 1973. Relation of physical and mineralogical properties to streambank stability. *Water Research Bulletin* 9:140-144.

Greenwood, K. L., and B. M. McKenzie. 2001. Grazing effects on soil physical properties and the consequences for pastures: a review. *Australian Journal of Experimental Agriculture* 41:1231-1250.

Grissinger, E. H., W. C. Little, and J. B. Murphey. 1981. Erodibility of streambank materials of low cohesion. *Transactions of the American Society of Agricultural Engineers* 24:624-630.

Grossman, R. B. and T. G. Reinsch. 2002. Bulk density and linear extensibility. *In:* J. H. Dane and G. C. Topp [EDS.]. Methods of soil analysis, Part 4. Madison, WI: American Society of Agronomy. p. 201-228.

Heady, H. F. and R. D. Child. 1994. Rangeland ecology and management. Boulder, CO: Westview Press, Inc. 519 p.

Hillel, D. 1980. Fundamentals of soil physics. New York, NY: Academic Press. 413 p.

Hooke, J. M. 1980. Magnitude and distribution of rates of river bank erosion. *Earth Surface Processes and Landforms* 5:143-157.

Inouye, D. 1996. The digital stopwatch as a source of random numbers. *Bulletin of the Ecological Society of America* 77:217-218.

Jackson, R. B., W. T. Pockman, and W. A. Hoffman. 1999. The structure and function of root systems. *In:* F. I. Pugnaire, and F. Valladares [EDS.]. Handbook of functional plant ecology. New York, NY: Marcel Dekker. p. 195-220.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Kaspar, T. C. and R. P. Ewing. 1997. ROOTEDGE: software for measuring root length density from desktop scanner images. *Agronomy Journal* 89:932-940.

Kauffman, J. B. and W. C. Krueger. 1984. Livestock impacts on riparian ecosystems and streamside management implications: a review. *Journal of Range Management* 37:430-438.

Kauffman, J. B., A. S. Thorpe, and E. N. J. Brookshire. 2004. Livestock exclusion and belowground ecosystem responses in riparian meadows of eastern Oregon. *Ecological Applications* 14:1671-1679.

Kleinfelder, D., S. R. Swanson, G. Norris, and W. Clary. 1992. Unconfined compressive strength of some streambank soils with herbaceous roots. *Soil Science Society of America Journal* 56:1920-1925.

Klute, A. [ED.]. 1986. Methods of soil analysis. Part I. Physical and mineralogical methods. Madison, WI: American Society of Agronomy and Soil Science Society of America. 1188 p.

Laycock, W. A., H. Buchanan, and W. C. Krueger. 1972. Three methods of determining diet, utilization, and trampling damage on sheep ranges. *Journal of Range Management* 25:352-356.

Lull, H. W. 1959. Soil compaction on forest and rangelands. U.S. Department of Agriculture, Forest Service Miscellaneous Publication. No. 768.

Manning, M. E., S. R. Swanson, T. Svejcar, and J. Trent. 1989. Rooting characteristics of four Intermountain meadow community types. *Journal of Range Management.* 42:309-312.

Mergen, D. E. 1998. Plant cover effects on surface roughness, infiltration, runoff, and sediment yield of a sagebrush-grass rangeland [dissertation]. Fort Collins, CO: Colorado State University. 134 p.

McBride R. A. and G. C. Watson. 1990. An investigation of the re-expansion of unsaturated, structured soils during cyclic static loading. *Soil and Tillage Research* 17:241-253.

McGarigal, K., S. Cushman, and S. Stafford. 2000. Multivariate statistics for wildlife and ecology research. New York, NY: Springer-Verlag. 283 p.

Micheli, E. R., and J. W. Kirchner. 2002. Effects of wet meadow vegetation on streambank erosion. 2. Measurements of vegetated bank strength and consequences for failure mechanics. *Earth Surface Processes and Landforms* 27:687-697.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Milchunas, D. and W. Lauenroth. 1993. Quantitative effects of grazing on vegetation and soils over a global range of environments. *Ecological Monographs* 63:327-366.

Naiman, R. J. and H. Décamps. 1997. The ecology of interfaces: Riparian zones. *Annual Review of Ecology and Systematics* 28:621-658.

NOAA (National Oceanic and Atmospheric Administration). 1995. Climatological data. Red Feather Lakes, Colorado, USA. Asheville, NC: U.S. Department of Commerce.

Ott, L. 1988. An introduction to statistical methods and data analysis. Boston, MA: Kent Publishing Company. 1152 p.

Parker, D. B., T. G. Michel, and J. L. Smith. 1995. Compaction and water velocity effects on soil erosion in shallow flow. *Journal of Irrigation Drainage Engineering* 121:170-178.

Pearce, R. A. 1995. Sediment movement and filtration within laboratory and riparian vegetation buffer strips [dissertation]. Fort Collins, CO: Colorado State University.

Pearce R. A., M. J. Trlica, W. C. Leininger, D. E. Mergen, and G. Frasier. 1998. Sediment movement through riparian vegetation under simulated rainfall and overland flow. *Journal of Range Management* 51:301-308.

Platts, W. S. 1991. Livestock Grazing. *In:* William R. Meehan [ED.]. Influences of forest and rangeland management on salmonid fishes and their habitats. Bethesda, MD: American Fisheries Society Special Publication 19. p. 389-423.

Platts, W. S. and R. F. Raleigh. 1984. Critique - Impacts of grazing on wetlands and riparian habitat. *In*: Developing strategies for rangeland management. Boulder, CO: Westview Press. p. 1105-1118.

Polomski, J. and N. Kuhn. 2002. Root research methods. *In:* Waisel, Y., A. Eshel, and U. Kafkafi [EDS.]. Plant roots: the hidden half. New York, NY: Marcel Dekker, Inc. p. 295-321.

Popolizio, C. A., H. Goetz, and P. L. Chapman. 1994. Short-term response of riparian vegetation to 4 grazing treatments. *Journal of Range Management* 47:48-53.

Quinn, J. A. and D. F. Hervey. 1970. Trampling losses and travel by cattle on sandhills range. *Journal of Range Management* 23:50-55.

Rosgen, D. L. 1996. Applied river morphology. Pagosa Springs, CO: Wildland Hydrology.

SAS Institute Inc. 1988. SAS/STAT User's Guide, release 6.03. Cary, NC: SAS institute.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Schultz, T. and W. C. Leininger. 1990. Differences in riparian vegetation structure between grazing areas and exclosures. *Journal of Range Management* 43:295-299.

Scholefield, D. and D. M. Hall. 1986. A recording penetrometer to measure the strength of soil in relation to stresses exerted by a walking cow. *Journal of Soil Science* 37:165-172.

Selby, R. 1982. Hillslope materials and processes. New York, NY: Oxford University Press. 264 p.

Skovlin, J. M. 1984. Impacts of grazing on wetlands and riparian habitat: a review of our knowledge. *In*: Developing strategies for range management. Boulder, CO: Westview Press. p. 1001-1102.

Simon, A., N. Pollen, and E. Langendoen. 2006. Influence of two woody riparian species on critical conditions for streambank stability: Upper Truckee River, California. *Journal of the American Water Resources Association* 42:99-113.

Smith, D. G. 1976. Effect of vegetation on lateral migration of anastomosed channels of a glacier meltwater river. *Bulletin of the Geological Society of America* 87:857-860.

Steel, R. G. D. and J.H. Torrie. 1976. Introduction to statistics. New York, NY: McGraw-Hill. 382 p.

Stringham, T. K., W. C. Krueger, and D. R. Thomas. 2001. Application of non-equilibrium ecology to rangeland riparian zones. *Journal of Range Management* 54:210-217.

Storer, D. A. 1984. A simple high volume ashing procedure for determining soil organic matter. *Commercial Soil Science Plant Analysis* 15:759-772.

Tanner, C. B. and C. P. Mameril. 1959. Pasture soil compaction by animal traffic. *Agronomy Journal* 51:329-331.

USDA, Natural Resources Conservation Service. 2004. Field office technical guide. Larimer County, CO.

USDA, Soil Conservation Service and Forest Service. 1980. Soil survey report. Larimer County, CO. Washington, DC: U.S. Government Printing Office. 239-812/48.

Warren, S. D., M. B. Nevill, W. H. Blackburn, and N. E. Garza. 1986a. Soil response to trampling under intensive rotation grazing. *Soil Science Society of America Journal* 50:1336-1341.

Warren, S. D., T. L. Thurow, W. H. Blackburn, and N. E. Garza. 1986b. The influence of livestock trampling under intensive rotation grazing on soil hydrologic characteristics. *Journal of Range Management* 39:491-495.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Weaver, J. E. 1954. North American prairie. Lincoln, NE: Johnsen Publishing Company. 348 p.

Wester, D. B. 1992. Viewpoint: replication, randomization, and statistics in range research. *Journal of Range Management* 45:285-290.

Wheeler, M. A., M. J. Trlica, G. W. Frasier, and J. D. Reeder. 2002. Seasonal grazing affects soil physical properties of a montane riparian community. *Journal of Range Management* 55:49-56.

Williamson, R. B., R. K. Smith, and J. M. Quinn. 1992. Effects of riparian grazing and channelisation on streams in Southland, New Zealand. 1. Channel form and stability. *New Zealand Journal of Marine and Freshwater Resources* 26:241-258.

Winward, Alma H. 2000. Monitoring the vegetation resources in riparian areas. General technical report. RMRSGTR-47. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 49 p.

Ziemer, R. R. 1978. An apparatus to measure the crosscut shearing strength of roots. *Canadian Journal of Forestry Research* 8:142-144.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Figure 3.1. Orientation of the pin-table to the streambank within a 5 x 5 m plot adjacent to Sheep Creek.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Figure 3.2. The hoof simulator in operation, configured for hoof impression.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

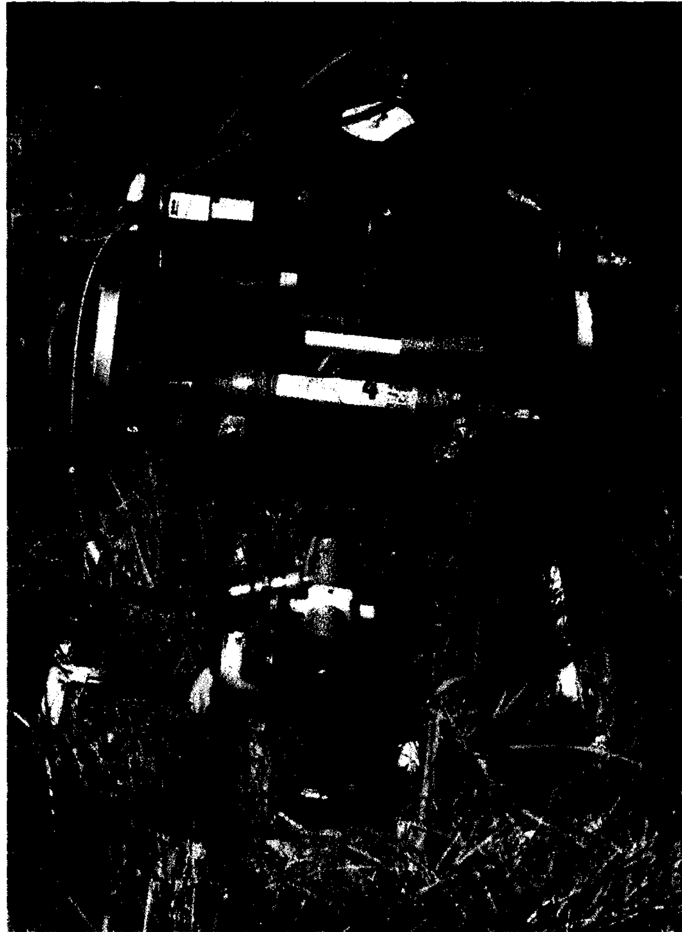


Figure 3.3. Hoof simulator in configuration to perform shear test on 10 cm diameter soil cores.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

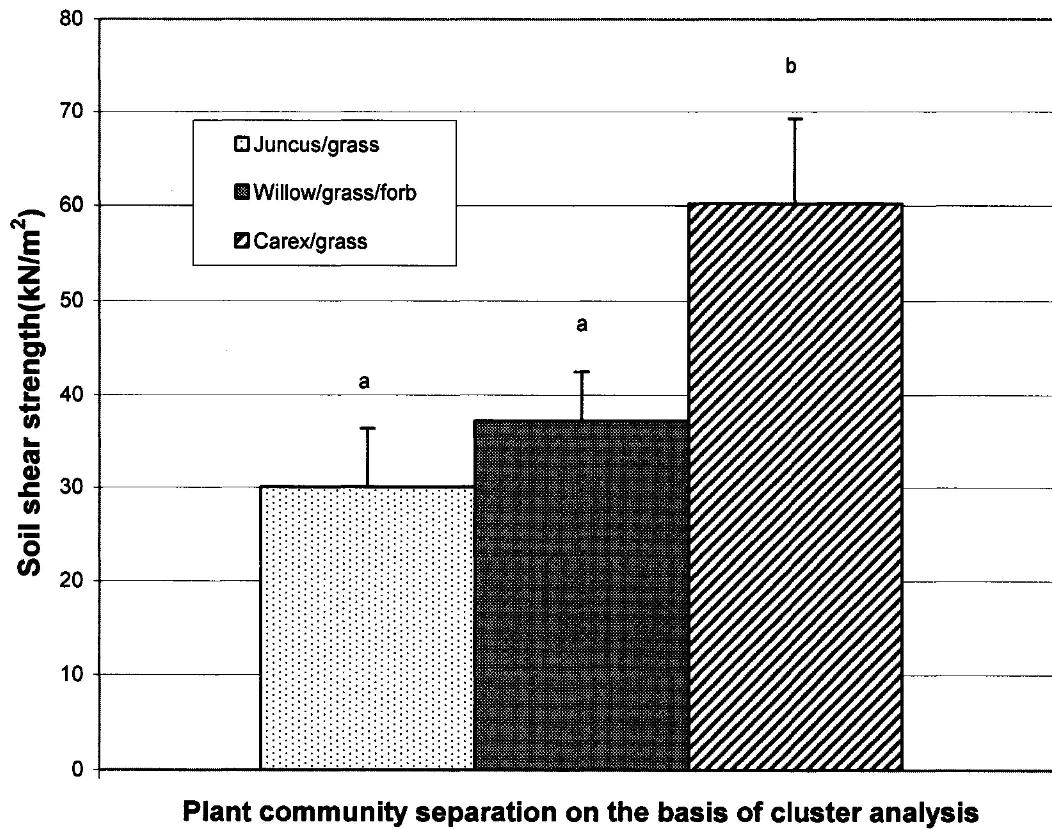


Figure 3.4. Comparison of soil shear strength for three montane riparian communities. Bars with different letters are significantly different. Means for each variable with different letters above a bar across treatments are significantly different ($p \leq 0.10$). Error bars represent 1 SE.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 3.1. Means and standard errors for soil and plant characteristics in each of the three grazing histories that were found to be significantly different at $p \leq 0.10$. Standard errors are in parentheses and means within a row followed by a different letter are significantly different ($p \leq 0.10$).

Characteristic	Exclosures	Opened to grazing in 1988	Continuous grazing	p-value
Soil organic matter (%)	12.5 (0.2) b	9.6 (0.5) ab	8.1 (0.4) a	0.0178*
Soil bulk density (g/cm^3)	0.73 (0.04) a	0.83 (0.04) ab	0.90 (0.02) b	0.0211*
Carex utriculata (%)	4 (1) ab	<1.0 (0.1) a	14 (2) b	0.0125**
Grass cover (%)	55 (8) b	43 (3) ab	33 (2) a	0.0171**
Root biomass (g/cm^3)	0.009 (0.001) a	0.014 (0.001) b	0.010(0.001) ab	0.0884
Root length for <0.5 mm diameter (cm)	4622 (1876) b	1726 (273) a	1951 (184) a	0.1110
Hoof impression (mm)	2.8 (1.2) a	4.5 (3.0) a	5.0 (1.2) a	0.08501***
Soil shear strength (kN/m^2)	23.6 (7.7) a	40.9 (7.0) a	50.5 (7.2) a	0.1300***

* Soil characteristics for exclosure were significantly different ($p \leq 0.10$) from both open to grazing in 1988 soils and continuous grazed soils.

** Canopy of *Carex utriculata* and grass cover were significantly different ($p \leq 0.10$) in the continuous grazed area compared with exclosures and opened to grazing in 1988.

*** Graphic differences were observed, but the lack of significant differences among grazing treatments was strongly influenced by sample size among grazing histories. Only two sites within exclosures were sampled: four in the opened to grazing in 1988 areas, and 9 within the continuous grazed areas.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 3.2. Root characteristics for vegetation lifeforms of riparian plant species at Sheep Creek, Colorado. Standard errors are in parentheses below the mean.

Root characteristic	Sedge (*Carex*)	Rush (*Juncus*)	Grass	Shrub (*Salix*)	Forb
Average root diameter (mm)	1.5b[1] (0.05)	2.2c (0.14)	0.7a (0.04)	3.3d (0.28)	0.4a (0.04)
Average area for root cross-section (mm^2)	2.5a (0.18)	6.3b (0.72)	0.5a (0.06)	16.0c (3.05)	0.1ab (0.02)
Force at root tensile failure (Newtons)	14.1a (0.94)	22.0a (2.88)	6.1a (0.55)	73.0b (17.31)	3.7a (0.94)
Displacement at root tensile failure (mm)	25.8c (0.61)	21.3b (0.92)	12.1a (0.52)	12.4a (0.76)	5.2a (6.09)
Stress Force/root cross-section area (N/mm^2)	7.4a (0.23)	6.5a (0.59)	24.8b (2.39)	5.6a (0.39)	36.6c (11.81)
Strain (mm/mm) (displacement/original length)	0.4a (0.01)	0.3c (0.01)	0.3c (0.01)	0.2b (0.01)	0.13b (0.02)
Sample size (number)	393	157	167	122	8

[1]Different letters within a row indicate significant differences ($p \leq 0.10$) among life form means for root characteristics analyzed.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 3.3. Results of stepwise linear regression analyses for dependent variables hoof simulator effect and soil shear strength. The complete data set was used before grazing history stratification of data was conducted.

Model	Dependent variable	Stepwise linear regression equation	r^2
Complete data set	Hoof imprint	-2.57 + 0.16 (surface soil moisture)	0.08
Exclosure	Hoof imprint	No significant ($p \leq 0.10$) variables were selected in stepwise regression procedure	*
Opened in 1988	Hoof imprint	131.69 – 1.66 (% sand) – 0.91 (root length density)	0.41
Continuous grazing	Hoof imprint	No significant ($p \leq 0.10$) variables were selected in stepwise regression procedure	*
Complete data set	Shear strength	= 1.45 + 0.66 (% *Carex* canopy) + 0.57(surface soil moisture)	0.34
Exclosure	Shear strength	No significant ($p \leq 0.10$) variables were selected in stepwise regression procedure	*
Opened in 1988	Shear strength	= 171.59 – 2.27 (% sand) + 0.45 (surface soil moisture)	0.81
Continuous grazing	Shear strength	= 24.83 + 1.05 (% *Carex* canopy)	0.32

* Variable selection criteria set at significance of $p \leq 0.10$; no variables were significant at this level.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

CHAPTER IV

ROOT TENSILE STRENGTH OF MONTANE STREAMBANK SPECIES

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

INTRODUCTION

The resistance and resilience of streambanks to animal traffic reflects the effects of compaction and shear imposed by an animal hoof (in the case of large ungulates) on a soil medium (Trimble and Mendel 1995) versus the inherent properties of that medium and its tendency to recover (Wheeler et al. 2002). Neither soil physics nor root biomass alone account for the behavior of a matrix of layered, graded soil, mixed with gravel and cobble material interwoven with a network of plant roots and fungal mycelium at variable moisture contents. Selby (1982) discussed the factors that contribute strength to soils in sloped situations, and concluded that mechanical reinforcement of the soil was provided by root networks, particularly tree roots. Simon et al. (2006) quantified root reinforcement by Lodgepole pine and Lemmon's willow, and found willow to provide significant mechanical reinforcement of streambank stability, (though they defined stability more broadly than I), in terms of bank failure, while my work measured changes in bank conformation above the water's edge.

Excellent early work was done by Weaver (1926), Kramer and Weaver (1936), and Weaver (1954) who assessed relationships of root morphology and root mass with soil erosive forces. Hathaway and Penny (1975) examined the tensile strength of cottonwood (*Populus* spp.) and willow (*Salix* spp.) roots as related to anatomy and chemical composition, and found the amount of root stele tissue and its specific gravity were the most important factors that determined root tensile strength. Niklas (1992) addressed the biomechanics of roots and aboveground plant parts and pointed out unstudied aspects of anatomical and geometrical heterogeneity that plants bring to any consideration of engineering principles in the plant realm.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Thorne and Tovey (1981) described a 25 cm-deep-zone along a streambank where roots formed a mat reinforcing the tensile strength of the soil, but did not present sufficient data to support this reinforcement. Thorne (1990) stated that a dense network of fibrous roots was of more benefit than a streambank with a sparse network of woody roots, and stated that vegetation introduced extra cohesion over and above intrinsic cohesion in streambank material. Vidal (1969), quoted in Thorne (1990), described roots as effective both in adding tensile strength to the soil and, through their elasticity, in distributing stresses through the soil, thereby avoiding local stress build-ups and progressive failures.

Researchers including Manning et al. (1989) have examined the mass and root length density of riparian plant communities and have reported large values for root biomass and root length density compared with agronomic ecosystems. More recent work by Pregitzer et al. (2000) resulted in surprising lengths of fine aspen (*Populus tremuloides* Michx.) roots, approximately 125 m/g for root dimensions of less than 0.4 mm in diameter. Waldron (1977) and Waldron and Dakessian (1981) examined soil reinforcement provided by roots and found, compared with a fallow (non-willow) state, increases of 100 % or more in the shear strength of soils associated with a mature stand of willows. Historic values of tensile strength of willow roots have been reported to be as much as 176 kg/cm^2 (E. Engber, pers. comm, 2000). Easson and Yarbrough (2002) quantified effects of root reinforcement on a fine-grained soil matrix in Mississippi by excavating, mapping, measuring, and modeling root reinforcement. The tensile strength of soil without roots is 3-5 orders of magnitude weaker than that of soil with tree roots under tension (Coutts 1983). The effects of cattle grazing on root and soil strengths have not been well examined.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Livestock can contribute to streambank instability in at least two ways: 1) they may leave insufficient vegetation on banks for protection, and 2) the direct effect of 'chiseling' and soil compaction by hoof action (Skovlin 1984, Platts 1991, George et al. 1992). Long-term browsing and trampling of riparian shrubs may cause the most deleterious effect (Skovlin 1984). However, Platts and Raleigh (1984) believed that hoof action (chiseling) was the predominant deleterious effect of livestock on streambank stability. Williamson et al. (1992) found undercutting of banks in New Zealand was largely unaffected by grazing stream margins, whereas channelized streams led to severe streambank erosion. Greenwood and McKenzie (2001) reviewed the impacts of grazing for many different species of grazing animals, described average values of force applied, and described elements of soil strength and resilience, concluding that soil damage was particularly great when soil moisture was high.

Böhm (1979), in his very thorough study, cited Zuber (1968) (among others) who related the absolute force necessary to uproot a plant to soil structure and soil water content. Böhm mentioned studies by King and Beard (1969) and Dunn and Engel (1970) who used vertical and horizontal force techniques to measure adhesion between the soil contained in a piece of sod and the underlying soil. Böhm (1979), in this compilation of root study methods, mentioned investigators who measured root tensile strength but not explicitly in riparian situations. No other examples were found in the literature of streambank experiments to test the inherent resistance of herbaceous riparian plant roots to external force, as an indication of the ability of these plants to reinforce the soil matrix.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Hypotheses

1. Streambank morphology, soil physical properties, herbaceous plant communities, and root characteristics of streambank soils contribute to the resistance of streambanks to livestock traffic.
2. Streambank stability in grazed riparian areas is inversely related to intensity of livestock trampling.

The objective of this study was to relate riparian species root strength to streambank stability measured as soil shear strength. This included relating plant lifeforms and plant communities to soil and root characteristics to help explain soil-root matrix strength. From the work of Winward (2000) and others, it was hypothesized that willows and grass-like plants would have greater overall strength than would grasses and forbs, due to their more robust roots. The focus of this experiment was above the high water line to avoid the further complexity of fluvial effects.

STUDY AREA

The study took place during the summer of 1996 at 40^0 38' N latitude and 105^0 38' W longitude in the riparian zone along Sheep Creek in the Roosevelt National Forest of North Central Colorado. The research site was located along 2.4 km of Sheep Creek. Sheep Creek is classified as a C-4 stream according to Rosgen (1996).

The research area is approximately 80 km northwest of Fort Collins, Colorado at an elevation of about 2500 to 2550 m. The area historically had 'checkerboarded' land ownership shared by the Union Pacific Railroad and the US Forest Service (USFS), but is now under USFS management. The area is open to recreation (such as fishing, hunting, and

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

camping) and is used for livestock grazing, timber harvesting, and as a water catchment for downstream irrigation.

Soils in the study area were derived from granitic parent material and are deep, coarse, sandy to clay loam family of pachic cryoborolls (USDA 1980). Climate at Sheep Creek is temperate montane. Mean annual precipitation for the study site is approximately 400 mm. Growing season precipitation averages about 240 mm (NOAA 1995).

Vegetation of the riparian zone along Sheep Creek consists primarily of mixtures of willows (*Salix* spp.), sedges (*Carex* spp.), rushes (*Juncus* spp.), Kentucky bluegrass (*Poa pratensis* L.), tufted hairgrass (*Deschampsia caespitosa* (L.) Beauv.), Canadian reedgrass (*Calamagrostis canadensis* (Michx.) Beauv.), and other minor species (Schultz and Leininger 1990).

MATERIALS AND METHODS

Clumps of herbaceous roots and *Salix* species roots were obtained from riparian plant communities along Sheep Creek for 13 taxa: *Calamagrostis canadensis* (Michx.) Beauv.; *Deschampsia caespitosa* (L.) Beauv.; *Poa pratensis* L.; *Juncus arcticus* Willd. ssp. *littoralis* (Engelm.) Hultén; *Carex microptera* Mackenzie; *Carex nebrascensis* Dewey; *Carex utriculata* Boott; *Salix exigua* Nutt.; *Salix planifolia* Pursh; *Phleum pratense* L.; *Trifolium* spp.; and *Fragaria vesca* L. (PLANTS database USDA NRCS 2006). Root samples were placed in coolers and transported to a lab in Fort Collins, Colorado. Root clumps were rinsed with water, separated into similar-sized root diameters, cut into sub-samples that were 10-20 cm long, and placed into heavy-duty re-sealable plastic bags in a solution of 50% isopropyl alcohol, and then refrigerated at 5^0 C.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Testing equipment at CSU Orthopaedic Research Group (CSU OIRP) located in the Colorado State University Veterinary Medicine facility was used in this study. A servohydraulic biaxial mechanical testing machine (MTS) (model 809), with a low force load cell (model 662.20C-01) (MTS Systems Corporation, Eden Prairie, Minnesota, USA), was used to measure root tensile strength (Figure 4.1). Instron grips were used to hold the intact root segments to be tested as each testing cycle proceeded. The MTS hydraulics were computer mediated, and test results were generated as digital ASCII files that were transferred into spreadsheets.

The hydraulic system pressure was 150 MPa. The low-force load cell was used, and force was applied at a constant rate of 6.35 cm/minute until each root failed (Figure 4.2). Data generated included time elapsed, distance traveled (extension), and force applied. These values were converted to metric units in data spreadsheets.

Roots tested for strength were first scanned to estimate diameters. The average diameter for three measurements along a root segment was used to relate root diameter to force applied at root tensile failure. Variability in the hydraulic measurement system averaged 0.9 Newton and was measured by the collection of at least three 'unloaded' samples during each run of root samples.

Diameters of the roots were obtained by measuring images scanned at an optical resolution of 236 dots per cm (600 dots per inch; equivalent to resolution of 23.6 pixels/mm). Length and width of a scanned pixel at this resolution is 0.042 mm; diameter of an average human hair is 0.13 mm. Root material greater than 0.1 mm was selected as a minimum diameter to reduce the potential for exaggerated root length values and misidentification with fungal hyphae. The minimum root diameter used by Kaspar and Ewing (1997) was 0.15 mm.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Fungal hyphae represented diameters in the range of approximately 1-3 μm (micrometers) and average minimum diameters of root hairs were 1 μm and fine roots 50 μm (Polomski and Kuhn (2002) in Waisel et al. (2002)). Root lengths were calculated using ROOTEDGE software (Kaspar and Ewing 1997) and summarized by 13 width categories of root (from < 0.1mm to > 2 mm). Root categories were further summarized into 3 larger width categories to represent roots smaller than 0.5 mm, 0.51 mm to 1.0 mm, and roots greater than 1.0 mm.

Thirteen plots were located on the banks of Sheep Creek. Four 1.2 m^2 subplots were located within each 5 x 5 m plot, corresponding to a 100-point frame (pin-table) of dimensions 0.6 m x 2 m used to characterize vegetation canopy and include soil surface characteristics, species composition, litter, and bare soil of each subplot (Mergen 1998). Plant canopy values were calculated as percentage frequency of the 100 points.

Soil samples were collected at each sub-plot. Soil physical properties within each subplot were also measured. Three soil cores of dimensions 7 x 10 cm were taken within each subplot at even intervals beneath the 2 m long pin-table. Soil texture, soil moisture and organic matter were determined. Soil texture was determined using hydrometer analysis (Bouyoucos 1962). Soil samples were dried at 105^0C for 40 hours to determine soil moisture and then the samples were ashed at 550^0C for 5 hours (Storer 1984, Klute 1986, Pearce 1995) for organic matter determination. Soil textures were run on additional samples to perform hydrometer particulate analyses (Bouyoucos, 1962). Bulk density was also obtained for these samples following the NRCS methodology of Grossman and Reinsch (2002).

Three to five soil cores were collected by driving a soil core sampler of dimensions 7 x 10 cm horizontally into the streambank along the edge of the subplot within the 0-10 cm range of depth. Samples were collected horizontally to better represent a single surface soil

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

horizon. These cores were then placed into the vertical shear column and pressure applied to the upper (mobile) portion of the column with the lower portion immobile until the sample was completely sheared. This was equivalent to a shear force directed vertically downward into the surface soil horizon. Maximum pressure to shear the soil core was measured and recorded. A portion of the maximum pressure reading obtained was derived from overcoming friction in the device. Values related to friction were subtracted from the maximum pressure to yield applied pressure. Applied pressure was multiplied by the diameter of the piston in the hydraulic cylinder (2.54 cm) to arrive at the final value in kN/m^2. Shear strength of soil cores obtained in each subplot within the surface (0-10 cm) soil horizon and within 2 m of the stream was determined.

Experimental Design and Data Analyses

This is an observational study where data from 4 subplots were collected from each of 13 plots along Sheep Creek. The data set was then analyzed by cluster analysis to create vegetation groups (Hall and Khanna 1977). Analyses were also conducted before stratifying data into groups. Vegetation groups derived from the cluster analysis were populations of interest (Wester 1992). The objective was to relate root and soil characteristics, and the associated plant canopy cover, with the shear strength of soil. The experimental unit was the subplot because each subplot was placed into a group based on vegetation cover, and adjacent subplots may have been assigned to different vegetation groups.

Samples of individual herbaceous and willow plants mentioned above, were excavated, but were not associated with individual subplots. These plants were collected throughout the reach of Sheep Creek near subplots to prevent destruction of the experimental subplots. Root tensile strength per mm^2 of diameter was calculated by dividing root tensile

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

strength at failure by average root diameter. Data for individual plants species were also combined into life form categories. Plant roots for species and lifeforms were not associated with a specific subplot. Therefore, to include root tensile strength, root tensile strength by area, and root extension in stepwise regression analyses the average value of each variable was weighted (by multiplying canopy cover from each subplot by root strength or extension values). This method was only used to include a proportion of root strength or extension based on canopy cover and its possible contribution to soil shear strength. Root strengths and extension by species and lifeforms were ranked using measured values to show differences.

Normality tests (Ott 1988) were conducted on four dependent variables (soil shear strength, whole root strength, tensile strength (per cross sectional area), and extension). Data were analyzed using multiple stepwise regression and correlation analyses (Steel and Torrie 1980) both before and after formation of vegetation groups.

Cluster analysis was performed based on the percentage canopy cover for various cover classes (grasses, *Carex*, *Juncus*, forbs, shrubs, bare ground, and litter). Data for the classes were analyzed using a nonhierarchical cluster analysis procedure (ISODATA) to form groups based on within-group similarities and between-group differences (Hall and Khanna 1977). Results of this analysis were used to form three vegetation plant communities compared in this study.

Simple linear regression analyses were used to determine slopes and relationships between root tensile strength, root area and extension roots before failure for major riparian species and vegetation lifeforms before cluster analyses (PROC NOINT, SAS 1988) were conducted. Y-intercepts were forced through the origin to simplify comparisons. Stepwise multiple linear regression and correlation analyses (Steel and Torrie 1980) were performed to

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

determine root tensile strength relationships for each vegetation cluster group. This process was used to select a set of independent variables based on plant cover and soil characteristics to be included in regression models (SAS 1988). The analyses contained independent variables that included means for percentage cover of grasses, *Carex*, *Juncus*, forbs, and shrubs. Soil characteristics included were soil moisture, soil organic matter, soil bulk density, and texture. The dependent variables were root tensile strength, soil shear strength, and extension to root failure.

Each vegetation cover group was considered a population of interest and a general linear model (GLM) one-way analysis of variance (ANOVA) was performed to test for differences among the vegetation communities (Ott 1988). Least significant difference tests (LSD) were used to separate significant ($p \leq 0.10$) means (SAS 1988).

Comparisons of root strength were standardized to strength (Newtons) per unit area (cross-section mm^2) for another method of comparison, often described as tensile strength. Extension was also examined, describing root 'stretch'. Root abundance characteristics like total root length, root biomass, and root length density were analyzed to determine which variables might be used to predict streambank stability (measured as soil shear strength).

RESULTS AND DISCUSSION

Root Tensile Strength and Extension

Figure 4.2 shows a typical one-stage root failure response, whereas Figure 4.3 shows a two-stage failure of a root when force was applied. Two-stage failure was apparent on a few samples of both *Carex utriculata* and *Juncus arcticus*. The first stage was cortex failure, and second stage failure appeared to be of the stele within the root. But the initial force to first stage failure reflects strain on both cortex and stele until the bonds between them fail.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Root Diameters

Table 4.1 relates root diameter for several species to force applied at tensile failure. Forbs were not included since their 'n' values were too low. Average root diameter of the 847 samples was measured and compared for differences among plant lifeforms and significant differences were detected ($p \leq 0.10$) (Table 4.2). Average grass (0.7 mm) and forb (0.4 mm) root diameters were smallest compared with the other lifeforms and were similar in diameter to each other. Shrubs (3.3 mm) had greater root diameter than rushes (2.2 mm), which in turn had greater root diameters than sedges (1.5 mm).

Simple linear regression analyses

Comparisons of force (N) for root failure (root strength) for a whole root, rather than the strength displayed on a per mm^2 of cross sectional area basis (tensile strength), showed that willow roots were significantly ($p = 0.10$) stronger (required greater force to fail) than grasses and forbs (Table 4.2). Shrub roots were 3 and 5 times stronger than rushes and sedge roots, respectively (Table 4.2). When a one-way analysis of variance was conducted on log-transformed force data (because data were determined to be non-normal), results were similar except that force required for forb root failure was now significantly less ($p = 0.01$) compared with shrubs and rushes (Table 4.2).

Root Extension (mm)

An analysis of the absolute amount of stretch or extension for riparian roots until they failed was performed, as was a further description of this extensibility as engineering 'strain', dividing the amount of extension by the original length of root restrained for measurement.

Whole root comparisons

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Analyses of root extension at failure when whole roots were compared for lifeform classes (not on a cross sectional basis, mm^2) showed that shrub roots were extended significantly less ($p = 0.05$) compared with sedges and rushes (Table 4.2). *Carex* roots stretched twice as much as compared with grass and shrub roots and about five times greater than forb roots (Table 4.2). Strain values for *Carex* were greater than for other lifeforms (Table 4.2).

Correlation analysis of all root samples tested for strength at failure resulted in a strong correlation of 0.68 ($p = 0.0001$) between root diameter and force at failure. Individual analyses of force at tensile failure versus root diameter where the root broke for each individual species exhibited a positive relationship between increasing force with increasing root diameter for root failure (example Figure 4.5). These results were expected and are what was observed when whole roots were compared instead of root failure on a cross sectional area (i.e., the latter is tensile strength). Karrenberg et al. (2003) noted that the cortex was of minor importance as a load-bearing tissue under tension, which is why total root diameter may not be a reliable indicator for root tensile strength. Therefore the values for tensile strength of *Salix* roots, where root diameter includes significant cortex tissue, may attribute more strength to greater root diameter than is warranted. Whereas the role of the cortex is minor for load-bearing under tension, it may still play a role as it contributes to the external conformation of the root and to soil-root friction as forces are applied during shear stress. For *Salix* species much of the cortex may be shed during secondary growth (Esau 1965), further diminishing the role of the cortex in load bearing for these woody species.

A general trend was observed with root extension when compared using whole root measurements (Table 4.4). Herbaceous mesic plant roots, like *Carex* and rushes, were

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

extended a greater distance (mm) before root failure compared with lifeforms associated with dryer upland grasses and forbs. Strain values followed a similar pattern.

There are large differences depending on whether comparisons are made on a whole root basis or a cross-sectional area (mm^2). These observed inverse results have also been reported by Hathaway and Penny (1975). Table 4.4 displays results for individual species and lifeforms ranked by root strength, root tensile strength (per mm^2), and extension. The simple sorting of root strengths displayed in Tables 4.4 and 4.5 by species and lifeforms illustrates results that are opposite depending on which variable is used. Root strength of whole roots compared by lifeforms shows that shrubs and rushes would be the stronger roots, and grasses and forbs would rank as weakest, with *Carex* located in the middle of the rankings. Compared as root tensile strength per mm^2 of cross sectional area, forbs followed by grasses would be strongest, with rushes and willows the weakest and *Carex* again in the middle of the rankings. Extension for individual species showed that *Carex* spp. had the greatest extension, followed by the rushes, with grasses and shrubs near the bottom, but with both forb species having the least extension (Table 4.4).

Individual values for species (Table 4.5) were ranked in order of decreasing root tensile failure and extension and are displayed in Table 4.4. This ranking clearly showed that *Salix* roots, which contained the greatest woody material, required the greatest force to reach failure, followed by the rush (*Juncus arcticus*), and then followed by *Carex* spp. and grasses, with forbs having little root strength as whole roots (Table 4.4). When root extension was ranked (Table 4.4), results clearly showed that *Carex* roots were able to stretch the most, followed by the rush, then followed by grasses and *Salix* species. Forbs displayed the least extension (Table 4.6).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Shrub roots were the strongest when compared as a whole root with the other lifeforms. Shrub roots required 73 N of force to break the average 3.3 mm diameter root. However, when compared on a cross sectional area (as root tensile strength), shrub roots were the weakest of all lifeforms. They required only 5.6 Nmm^{-2} to reach root tensile failure, while the smaller roots of grasses and forbs required a much greater force of 24.8 Nmm^{-2} and 36.6 Nmm^{-2}, respectively, to fail.

Root Morphology and Anatomy

Belowground roots and rhizomes of common riparian plants were collected and tested for physical response to stress. This was consistent with manipulations performed on streambank soils populated by these plants in a montane riparian area.

There are many complexities and subtleties among the anatomical details of riparian roots and rhizomes. These include the distinction between the anatomy of roots and rhizomes (Esau 1965); differences in the behavior of different aged roots and rhizomes as they respond to stress; anatomical differences between species; anatomical differences within species, including cellular response to anaerobic conditions (McDonald et al. 2002); and varying degrees of pathological organisms afflicting and weakening the tissues belowground (Agrios 1978). No distinctions among the possible differences listed above were made for the root segments tested in this study, other than separation by species.

Investigations of typical live root segments of riparian species in the present study showed that there were differences in root morphology associated with species that relate to tensile strength (Figure 4.4 is an example). Intermediate-sized *Salix* roots often presented a suberized, 'gnarled' appearance with many short segments with divergent angles. Whereas this morphology may have been effective in enhancing anchoring and slip resistance in

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

coarse subsoils *Salix* frequented, it was not an advantage to resisting force of tension along a single axis applied during this experiment. Other roots appeared to have occasional lesions on their surface, not unexpected in this environment, which often correlated with the break point under stress. Non-woody roots have very little lignin in their cell walls, whereas woody roots have lignin, cellulose, and hemicellulose in their cell walls and an outer bark that contains suberin (Persson 2002), though woody cortex tissue will often slough (Esau 1965). Differences attributable to potential and actual anatomical differences among the root samples were not explored.

Karrenberg et al. (2003) noted that the cortex was of minor importance as a load-bearing tissue under tension, which is why total root diameter was not a reliable indicator of root tensile strength (for species with significant cortex tissue, e.g. *Salix* spp. in this study). Therefore values for tensile strength of *Salix* roots that equate force to failure with root diameter overstate the diameter including cortex tissues. But although the role of the cortex is minor for load-bearing under tension, it still plays a role in contributing to soil-root friction as forces are applied during shear stress.

Contortions of some root fragments, developed as the soil volume was explored for water and nutrients, rendered those samples more susceptible to a unidirectional load applied in an experimental setting. Older, angular, and lignified *Salix* roots seemed to fail more often at those angles. Although these root angles may represent a point of relative weakness, my experimental protocol, removing the *Salix* roots from the soil matrix, does not necessarily reflect real-world resistance to tension. Woody roots have lignin, cellulose, and hemicellulose in their cell walls and an outer bark that contains suberin (Persson 2002), contributing strength to *Salix* roots, whereas a portion of the cross sectional diameter is

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

composed of cortex tissue which does not contribute greatly to strength (Karrenberg et al. 2003). Karrenberg also noted that roots that developed in sand had a regular round form, whereas those that forced their way through gravel generally had a contorted appearance with an irregular cross-section. Sloughing of cortex tissue by woodier willow roots further complicates strength relationships (Esau 1965). Although Stokes (2002) described the role of both root tensile strength and root architecture in soil reinforcement and soil shear strength, she ascribed to root morphology an important role.

Easson and Yarbrough (2002) further observed that root physiology directly related to each species specific root diameter-root tension relationship, but the root's ecological circumstances also contributed and perhaps skewed the experimental results. They stated that these factors contributed to variance and included soil type, soil moisture, seasonal weather conditions, and the fact that roots are of living tissue. Fitter (2002) attributed phenotypic plasticity in a heterogeneous environment to this variability. He speculated that quantity of roots might influence strength, but found no information on this for herbaceous plants. Ennos (1989, 1990) and Fitter and Ennos (1989) showed that a root will break before an applied force can be transmitted to the distal parts of the root, and concluded that the finest roots and finely branched regions therefore play a small role in anchorage. Although 90% of plants form mycorrhizal associations (Smith and Read 1997), the influence of these associations on root tensile strength is unknown.

Cluster analyses created three vegetation groups based on canopy cover of vegetation species within the study area. These communities had some significant differences in soil characteristics which confounded results somewhat. Results of soil shear strength within the three plant communities showed the *Carex*/grass community would have the greater soil

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

strength when examined at the community level (Table 4.7). This is partially explained by *Carex* root extension, root biomass, and root length density, all of which are greater in the *Carex*/grass community compared with the other two communities. The grass/rush community appeared to have the weakest soil stability (measured as shear strength, 50% less compared to the *Carex*/grass group). The grass/forb/shrub community had intermediate soil stability. These results showed that individual root strength alone was unable to provide adequate explanation for soil stability (measured as soil shear strength) when compared at the plant community level (Table 4.7). However, root abundance characteristics like total root length, root biomass, and root length density may provide better predictive capabilities of soil stability measured as soil shear strength within a plant community.

Many root samples, especially of *Carex nebrascensis,* illustrated biphasic failure of roots (Figure 4.2). From observation it was clear that this was usually the result of a pronounced difference between the exterior root tissue and the stele tissue of the interior. Hathaway and Penny (1975) investigated the tensile strength of the roots of six *Populus* and *Salix* clones in New Zealand. They related the tensile strength of these roots to their anatomy and chemistry. They found that the amount of stele in the roots, and their specific gravity, were the most important factors that determined root tensile strength. The roots they studied were selected from 4-8 mm in diameter, less than 1 year old, and collected between 0-30 cm in depth. This tends to corroborate my observations of the important role of the stele in relation to tensile strength. They found that the load at failure did not increase linearly with the diameter of the roots. In this study, regression trendlines other than linear improved r^2 values considerably, suggesting that non-linear changes in root tissue affecting strength with

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

changes in root diameter. Only three species with poor r^2 were not improved by non-linear regression trendlines.

Hathaway and Penny (1975) also noted that tensile strength of the roots, defined as load at failure/cross-sectional area of the root (stele in their case), decreased with increasing diameter. This too was the pattern seen for riparian species roots (Table 4.3) in the present study. They hypothesized that the variations in tensile strength were likely to be caused by variations in anatomy and composition, which they investigated. The concept that root tensile strength often increases with decreasing diameter should not be carried too far, however. Fitter (2002) pointed out in several taxonomic groups of plants, especially grasses, rushes, and sedges, root systems have very fine terminal branches (< 100 μm diameter) that seemed to approach an effective minimum diameter, determined by the need for a stele and surrounding tissues (endodermis, cortex, epidermis) to provide transport to and from the root tip and absorbing cells. It is not sensible that root tensile strength would approach a maximum in such circumstances. Fitter (2002) went on to cite Cutler et al. (1987) who recorded great variation in internal anatomy of roots. Stokes (2002) noted that contrary to the increase in tensile strength with decreasing root size, compression and bending strength decreased with decreasing root size, and he attributes this to increased lignin content (in woodier plants).

Waldron (1977), from his agronomic studies, estimated the strength of a generic soil-root bond to be about 20 g cm^{-2}. Waldron and Dakessian (1981) noted that plant roots were irregular, had root hairs, branching laterals, and could grow into tortuous pore spaces of coarse textured soils and become firmly anchored. Waldron and Dakessian (1981) further

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

noted that enhanced root reinforcement could be obtained if roots extend into unsaturated soil.

The contribution of fungal mycelia to this soil matrix and soil strength is not readily measurable. Fungi and associated organic compounds are largely responsible for soil aggregation and soil structure (Foth 1978). Fungal dimensions are orders of magnitude smaller than the root diameters that were measured in this study, but may have affected strengths of some colonized roots.

A correlation analysis of all 849 root samples tested for strength at failure resulted in a Pearson's Correlation Coefficient of 0.68, $p < 0.001$, between root diameter and force at failure. A graph of force at tensile failure versus root diameter at the breaking point for individual species (Figure 4.5) exhibited the positive relationship between increasing force required with increasing root diameter for root failure. Regression lines (by species) were developed for force to failure versus root diameter that were forced through the origin for comparison purposes (Figure 4.5). This slope relates the 'y' value as force (Newtons) N, with the 'x' values of average root diameter (mm). Steeper y/x slopes indicated increased ability to tolerate unidirectional force relative to average root diameter. The observed pattern of root strength was greater for willows and least for grasses, with grass-like plants in the mid-range (Table 4.1).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Correlations Among Root Variables

To simply focus on root tensile strength ignores the important variables of length and mass of roots in the aggregate within these riparian soils. Roots do not exist as units, but rather as interwoven masses that are made up of differing functional groups of plants, with tapering and branched roots that sequester moisture and nutrients, entangled and pierced by fungi, nematodes, and other soil organisms.

CONCLUSIONS

Root tensile strength for individual roots indicates shrubs withstand significantly greater force before failure as compared with sedges, rushes, grasses, and forbs. When force at root failure was standardized by dividing force (N) by the cross-sectional area (mm^2) of roots (described as tensile failure), forbs were significantly stronger than shrub roots. When life forms were ranked in order of individual whole root strength, plants like willows, rushes, and sedges were stronger than grass and forb roots.

Results of root extension at tensile failure followed this last trend. When observed as entire root segments, *Carex* roots had greater extension, followed by a rush and then grasses and shrubs. Forb root extension was ranked last. This was a function of root diameter, therefore when compared with regression analyses where extension (y) and cross-sectional area (mm^2) (x) were used, forbs appeared to have a much greater extension than grasses and other lifeforms on a mm^2 basis. Root comparisons are more meaningful as whole roots (rather than per mm^2 cross section) because it is the whole root and its interaction with the soil matrix that contribute to streambank stability (Hathaway and Penny 1975). Root strain, where extension was divided by original sample length, exhibited similar patterns to extension (Table 4.2).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

The results of the individual and life form comparisons of root tensile strength and extension contributed to the explanation of streambank stability as measured by soil shear strength within a riparian plant community. *Carex* root extension and total root length were important variables to help explain streambank stability. However, soil texture, organic matter, and moisture were also determined to be important.

Results of this study indicated that the *Carex*/grass community should provide the greatest streambank stability. This should be the community that managers of riparian areas similar to Sheep Creek would select if it is determined streambank stability is a management objective and soil shear strength is an adequate measure of streambank stability.

An examination of 849 riparian root samples showed significant differences in patterns of overall root strength, and in tensile strength (reflecting force applied to failure divided by root cross sectional area). These differences have implications for the relative resistance to and resilience from forces imposed on streambanks. Abernethy and Rutherford (2001) attempted to quantify increases in sediment strength of a streambank from root reinforcement, and measured both spatial distribution of roots as well as tensile strength. They found, as I did, that root diameter at the point of rupture was highly correlated with root strength.

From my observations of the species sampled in the present study that included different plant functional types and ages in a natural setting, there were other sources of variation less esoteric that were not captured in the meager literature of riparian roots. Some root samples exhibited lesions and wounds that reflected damage from other macro- and micro- organisms. In the soil, the root is constantly exposed to a variety of pathogenic organisms (Sievers et al. 2002). Waisel and Eshel (2002) noted that at any instance in time,

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

root segments of different ages and degrees of development can be found along the same root axis, and these stages of maturation correlate with differences in associated microbial and mycorrhizal activities.

To focus this discussion on root tensile strength ignores the length and mass of roots in the aggregate within these riparian soils. Easson and Yarbrough (2002) and Stokes (2002) indicated that root fibers increased the shear strength of soil by transferring shear stresses from the soil matrix into tensile resistance in the fiber inclusions of roots. They also noted that it was necessary that the roots be confined with sufficient pressures to secure the root firmly within the soil matrix and allow for the transfer of shear stress to tensile resistance. This may help explain the effectiveness of soils with higher bulk densities to resist hoof impressions, as root tensile strength is brought into play earlier to resist deformation.

Collison et al. (2005) noted that the dominant mechanical effect of streambank vegetation is soil reinforcement by roots. Roots are strong in tension but weak in compression, whereas soil is weak in tension and strong in compression. Root permeated soil is a composite material with tensile fibers transmitting stresses beyond the immediate shear zone to mobilize additional soil strength. They further note that whereas soil peak strength is mobilized in the first few millimeters of strain, in roots extension 'takes up the strain' on tensile fibers, and encompasses the processes of root straightening as torturous roots are pulled into line, as well as elastic and later non-elastic strengthening. This helps to explain how *Carex* roots with their greater extension lend greater strength to the soils they reinforced in this study.

A clear relationship was found between root diameter and force at failure. Root diameter at the point of rupture was found to be highly correlated with root strength. When

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

life form strengths were ranked in order of individual root tensile strength, plants like willows, rushes, and sedges were stronger than grass and forb roots. When observed as entire root segments, *Carex* roots had greater extension, followed by a rush and then grasses and shrubs. Forb root extension was ranked last.

The results of the individual and life form comparisons of root tensile strength and extension contributed to the explanation of streambank stability as measured by soil shear strength within a riparian plant community. *Carex* root extension and total root length were important variables to help explain streambank stability. However, soil texture, organic matter, and moisture were also determined to be important.

Results of this study indicated that the *Carex*/grass community should provide the greatest streambank stability. This should be the community that managers at Sheep Creek would select if it is determined that soil bank stability is a management objective and soil shear strength is an adequate measure of streambank stability. However shrubs such as willows have large, deep roots that help anchor the streambank beneath them.

From the relationships described above, I would reject the null hypothesis of no differences for root strength among riparian species.

Topics for future study include quantifying soil shear values and plant community metrics across greater differences in soil texture than found in the present study, to examine a greater range of responses. An investigation of a more closely georeferenced study that might assess relationships among soil shear strength, soil malleability to impressions, and specific plant community mixtures of roots and could illuminate soil plant relationships for high elevation riparian areas. Answers to these relationships could lead to clearer

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

management recommendations for both wild and domestic ungulate grazing and streambanks.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

LITERATURE CITED

Abernethy, B. and I. D. Rutherfurd. 2001. The distribution and strength of riparian tree roots in relation to riverbank reinforcement. *Hydrological Processes* 15:63-79.

Agrios, G.N. 1978. Plant pathology. 2nd Ed. New York, NY: Academic press. 703 p.

Böhm, W. 1979. Methods of studying root systems. New York, NY: Springer-Verlag. 188 p.

Bouyoucos, G. J. 1962. Hydrometer method improved for making particle size analysis of soils. *Agronomy Journal* 54:464-465.

Collison, A., N. Pollen, and A. Simon. 2005. The effects of riparian buffer strips on streambank stability: root reinforcement, soil strength, and growth rates. *In:* Zobel, R.W. and S.F. Wright [EDS.]. Roots and soil management: interactions between roots and the soil. Agronomy Monograph #48. Madison, WI: American Society of Agronomy. p. 15-32.

Coutts, M. P. 1983. Root architecture and tree stability. *Plant and Soil* 71:171-188.

Cutler, D. F., P. J. Rudall, and P. Gasson. 1987. Root identification manual of trees and shrubs. London: Chapman and Hall. 245 p.

Dunn, J. H. and R. E. Engel. 1970. Rooting ability of Merion Kentucky bluegrass sod grown on mineral and muck soil. *Agronomy Journal* 62:517-520.

Easson, G. and L. D. Yarbrough. 2002. The effects of riparian vegetation on bank stability. *Environmental and Engineering Geoscience* 8:247-260.

Engber, E. 2000. Bioengineering. Personal communication.

Ennos, A. R. 1989. The mechanics of anchorage in seedlings of sunflower, *Helianthus annus* L. *New Phytologist* 113:185-192.

Ennos, A. R. 1990. The anchorage of leek seedlings: the effect of root length and soil strength. *Annals of Botany* 65:409-416.

Esau, K. 1965. Plant anatomy. 2nd Ed. New York, NY: John Wiley & Sons, Inc. 767 p.

Fitter, A. H. 2002. Characteristics and functions of root systems. *In*: Plant roots: the hidden half. Waisal, Y., A. Eshel, and U. Kafkafi [EDS.]. New York, NY: Marcel Dekker, Inc. p. 15-32.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Fitter, A. H. and R. A. Ennos. 1989. Architectural constraints to root system function. *In*: Robinson, D. [ED.]. Roots and the soil environment. *Aspects of Applied Biology* 2:15-22.

Foth, H. D. 1978. Fundamentals of soil science. New York, NY: John Wiley and Sons. 436 p.

George, M. R., D. Lile, and N. McDougald. 1992. Monitoring livestock impacts in mountain meadows. Unpublished Report. Dept. of Agronomy and Range, University of California, Davis, CA. 42 p.

Greenwood, K.L. and B.M. McKenzie. 2001. Grazing effects on soil physical properties and the consequences for pastures: a review. *Australian Journal of Experimental Agriculture* 41:1231-1250.

Grossman, R. B. and T. G. Reinsch. 2002. Bulk density and linear extensibililty. *In*: J.H. Dane and G.C. Topp [EDS.]. Methods of Soil Analysis, Part 4. Madison, WI: American Society of Agronomy. p. 201-228.

Hall, D. J. and D. Khanna. 1977. The ISODATA method of computation for the relative perceptions of similarities and differences in complex and real data. *In*: K. Enslein, A. Ralston, and H.W. Wilf [EDS.]. Statistical methods for digital computers, Volume 3. New York, NY: John Wiley and Son. p. 340-373

Hathaway, R.L. and D. Penny. 1975. Root strength in some *Populus* and *Salix* clones. *New Zealand Journal of Botany* 13:333-344.

Karrenberg, S., S. Blaser, J. Kollmann, T. Speck, and P.J. Edwards. 2003. Root anchorage of saplings and cuttings of woody pioneer species in a riparian environment. *Functional Ecology* 17:170-177.

Kaspar, T. C. and R. P. Ewing. 1997. ROOTEDGE: software for measuring root length density from desktop scanner images. *Agronomy Journal* 89:932-940.

King, J. W. and J. B. Beard. 1969. Measuring rooting of sodded turfs. *Agronomy Journal* 61:497-498.

Klute, A. [ED.]. 1986. Methods of soil analysis. Part I. Physical and mineralogical methods. Madison, WI: American Society of Agronomy and Soil Science Society of America. 1188 p.

Kramer, J. and J. E. Weaver. 1936. Relative efficiency of roots and tops of plants in protecting the soil from erosion. Bulletin 12. Conservation Department of the Conservation and Survey Division. Lincoln, NE, University of Nebraska.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Manning, M. E., S. R. Swanson, T. Svejcar, and J. Trent. 1989. Rooting characteristics of four Intermountain meadow community types. *Journal of Range Management* 42:309-312.

McDonald, M.P., N.W. Galwey, and T.D. Colmer. 2002. Similarity and diversity in adventitious root anatomy as related to root aeration among a range of wetland and dryland grass species. *Plant Cell and Environment* 25:441-451.

Mergen, D. E. 1998. Plant cover effects on surface roughness, infiltration, runoff, and sediment yield of a sagebrush-grass rangeland (dissertation). Fort Collins, Colorado. Colorado State University. 134 p.

Niklas, K. J. 1992. Plant biomechanics: an engineering approach to plant form and function. Chicago, IL: The University of Chicago Press. 607 p.

NOAA (National Oceanic and Atmospheric Administration). 1995. Climatological data. Red Feather Lakes, CO, USA. Asherville, NC: U.S. Department of Commerce,. ISSN 0145-0506.

Ott, L. 1988. An introduction to statistical methods and data analysis. 3rd Ed. Boston, MA: Kent Publishing Company. 1152 p.

Pearce, R. A. 1995. Sediment movement and filtration within laboratory and riparian vegetation buffer strips (dissertation). Fort Collins, CO: Colorado State University.

Persson, H. A. 2002. Root systems of arboreal plants. *In*: Plant roots: the hidden half. Waisal, Y., A. Eshel, and U. Kafkafi. [EDS.]. New York, NY: Marcel Dekker, Inc. p 175-186.

Platts, W. S. and R. F. Raleigh. 1984. Critique - impacts of grazing on wetlands and riparian habitat. *In*: Developing strategies for rangeland management. Boulder, CO: Westview Press. p. 1105-1118.

Platts, W. S. 1991. Livestock grazing. *In:* William R. Meehan [ED.]. Influences of forest and rangeland management on salmonid fishes and their habitats. Bethesda, MD: American Fisheries Society. Special Publication 19. p. 389-423.

Polomski, J. and N. Kuhn. 2002. Root research methods. *In:* Waisel, Y., A. Eshel, and U. Kafkaf [EDS.]. Plant roots: the hidden half. 3rd Ed. New York, NY: Marcel Dekker, Inc. p. 295- 321.

Pregitzer, K. S., D. R. Zak, J. Maziasz, J. DeForest, P. S. Curtis, and J. Lussenhop. 2000. Interactive effects of atmospheric CO_2 and soil-N availability on fine roots of *Populus tremuloides*. *Ecological Applications* 10:18-33.

Rosgen, D. L. 1996. Applied river morphology. Pagosa Springs, CO: Wildland Hydrology.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

SAS Institute Inc. 1988. SAS/STAT user's guide, release 6.03. Cary, NC: SAS Institute.

Schultz, T. and W. C. Leininger. 1990. Differences in riparian vegetation structure between grazing areas and exclosures. *Journal of Range Management* 43:295-299.

Selby, R. 1982. Hillslope materials and processes. New York, NY: Oxford University Press. 264 p.

Sievers, A., M. Braun, and G. B. Monhausen. 2002. The root cap: structure and function. *In*: Plant roots: the hidden half. Waisal, Y., A. Eshel, and U. Kafkafi [EDS]. New York, NY: Marcel Dekker, Inc. p. 33-48.

Simon, A., N. Pollen, and E. Langendoen. 2006. Influence of two woody riparian species on critical conditions for streambank stability: Upper Truckee River, California. *Journal of the American Water Resources Association* 42:99-113.

Skovlin, J. M. 1984. Impacts of grazing on wetlands and riparian habitat: a review of our knowledge. *In*: Developing strategies for range management. Boulder, CO: Westview Press. p. 1001-1102.

Smith, S. E. and D. J. Read. 1997. Mycorrhizal symbiosis. 2nd Ed. San Diego, CA: Academic Press.

Steel, R. G. D. and J. H. Torrie. 1980. Principles and procedures of statistics: a biometrical approach. 2nd Ed. New York, NY: McGraw-Hill.

Stokes, A. 2002. Biomechanics of tree root anchorage. *In*: Plant roots: the hidden half. Waisal, Y., A. Eshel, and U. Kafkafi [EDS.]. New York, NY: Marcel Dekker, Inc. p. 175-186.

Storer, D. A. 1984. A simple high volume ashing procedure for determining soil organic matter. *Communications in Soil Science and Plant Analysis* 15:759-772.

Thorne, C. R. 1990. Effects of vegetation on riverbank erosion and stability. *In*: J.B. Thornes [ED.]. Vegetation and erosion. New York, NY: Wiley and Sons. p. 125-144.

Thorne, C. R. and N. K. Tovey. 1981. Stability of composite river banks. *Earth Surface Processes and Landforms* 6:469-484.

Trimble, S. W. and A. C. Mendel. 1995. The cow as a geomorphic agent - a critical review. *Geomorphology* 13:233-253.

USDA, Soil Conservation Service and Forest Service. 1980. Soil survey report. Larimer County, CO. Washington, DC: U.S. Government Printing Office. 239-812/48..

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Vidal, H. 1969. The principle of reinforced earth. *Highway Research Record* 282:1-16.

Waisel, Y. and A. Eshel. 2002. Functional diversity of various constituents of a single root system. *In*: Plant roots: the hidden half. 3rd Ed. New York, NY: Marcel Dekker, Inc. p. 157-174.

Waisel, Y., A. Eshel, and U. Kafkafi. 2002. Plant roots: the hidden half. 3rd Ed. New York, NY: Marcel Dekker, Inc. 1120 p.

Waldron, L. J. 1977. The shear resistance of root-permeated homogeneous and stratified soil. *Journal of the Soil Science Society of America* 41:843-849.

Waldron, L. J. and S. Dakessian. 1981. Soil reinforcement by roots, calculation of increased soil shear resistance from root properties. *Soil Science* 132:427-435.

Weaver, J. E. 1926. Methods of studying root development. *In:* Root development of field crops. New York, NY: McGraw-Hill. p. 253-261

Weaver, J. E. 1954. North American prairie. Lincoln, NE: Johnsen Publishing Company. 348 p.

Wester, D. B. 1992. Viewpoint: replication, randomization, and statistics in range research. *Journal of Range Management* 45:285-290.

Wheeler, M. A., M. J. Trlica, G. W. Frasier, and J. D. Reeder. 2002. Seasonal grazing affects soil physical properties of a montane riparian community. *Journal of Range Management* 55:49-56.

Williamson, R. B., R. K. Smith, and J. M. Quinn. 1992. Effects of riparian grazing and channelisation on streams in Southland, New Zealand. 1. Channel form and stability. *New Zealand Journal of Marine and Freshwater Resources* 26:241-258.

Winward, A. H. 2000. Monitoring the vegetation resources in riparian areas. General Technical Report. RMRSGTR-47. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 49 p.

Zhou, Y., D. Watts, Y. Li, and X. Cheng. 1998. A case study of effect of lateral roots of *Pinus yunnanensis* on shallow root reinforcement. *Forest Ecology and Management* 103:107-120.

Zuber, M. S. 1968. Evaluations of corn root systems under various environments. Reports of the 23rd Corn Sorghum Research Conference, Chicago, IL.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

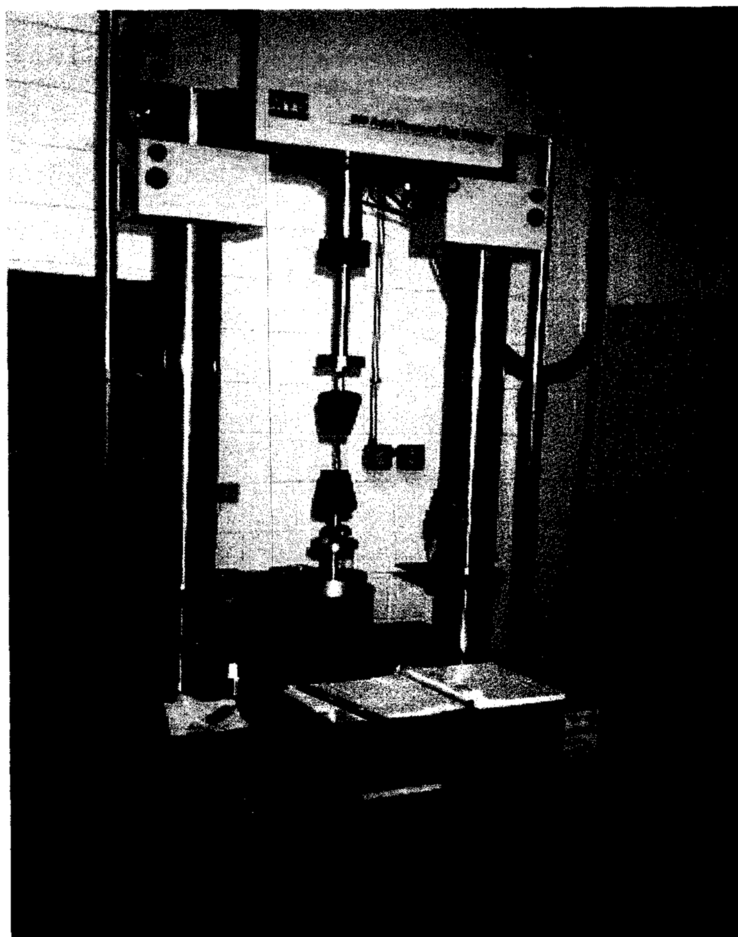


Figure 4.1. Servohydraulic biaxial mechanical testing machine used to determine root tensile strength, CSU Veterinary School.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

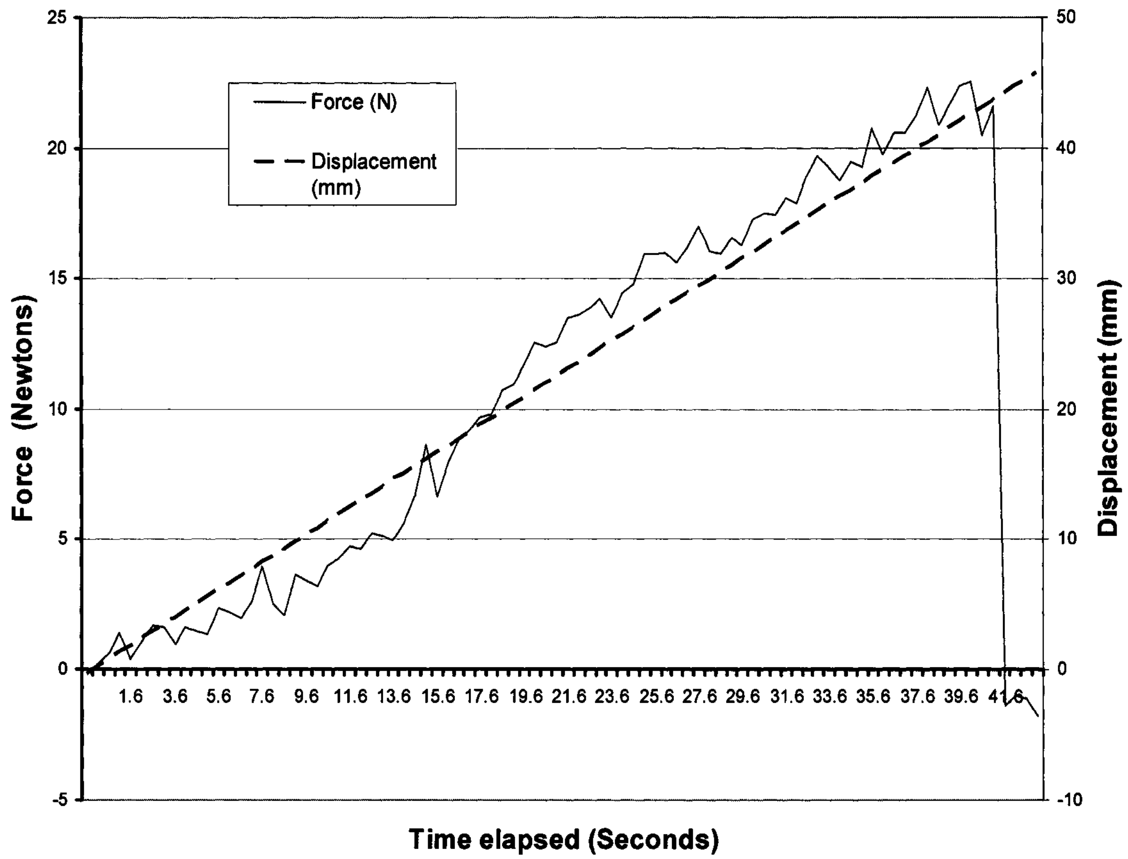


Figure 4.2. Typical tensile failure for *Juncus arcticus* with applied force.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

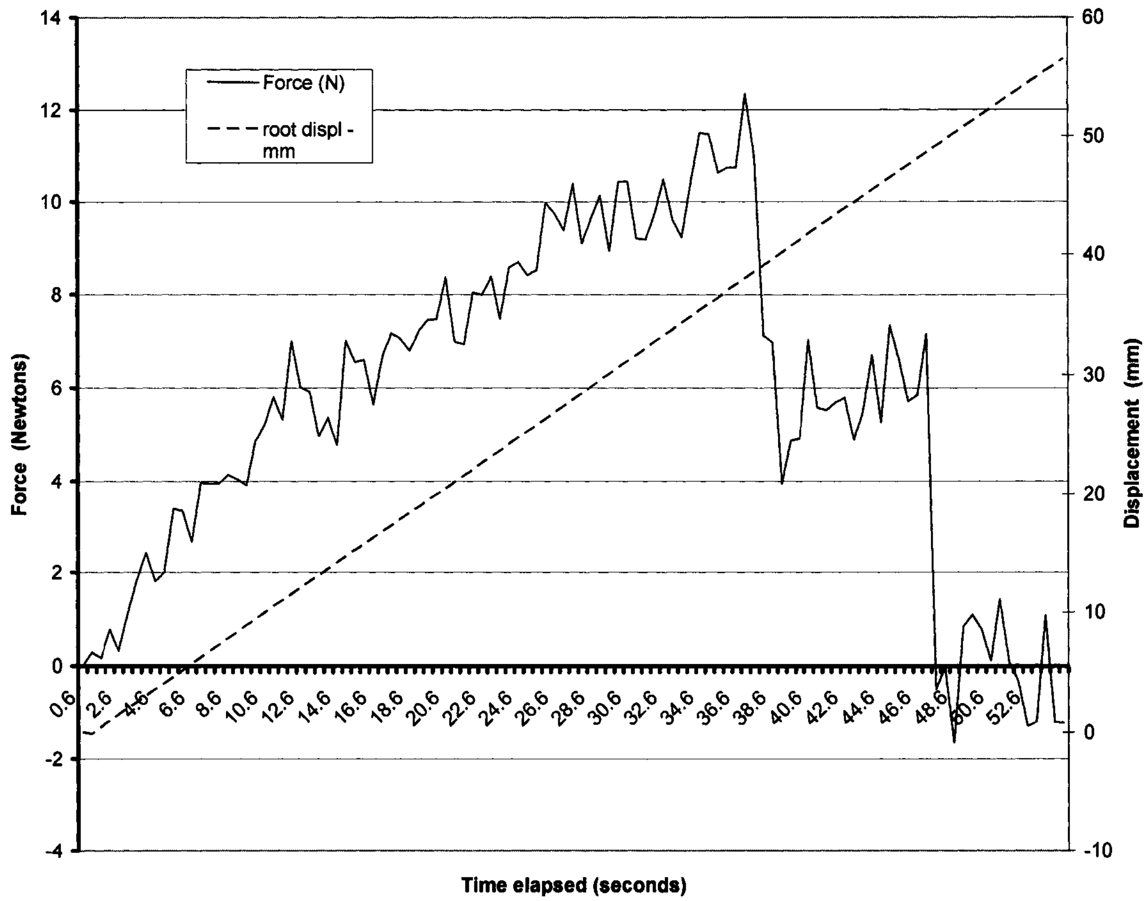


Figure 4.3. Two-stage root tensile failure for *Juncus arcticus*; cortex failure at 12 Newtons, and stele failure at 7 Newtons, but 10 seconds later.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

(Scale – 118 mm)

Figure 4.4. Example of root structure for *Juncus arcticus*.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

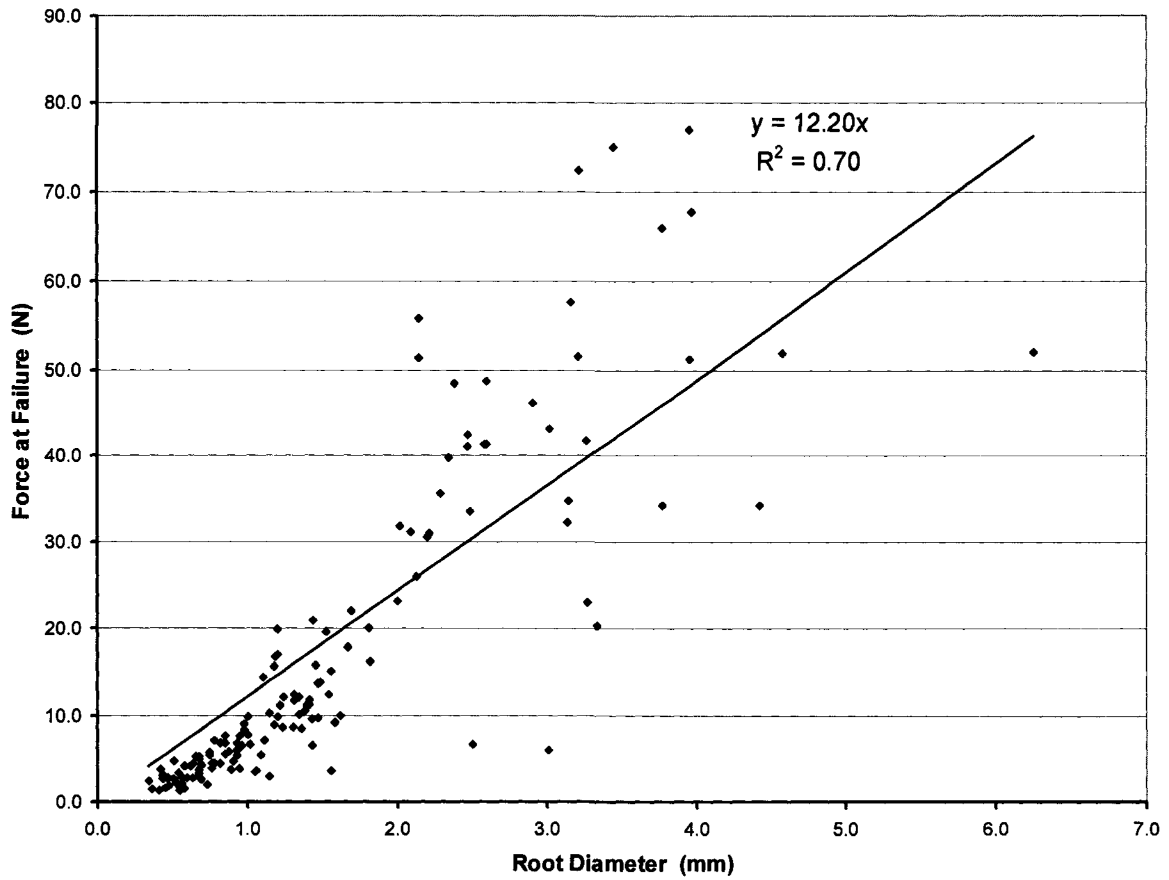


Figure 4.5. Typical plot of force to failure for varying root diameters of *Carex aquatilis*. Regression line forced through the origin.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 4.1. Regression relationships of force at failure with root diameter for riparian species x = root diameter (mm) and y = force (Newtons).

	Linear trend	R^2	Other trendline	R^2	Line equation	n
Salix exigua	y = 36.95x	0.44	power	0.78	$y=2.95x^{1.88}$	84
Salix planifolia	y = 26.47x	0.76	power	0.95	$y=9.24x^{1.81}$	38
Carex nebrascensis	y = 15.02x	0.62	power	0.78	$y=6.73x^{1.58}$	106
Trifolium sp.	y = 12.50x	-0.01	no improvement			5
Phleum pratense	y = 12.28x	0.70	power	0.75	$y=9.64x^{1.01}$	49
Carex utriculata	y = 12.20x	0.71	power	0.83	$y=7.17x^{1.49}$	139
Juncus arcticus	y = 11.48x	0.37	no improvement			157
Calamagrostis canadensis	y = 11.98x	0.50	exponential	0.65	$y=.44e^{3.51x}$	29
Poa pratensis	y = 7.53x	0.44	power	0.61	$y=7.11x^{0.96}$	66
Carex rostrata	y = 6.12x	0.33	no improvement			131
Fragaria sp.	y = 5.69x	0.44	power	0.85	$y=50.85x^{4.14}$	3
Deschampsia caespitosa	y = 4.86x	0.50	polynomial	0.62	y=5.01x2+1.88x-0.31	23
Carex microptera	y = 4.13x	0.71	power	0.85	$y=3.72x^{1.43}$	17

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 4.2. Root characteristics for five vegetation classes of riparian species, 1996.

Variable	Sedge	Forb	Grass	Rush	Shrub
Average root diameter (mm)	1.5b [1/]	0.4a	0.7a	2.2c	3.3d
Force at tensile failure (kN/m^2)	14.1ab	3.7ab	6.1a	22.0b	73.0c
Displacement at failure (mm)	25.8a	5.2b	12.2c	21.3d	12.4c
Stress (N/mm^{-2}) (force at failure/cross section area)	7.5a	10.0b	8.2c	8.1c	13.1b
Strain (mm/mm) (displacement/original length)	0.39a	0.13b	0.27c	0.28c	0.20b
Original length (mm)	65.4b	38.6a	45.5a	76.2c	64.8b
N =	393	8	167	157	122

[1/] Different letters in a row indicate significantly different values ($p \leq 0.10$).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 4.3. Results of simple linear regression showing relationship of extension at root failure and root cross-section (mm^2) for major riparian plant species and lifeforms at Sheep Creek, Colorado.

Plant species	Model (extension=area)	r^2	Standard error	Prob.
Sedges	y = 3.7(x)	0.32	0.3	0.0001
Carex aquatilis	y = 3.1(x)	0.30	0.4	0.0001
Carex microptera	y = 19.6(x)	0.77	2.7	0.0001
Carex nebrascensis	y = 3.4(x)	0.39	0.4	0.0001
Carex utriculata	y = 7.7(x)	0.40	0.8	0.0001
Rush	y = 1.1(x)	0.25	0.2	0.0001
Juncus arcticus	y = 1.1(x)	0.25	0.2	0.0001
Grasses	y = 6.2(x)	0.19	1.0	0.0001
Calamagrostis canadensis	y = 27.2(x)	0.25	8.8	0.0046
Deschampsia caespitosa	y = 35.1(x)	0.58	6.3	0.0001
Phleum pretense	y = 4.5(x)	0.20	1.3	0.0011
Poa pratensis	y = 6.8(x)	0.33	1.2	0.0001
Shrub (Salix)	y = 0.2(x)	0.20	0.1	0.0001
Salix exigua	y = 0.2(x)	0.25	0.1	0.0001
Salix planifolia	y = 2.0(x)	0.69	0.2	0.0001
Forbs	y = 35.3(x)	0.80	1.0	0.0017
Fragaria virginiana	y = 28.4(x)	0.73	12.1	0.1431
Trifolium spp.	y = 45.9(x)	0.88	8.4	0.0055

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 4.4. Individual riparian species ranked, in descending order, for force at root failure, force/cross sectional area (tensile strength), and root extension at root failure. Plant life form is in column to the right of species code.

Force at root tensile failure (Newtons)	Lifeform	Nmm^{-2} (force/root cross sectional area)	Lifeform	Extension at root tensile failure	Lifeform
SAEX[1]	S[2]	TRSP[1]	F[2]	CAAQ	C[2]
SAPL	S	PHPR	G	CANE	C
JUBA	R	CACA	G	CAUT	C
CANE	C	POPR	G	CAMI	C
CAAQ	C	FRVI	F	JUBA	R
PHPR	G	DECA	G	CACA	G
CAUT	C	CAAQ	C	DECA	G
POPR	G	SAPL	S	SAPL	S
CACA	G	CANE	C	PHPR	G
TRSP	F	JUBA	R	SAEX	S
CAMI	C	CAUT	C	POPR	G
DECA	G	CAMI	C	FRVI	F
FRVI	F	SAEX	S	TRSP	F

1 SAEX = *Salix exigua*, SAPL = *Salix planifolia*, JUBA = *Juncus arcticus*, CANE = *Carex nebrascensis*, CAAQ = *Carex aquatilis*, PHPR = *Phleum pratense*, CAUT = *Carex utriculata*, POPR = *Poa pratensis*, CACA = *Calamagrostis canadensis*, TRSP = *Trifolium sp.*, CAMI = *Carex microptera*, DECA = *Deschampsia caespitosa*, FRVI = *Fragaria virginiana*

2 S = shrub, R = rush, C = sedge, G = grass, F = forb

Table 4.5. Summarized rankings for force at root failure of plant lifeforms of Table 4.4. Rankings in second column are compared by cross sectional area (tensile strength).

Force to failure for whole roots	Force to failure for roots by cross-sectional area (mm^2)
Shrubs	Forbs
Rush	Grasses
Sedges	Sedges
Grasses	Rush
Forbs	Shrubs

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 4.6. Root characteristics for major riparian plant species at Sheep Creek, Colorado. Standard errors are in parentheses below the mean.

Root characteristic	CAAQ[1]	CAMI	CANE	CAUT	JUBA	CACA	DECA	PHPR	POPR	SAEX	SAPL	FRVI	TRSP
Average root diameter (mm)	1.54 (0.09)	0.92 (0.10)	1.81 (0.11)	1.24 (0.06)	2.24 (0.14)	0.51 (0.04)	0.56 (0.04)	0.76 (0.10)	0.78 (0.05)	3.87 (0.38)	1.99 (0.21)	0.46 (0.05)	0.35 (0.04)
Average area (root cross-section mm^2)	2.75 (0.35)	0.79 (0.15)	3.55 (0.44)	1.53 (0.16)	6.25 (0.72)	0.25 (0.04)	0.28 (0.04)	0.80 (0.17)	0.60 (0.08)	21.30 (4.30)	4.39 (0.82)	0.17 (0.04)	0.10 (0.02)
Force at root tensile failure (Newtons)	17.05 (1.54)	3.57 (0.59)	20.74 (2.47)	6.92 (0.74)	22.03 (2.88)	4.86 (1.25)	2.51 (0.43)	8.61 (1.54)	6.10 (0.45)	89.53 (24.76)	36.47 (7.43)	2.40 (1.14)	4.48 (1.30)
Displacement at root tensile failure (mm)	29.19 (2.20)	21.63 (1.56)	27.37 (1.39)	26.26 (1.03)	21.28 (0.92)	15.95 (1.71)	14.42 (1.27)	13.14 (0.82)	9.01 (0.60)	11.56 (0.98)	14.35 (1.11)	5.66 (1.16)	4.88 (1.20)
Stress (Nmm^{-2}) (Force/root cross-sectional area)	9.24 (0.38)	5.52 (0.47)	7.02 (0.34)	6.10 (0.44)	6.48 (0.59)	24.89 (6.07)	9.50 (0.97)	38.68 (5.93)	19.67 (2.61)	4.43 (0.47)	8.32 (0.50)	12.87 (3.48)	50.80 (15.87)
Strain (mm/mm) (displacement/original length)	0.38 (0.01)	0.37 (0.02)	0.44 (0.02)	0.37 (0.01)	0.28 (0.01)	0.31 (0.03)	0.28 (0.02)	0.29 (0.02)	0.23 (0.01)	0.19 (0.02)	0.22 (0.02)	0.14 (0.02)	0.13 (0.03)
N	139	17	106	131	157	29	23	49	66	83	38	3	5

[1] CAAQ = *Carex aquatilis*, CAMI = *Carex microptera*, CANE = *Carex nebrascensis*, CAUT = *Carex utriculata*, JUBA = *Juncus balticus*, CACA = *Calamagrostis canadensis*, DECA = *Deschampsia caespitosa*, PHPR = *Phleum pratense*, POPR = *Poa pratensis*, SAEX = *Salix exigua*, SAPL = *Salix planifolia*, FRVI = *Fragaria virginiana*, TRSP = *Trifolium sp.*

Table 4.7. Means and standard errors of variables for the results of the three vegetation groups formed from the cluster analysis. These groups were derived to compare vegetation, soil, and root characteristics found along a riparian area at Sheep Creek, Colorado. Standard errors are in parentheses and means within a row followed by different letters were significantly different ($p < 0.05$).

Variable	Carex/grass	Grass/rush	Grass/forb/shrub	Significance
Grass cover (%)	38ab (2.7)	48a (4.6)	30b (2.7)	0.0135
Rush cover (%)	3a (1.2)	28b (3.8)	4a (1.7)	0.0001
Forb cover (%)	7a (0.8)	11b (1.2)	21c (3.1)	0.0001
Carex cover (%)	44a (2.5)	2b (0.8)	11c (2.1)	0.0001
Salix cover (%)	<1a (0.3)	3a (1.5)	20b (5.0)	0.0001
Soil moisture (%)	53a (2.6)	48a (6.9)	43a (2.9)	0.3030
Soil bulk density (g/cm^3)	0.86a (0.01)	0.76b (0.05)	0.87a (0.03)	0.0472
Soil organic matter (%)	9.7a (0.5)	10.0a (0.6)	7.5b (0.4)	0.0030
% sand	66a (1.2)	73b ()1.3	75b (2.0)	0.0001
% silt	20a (1.1)	12b (0.6)	13b (0.9)	0.0001
% clay	14a (0.5)	15a (1.3)	12a (1.5)	0.1529
Total root length (cm)	2226a (125)	5161b (1067)	4078ab (936)	0.0228
Root biomass (g/cm^3)	0.013a (0.001)	0.011b (0.001)	0.008c (0.001)	0.0002
Root length density (cm/cm^3)	24.17a (1.82)	14.93b (1.21)	11.57b (2.3)	0.0001
Root length for diameter less than or equal to 0.5mm (cm)	1636a (143)	3235b (884)	2025ab (344)	0.1099
Root length for diameter between (0.51-1.0mm) (cm)	490a (45)	1563b (324)	1756b (566)	0.0130
Root length for diameter greater than 1.0mm (cm)	100a (21)	386a (148)	298a (123)	0.1318
Soil shear strength (Newtons)	60.3a (9.0)	29.4b (6.5)	37.2b (5.3)	0.0116

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 4.8. Results of stepwise multiple linear regression analyses showing relationship of shear soil strength and weighted values for root tensile failure, and root cross-section (mm^2), root extension at root tensile failure, and canopy and soil variables for major plant life found at Sheep Creek, Colorado.

Model	Dependent variable	Stepwise linear regression equation	r^2
Complete	soil shear strength	soil shear = 20.5 + (0.04 * weighted *Carex* extension) + (0.6 * soil moisture in shear sample) – (1.9 * % silt)	0.43
Carex/grass group	soil shear strength	soil shear = -23.1 = (0.073 * weighted *Carex* extension)	0.28
Grass/rush group	soil shear strength	soil shear = 167 + (0.45 * soil moisture in shear sample)– (2.26 * %sand) + (0.001 * total root length)	0.72
Grass/forb/shrub group	soil shear strength	soil shear = -10.4 + (6.52 * soil organic matter %)	0.21

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

CHAPTER V

SUMMARY AND RESEARCH DIRECTIONS

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Riparian areas in the western United States represent 2% or less of the available public and private lands historically used for grazing (Kauffman and Krueger 1984). Riparian zones are frequently used by grazing livestock and by many wildlife species. Riparian vegetation influences streambank stability, water quality, sediment filtration, and is often the most productive community with deeper and more fertile soils compared with the surrounding uplands.

The purpose of this research was to study the relationships among various attributes of a montane riparian streambank (including soils, vegetation, and historical use), to learn what conferred resilience and resistance to physical disturbance, and what conferred vulnerability or predisposition to negative responses. This research also led to a clearer understanding of the impacts of past grazing use on riparian zones and how past use influenced soil and plant characteristics. These findings may help managers better understand how past and present grazing use may influence streambank stability, roots, and soil characteristics, and how to minimize current disturbances of certain riparian plant communities or soils. My study examined elements of stability above the waterline, avoiding streambank failure issues related to flowing water.

Improved management of riparian rangeland ecosystems is dependent on clarification of riparian streambank responses to disturbances and stressors. Ellison et al. (1951) were among the first in the late 1940's and 1950's to describe the condition and trend of higher elevation watersheds, and Skovlin (1984) and Kauffman and Krueger (1984) summarized research for various riparian disturbances, but the role that herbaceous roots play in streambank stability is still not well understood.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

This research was designed to determine basic streambank soil-plant relationships, with pragmatic objectives and techniques. The works of Weaver (1954), Platts (1991), Abdel-Magid et al. (1987), and Manning et al. (1989) inspired this effort, as did the disagreements over appropriate standards, recommendations, and measurements for riparian areas among federal and state land management agencies.

SUMMARY AND CONCLUSIONS

One part of this study was conducted with a mechanical hoof simulator to determine the direct chiseling effects of hoofprints on streambanks. Another study used live steers, which was beset with problems in data variability. The objective of these experiments was to relate the imprints from steer hooves and a hoof simulator on streambanks with independent variables such as soil texture, soil organic matter, plant community composition, root biomass, and root length density. The influence of past land use (i.e., previous grazing history) in the assignment and interpretation of treatments was also found to be important.

A second experiment of soil matrix shear strength was conducted to further characterize resilience of streambank soils as affected by soil type and plant dominance. The objective of this experiment was to determine the shear strength of soil cores and evaluate soil and vegetation characteristics that might be used to predict soil shear strength.

Soil bulk density for the 0-10 cm depth increased as long-term grazing history increased from exclosures, to 8 years grazing, to long-term (40+ years) grazing. Soil shear strength values also followed this trend, increasing to more than twice the strength in long-term grazed areas compared with exclosures. Soil organic matter declined over

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

these same paddocks. Hoof impacts were found to be significantly greater when the soil surface was wet. Length of fine roots was significantly greater in exclosures. *Carex*-dominated plant communities appeared to have greater soil shear strength than those communities not dominated by *Carex.*

Another study was conducted to relate riparian species root strength to root diameter. The objective was to determine if root strength might help explain soil-root matrix strength. Segments of riparian root samples were tested for tensile strength. Root diameter at the point of rupture was found to be highly correlated with strength, relating force to root failure. Greatest root strengths were found for species of sedges, rushes and willows. The observed pattern of root strength for whole roots was greater for willows, least for grasses, with grass-like plants in the mid-range. The results of the individual and life form comparisons of root tensile strength and extension contributed to the explanation of streambank stability as measured by soil shear strength within a riparian plant community. Sedge root extension and total root length were important variables to help explain streambank stability. However, soil texture, organic matter, and moisture were also determined to be important.

These and similar findings have management implications for land managers and public agencies for both domestic and wild grazing animals. Current guidance and literature available to managers of high elevation riparian areas is dominated by observational studies or experience, and lacks scientific substantiation. The studies described in this document can bolster the guidance described in Leonard et al. (1997), Clary and Leininger (2000), and Winward (2000), because they contain limited experimental data. Results of this research indicated that the sedge/grass community

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

should provide the greatest streambank stability. This should be the community that managers of montane riparian areas select if it is determined that soil bank stability is a management objective and soil shear strength is an adequate measure of streambank stability.

FUTURE RESEARCH NEEDS AND RECOMMENDATIONS

Skovlin (1984) listed 12 riparian research objectives in his review, including "autoecological and plant community studies that point to riparian system stability." Platts and Raleigh (1984) noted the scarcity of studies to determine the suitability of riparian habitat types for grazing. This scarcity remains.

The many recent attempts to rank riparian vegetation by so-called stability classes (Winward 1994, Bentrup and Hoag 1998) speak to the need for further quantification of inherent root strength and distribution of root systems. The role of herbaceous roots in streambank stability is not well understood, despite efforts in recent years by a few researchers to clarify this role (Buckhouse et al. 1981, Thorne and Tovey 1981, Kauffman and Krueger 1984, Abdel-Magid et al. 1987, Dunaway et al. 1994, Clary and Leininger 2000).

Efforts to understand the biomechanics of tree overthrow and tree root anchorage have led to an emerging discipline of 'ecoengineering'; using data on the mechanical behavior of individual roots and of entire root systems to guide foresters, ecologists, and landscape engineers (Stokes 2002). To date, this effort has not extended to the realm of herbaceous and small woody plants, other than the detailed and conceptual efforts of Niklas (1992). Despite technical advances enumerated by Böhm (1979), enormous difficulties remain with the pursuit of rigorous empirical root studies (Weaver 1954).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Winward (2000) reviewed monitoring vegetation resources in riparian areas, and specifically described plant species which functioned as colonizers or stabilizers of riparian streambanks. He also related these colonizers or stabilizers to plant succession, to early or late successional stages, and assigned stability classes to numerous riparian plant communities to portray their resistance to moving water. Although the focus of my research assessed the forces imposed by animal traffic and not hydraulic forces, my results generally agree with Winward (2000), and bring some quantitative rigor to his largely qualitative assessment. Further research is needed to continue to quantify riparian variables affected by animal traffic, given the continued concerns over the health and sustainability of these systems.

Collison et al. (2005) described research needs for riparian buffer strips (with many parallels to montane riparian areas) and noted that work was needed on a much wider array of species and ecozones, which certainly applies to riparian streambanks in general, to better understand both instability and stability processes. More work to clarify the spatial and temporal aspects of root reinforcement of streambanks should be done. Successional processes over time can move the plant community closest to the streambank into grass-like species stronger than the earlier succession grasses (Winward 2000), and the transition from herbaceous communities to slower growing willows with associated depth and strength of root patterns should also be explored (Collison et al. 2005). Simon et al. 2006 is successfully integrating individual woody root strength with streambank matrices, illuminating promising new approaches.

Further research should be conducted to determine whether soil compaction can serve as a streambank degradation indicator or that it is nearing a threshold. Compaction

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

and soil bulk density can indicate early stages of species replacement and diminished root growth. Grazing systems that can ameliorate compaction short of a threshold should be pursued. Although livestock removal has been advocated (Kauffman et al. 2004) as an approach to streambank restoration, increased understanding of plant succession and dynamics related to soil and hydrological properties (Stringham et al. 2001) can yield models that guide pragmatic and effective management prescriptions for both livestock and wildlife.

It appears that teasing apart the relationships of herbaceous riparian root systems, which have benefited from far less study than woody root systems, will depend on new research initiatives that recognize the critical role of herbaceous root systems to retain mature riparian streambanks, fish and wildlife habitat, and the many other ecosystem services they provide (Naiman and Rogers 1997). It may be that recognition of their role in carbon sequestration will trigger further study of these root systems (Follet et al. 2001).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

LITERATURE CITED

Abdel-Magid, A. H., M. J. Trlica, and R. H. Hart. 1987. Soil and vegetation responses to simulated trampling. *Journal of Range Management* 40:303-306.

Bentrup, G. and J. C. Hoag. 1998. The practical streambank bioengineering guide; a user's guide for natural streambank stabilization techniques in the arid and semi-arid west. Abderdeen, ID: USDA:NRCS Plant Materials Center. Interagency Riparian/Wetland Plant Development Project.

Böhm, W. 1979. Methods of studying root systems. New York, NY: Springer-Verlag. 188 p.

Buckhouse, J. C., J. M. Skovlin, and R. W. Knight. 1981. Streambank erosion and ungulate grazing relationships. *Journal of Range Management* 34:339-340.

Clary, W. P. and W. C. Leininger. 2000. Stubble height as a tool for management of riparian areas. *Journal of Range Management* 53:562-573.

Collison, A., N. Pollen, and A. Simon. 2005. The effects of riparian buffer strips on streambank stability: root reinforcement, soil strength, and growth rates. *In:* Zobel, R.W. and S.F. Wright [EDS.]. Roots and soil management: interactions between roots and the soil. Agronomy Monograph #48. Madison, WI: American Society of Agronomy. p. 15-32.

Dunaway, D., S. R. Swanson, J. Wendel, and W. Clary. 1994. The effect of herbaceous plant communities and soil textures on particle erosion of alluvial streambanks. *Geomorphology* 9:47-56.

Ellison, L., A. R. Croft, and R. W. Bailey. 1951. Indicators of condition and trend on high range watersheds of the Intermountain region. Washington, DC: U.S. Department of Agriculture Handbook 19. 66 p.

Follet, R. F., J. M. Kimble, and R. Lal. 2001. The potential of U.S. grazing lands to sequester carbon and mitigate the greenhouse effect. New York, NY: Lewis Publishers. 442 p.

Kauffman, J. B. and W. C. Krueger. 1984. Livestock impacts on riparian ecosystems and streamside management implications: a review. *Journal of Range Management* 37:430-438.

Kauffman, J. B., A. S. Thorpe, and E. N. J. Brookshire. 2004. Livestock exclusion and belowground ecosystem responses in riparian meadows of eastern Oregon. *Ecological Applications* 14:1671-1679.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Leonard, S., G. Kinch, V. Elsbernd, M. Borman, and S. Swanson. 1997. Riparian area management: grazing management for riparian areas. TR 1737-14. Denver, CO: USDI, Bureau of Land Management – Service Center. 63 p.

Manning, M. E., S. R. Swanson, T. Svejcar, and J. Trent. 1989. Rooting characteristics of four Intermountain meadow community types. *Journal of Range Management* 42:309-312.

Naiman, R. J. and K. H. Rogers. 1997. Large animals and system-level characteristics in river corridors: Implications for river management. *Bioscience* 47:521-529.

Niklas, K. J. 1992. Plant biomechanics: an engineering approach to plant form and function. Chicago, IL: The University of Chicago Press. 607 p.

Platts, W. S. and R. F. Raleigh. 1984. Critique - impacts of grazing on wetlands and riparian habitat. *In*: Developing strategies for rangeland management. Boulder, CO: Westview Press. p. 1105-1118.

Platts, W. S. 1991. Livestock grazing. *In:* William R. Meehan [ED.]. Influences of forest and rangeland management on salmonid fishes and their habitats. Bethesda, MD: American Fisheries Society Special Publication #19. p. 389-423.

Simon, A., N. Pollen, and E. Langendoen. 2006. Influence of two woody riparian species on critical conditions for streambank stability: Upper Truckee River, California. *Journal of the American Water Resources Association* 42:99-113.

Skovlin, J. M. 1984. Impacts of grazing on wetlands and riparian habitat: A review of our knowledge. *In*: Developing strategies for range management. Boulder, CO: Westview Press. p. 1001-1102.

Stringham, T. K., W. C. Krueger, and D. R. Thomas. 2001. Application of non-equilibrium ecology to rangeland riparian zones. *Journal of Range Management* 54:210-217.

Stokes, A. 2002. Biomechanics of tree root anchorage. *In*: Plant roots: the hidden half. Waisal, Y., A. Eshel, and U. Kafkafi [EDS.]. New York, NY: Marcel Dekker, Inc. p. 175-186.

Thorne, C. R. and N. K. Tovey. 1981. Stability of composite river banks. *Earth Surface Processes and Landforms* 6:469-484.

Weaver, J. E. 1954. North American prairie. Lincoln, NE: Johnsen Publishing Company. 348 p.

Winward, A. H. 1994. Management of livestock in riparian areas. *In:* G.A. Rasmussen and J.P. Dobrowolski [EDS.]. Riparian resources: a symposium on the

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

disturbances, management, economics, and conflicts associated with riparian ecosystems. Utah State University, Logan, UT. p. 9-52.

Winward, A. H. 2000. Monitoring the vegetation resources in riparian areas. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. General Technical Report RMRSGTR-47. 49 p.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

APPENDIX A SHEEP CREEK MAP

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

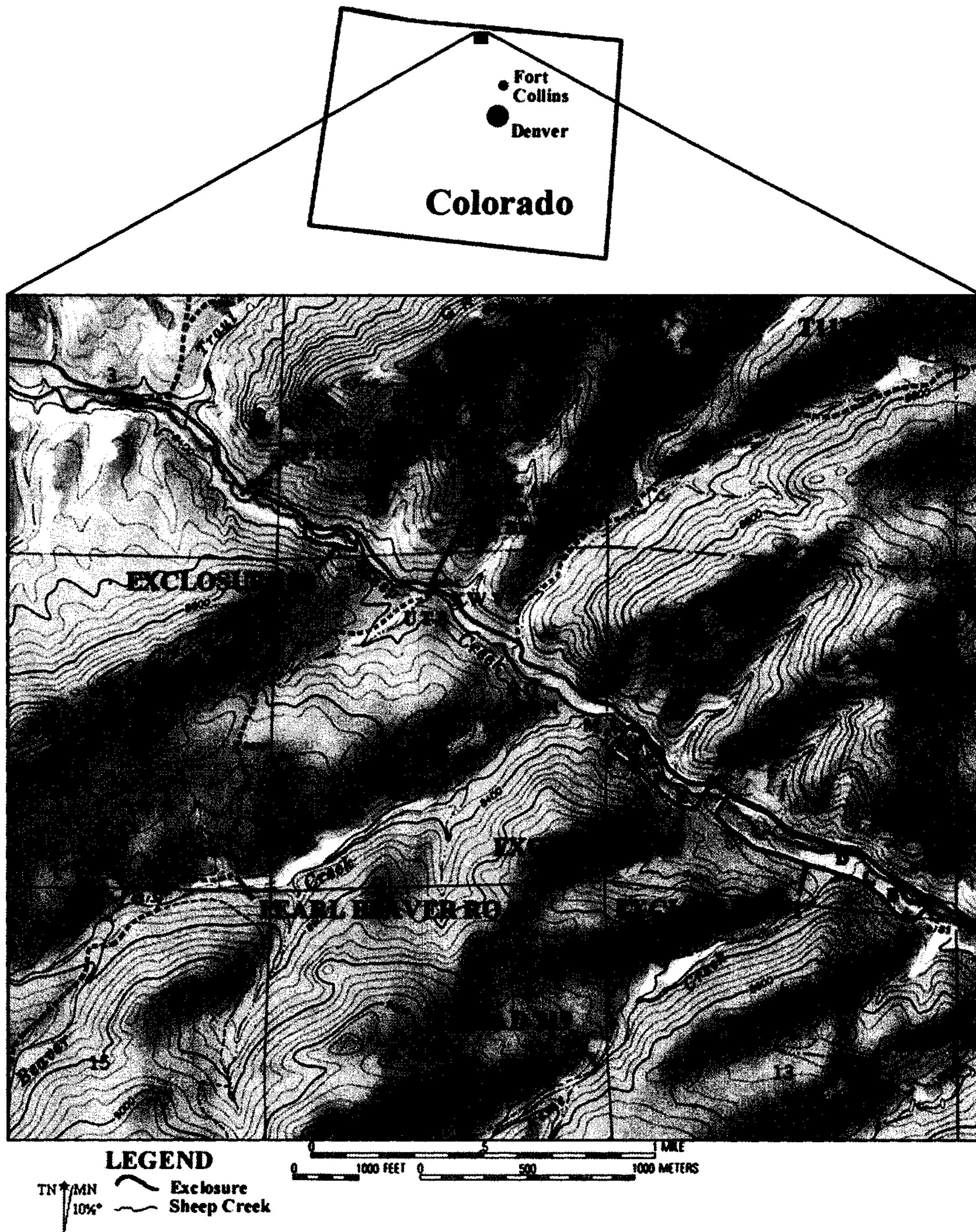


Figure 1.1. Approximate location of plots (represented by letters) along Sheep Creek in the Roosevelt National Forest, Colorado. The map is from the USGS Eaton Reservoir Quadrangle, Colorado-Wyoming 7.5 minute series, 1967.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

APPENDIX B CHAPTER II

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix B Table 1. Results of General Linear Model analysis of variance for difference (DIFF) observed in bank elevation (dependent variable) for steep section of streambank near water and results of LSD tests for differences among treatments means for 1995 data.

	DF	Sum of Squares	Mean Square	F-Value	Prob>F
Model	2	0.01	0.01	2.70	0.09
Error	27	0.01	0.01		
Corrected Total	29	0.02			

R-Square	C.V.	Root MSE	DIFF Mean
0.167	-564.47	0.02	-0.01

	DF	Type I SS	Mean Square	F-Value	Prob>F
TREAT	2	0.01	0.01	2.70	0.09

	DF	Type III SS	Mean Square	F-Value	Prob>F
TREAT	2	0.01	0.01	2.70	0.09

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix B Table 2. Results of stepwise multiple linear regression analysis for control (NONE) treatment for steep section of streambank within 1 m distance of water. This table includes the last step of the analysis and summary of the SAS output (SAS 1988).

	DF	Sum of Squares	Mean Square	F-Value	Prob>F	R-square
Regression	1	0.00	0.01	3.78	0.08	0.26
Error	11	0.00	0.01			
Total	12	0.00				

Variable[1]	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-0.04	0.02	0.01	5.18	0.04
SOM	0.01	0.01	0.01	3.78	0.08

[1]All variables in the model were significant at the 0.15 level. No other variables met the 0.15 significant level for entry into the model. SOM = % soil organic matter.

Summary of stepwise procedure for dependent variable difference in bank elevation (DIFF).

Step	Variable[1]	Number in	Partial r^2	Model r^2	F-Value	Prob>F
1	SOM	1	0.26	0.26	3.78	0.08

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix B Table 3. Results of stepwise multiple linear regression analysis for moderate (MODERATE) treatment for steep section of streambank within 1 m distance of water. This table includes the last step of the analysis and summary of the SAS output (SAS 1988).

	DF	Sum of Squares	Mean Square	F-Value	Prob>F	R-square
Regression	4	0.01	0.01	8.31	0.03	0.89
Error	4	0.01	0.01			
Total	8	0.01				

Bounds on condition number: 1.25, 19.14

Variable[1]	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-0.41	0.09	0.01	23.06	0.01
BGRASS	0.01	0.01	0.01	3.87	0.12
TOTCOVER	0.01	0.01	0.01	10.19	0.03
SAND	0.01	0.01	0.01	8.97	0.04
SOM	0.01	0.01	0.01	15.07	0.02

[1]All variables in the model were significant at the 0.15 level. No other variables met the 0.15 significant level for entry into the model. BGRASS = biomass of grass (g/m^2); TOTCOVER = total plant cover (%); SAND = % sand; SOM = % soil organic matter.

Summary of stepwise procedure for dependent variable difference in bank elevation (DIFF).

Step	Variable[1]	Number in	Partial r^2	Model r^2	F-Value	Prob>F
1	TOTCOVER	1	0.40	0.40	4.58	0.07
2	SOM	2	0.23	0.63	3.76	0.10
3	SAND	3	0.16	0.79	3.79	0.11
4	BGRASS	4	0.10	0.89	3.87	0.12

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix B Table 4. Results of stepwise multiple linear regression analysis for heavy grazing treatment (2) for steep section of streambank within 1 m distance of water. This table includes the last step of the analysis and summary of the SAS output (SAS 1988).

	DF	Sum of Squares	Mean Square	F-Value	Prob>F	R-square
Regression	1	0.01	0.01	13.32	0.01	0.69
Error	6	0.01	0.01			
Total	7	0.01				

Variable[1]	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	0.11	0.03	0.01	15.99	0.01
SOM	-0.01	0.01	0.01	13.32	0.01

[1] All variables in the model were significant at the 0.15 level. No other variables met the 0.15 significant level for entry into the model.

Summary of stepwise procedure for dependent variable difference in bank elevation (DIFF).

Step	Variable[1]	Number in	Partial r^2	Model r^2	F-Value	Prob>F
1	SOM	1	0.69	0.69	13.32	0.01

[1]Variable SOM = soil organic matter.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix B Table 5. Results of stepwise multiple linear regression analysis for grazing treatment for steep section of streambank within 1 m distance of water. This table includes the last step of the analysis for exclosures and summary of the SAS output (SAS 1988).

	DF	Sum of Squares	Mean Square	F-Value	Prob>F	R-square
Regression	4	0.01	0.01	10.52	0.01	0.88
Error	6	0.01	0.01			
Total	10	0.01				

Variable[1]	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-0.31	0.07	0.01	22.77	0.01
BGLIKE	-0.01	0.01	0.01	4.25	0.08
TOTCOVER	0.01	0.01	0.01	3.92	0.10
SAND	0.01	0.01	0.01	10.54	0.02
SOM	0.01	0.01	0.01	27.50	0.01

[1]All variables in the model were significant at the 0.15 level. No other variables met the 0.15 significant level for entry into the model. BGLIKE = biomass of grass-like plants (g/m^2); TOTCOVER = total plant cover (%); SAND = % sand; SOM = % soil organic matter.

Summary of stepwise procedure for dependent variable difference in bank elevation (DIFF).

Step	Variable[1]	Number in	Partial r^2	Model r^2	F-Value	Prob>F
1	SOM	1	0.47	0.47	7.90	0.02
2	TOTCOVER	2	0.18	0.65	4.15	0.08
3	SAND	3	0.14	0.79	4.51	0.07
4	BGLIKE	4	0.09	0.88	4.25	0.08

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix B Table 6. Results of stepwise multiple linear regression analysis for areas opened to grazing in 1988 for a steep section of streambank within 1 m distance of water. This table includes the last step of the analysis for exclosures and summary of the SAS output (SAS 1988).

	DF	Sum of Squares	Mean Square	F-Value	Prob>F	R-square
Regression	2	0.01	0.01	6.60	0.05	0.77
Error	4	0.01	0.01			
Total	6	0.01				

Variable[1]	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-0.24	0.09	0.01	7.72	0.05
SAND	0.01	0.01	0.01	9.80	0.04
SOM	0.01	0.01	0.01	5.00	0.09

[1]All variables in the model were significant at the 0.15 level. No other variables met the 0.15 significant level for entry into the model. SAND = % sand; SOM = % soil organic matter.

Summary of stepwise procedure for dependent variable difference in bank elevation (DIFF).

Step	Variable[1]	Number in	Partial r^2	Model r^2	F-Value	Prob>F
1	SAND	1	0.48	0.48	4.55	0.09
2	SOM	2	0.29	0.77	5.00	0.09

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix B Table 7. Results of General Linear Model analysis of variance for plant community effects on streambank difference (DIFF) observed in bank elevation (dependent variable) for steep section of streambank near water and results of LSD tests for differences among treatments for 1995 data. Data is separated into two *Carex* type communities; one community with *Carex* canopy greater than or equal to 41% canopy cover, and the other with less than 40% *Carex* cover.

Dependent Variable: DIFF

	DF	Sum of Squares	Mean Square	F-Value	Prob>F
Model	5	0.01	0.01	1.20	0.34
Error	24	0.01	0.01		
Corrected Total	29	0.02			

R-Square	C.V.	Root MSE	DIFF Mean
0.20	-586.89	0.02	-0.01

	DF	Type I SS	Mean Square	F-Value	Prob>F
CNTTRT [1/]	2	0.01	0.01	2.50	0.10
CARCOM [2/]	1	0.01	0.01	0.13	0.72
CNTTRT*CARCOM [3/]	2	0.01	0.01	0.42	0.66

	DF	Type III SS	Mean Square	F-Value	Prob>F
CNTTRT [1/]	2	0.01	0.01	2.61	0.09
CARCOM [2/]	1	0.01	0.01	0.27	0.61
CNTTRT*CARCOM [3/]	2	0.01	0.01	0.42	0.66

[1/] CNTTRT = control and treatment effects (moderate and high) [2/] CARCOM = *Carex* community effects [3/]. Interactions of [1/] and [2/].

Means with the same letter are not significantly different.

T Grouping	Mean	N	CARCOM
A	-0.01	15	GT41
A	-0.01	15	LT41

Level of CNTTRT[1/]	Level of CARCOM [2/]	N	DIFF Mean	SD
control	GT41	6	-0.01	0.02
control	LT40	7	-0.01	0.01
moderate	GT41	5	-0.01	0.02
moderate	LT40	4	-0.02	0.04
high	GT41	4	0.02	0.02
high	LT40	4	0.01	0.03

No significant difference between *Carex* type plant communities.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix B Table 8. Results of General Linear Model analysis of variance for plant community effects on streambank difference (DIFF) observed in bank elevation (dependent variable) for steep section of streambank near water and results of LSD tests for differences among treatments for 1995 data. Data is separated into two grassland type communities; one community with grass canopy greater than 31% canopy cover, the other less than 30% cover.

Dependent Variable: DIFF

	DF	Sum of Squares	Mean Square	F-Value	Prob>F
Model	5	0.01	0.01	1.25	0.32
Error	24	0.01	0.01		
Corrected Total	29	0.02			

R-Square	C.V.	Root MSE	DIFF Mean
0.21	-584.36	0.02	-0.01

	DF	Type I SS	Mean Square	F-Value	Prob>F
CNTTRT [1/]	2	0.01	0.01	2.52	0.10
GRASCOM [2/]	1	0.01	0.01	0.11	0.74
CNTTRT*GRASCOM [3/]	2	0.01	0.01	0.54	0.59

	DF	Type III SS	Mean Square	F-Value	Prob>F
CNTTRT [1/]	2	0.01	0.01	2.22	0.13
GRASCOM [2/]	1	0.01	0.01	0.00	0.95
CNTTRT*GRASCOM [3/]	2	0.01	0.01	0.54	0.59

[1/] CNTTRT = control and treatment effects (moderate and high) [2/]. GRASCOM = grass community effects [3/]. Interactions of [1/] and [2/].

T Grouping	Mean	N	GRASCOM
A	-0.01	17	LT30
A	-0.01	13	GT31

Level of CNTTRT	Level of GRASCOM	N	DIFF Mean	SD
control	GT31	6	-0.01	0.02
control	LT30	7	0.00	0.00
moderate	GT31	4	-0.01	0.02
moderate	LT30	5	-0.02	0.04
high	GT31	2	0.02	0.02
high	LT30	6	0.01	0.02

No significant difference between grass type plant communities.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix B Table 9. Raw data set variables for 1995 field season. Variables correspond for each column number at top of each column in Appendix Table 11.

Column number	Variable description for 1995 raw data file
1	Use code: E = Exclosure; O = Open to grazing in 1988 (was an exclosure); G = Long term grazing
2	Plot identifier
3	Canopy cover of litter (%)
4	Canopy cover of combined forb species (%)
5	Canopy cover of *Poa pratensis* (%)
6	Canopy cover of *Juncus arcticus* (%)
7	Canopy cover of *Phleum pretense* (%)
8	No canopy recorded on hit (%)
9	Canopy cover of *Deschampsia caespitosa* (%)
10	Canopy cover of *Carex* species (%)
11	Canopy cover of *Salix planifolia* (%)
12	Canopy cover of *Alnus incana ssp. tenuifolia*
13	Canopy cover of *Pascopyron smithii* (%)
14	Canopy cover of *Calamagrostis canadensis* (%)
15	Canopy cover of *Carex aquatilis* (%)
16	Canopy cover of *Carex utriculata* (%)
17	Canopy cover of *Salix lutea* (%)
18	Canopy cover of *Dasiphora floribunda* (%)
19	Canopy cover of *Agrostis scabra* (%)
20	Canopy cover of *Bromus inermis* (%)
21	Canopy cover of *Bromus* species (%)
22	Canopy cover of *Artemisia tridentata* (%)
23	Canopy cover of *Salix* species (%)
24	Canopy cover of *Salix exigua* (%)
25	Canopy cover of *Carex nebrascensis* (%)
26	Canopy cover of *Koeleria macrantha* (%)
27	Canopy cover of *Carex microptera* (%)
28	Soil surface cover of litter (%)
29	Soil surface cover of combined forb species (%)
30	Soil surface cover of bare ground (%)
31	Soil surface cover of moss species (%)
32	Soil surface cover of rock (%)
33	Soil surface cover of *Poa pratensis* (%)
34	Soil surface cover of *Juncus arcticus* (%)
35	Soil surface cover of *Phleum pratense* (%)
36	Soil surface cover of *Salix planifolia* (%)
37	Soil surface cover of *Carex* species (%)
38	Soil surface cover of *Carex aquatilis* (%)
39	Soil surface cover of *Salix lutea* (%)
40	Soil surface cover of *Carex utriculata* (%)
41	Soil surface cover of *Bromus inermis* (%)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix B Table 9. Raw data set variables for 1995 field season. Variables correspond for each column number at top of each column in Appendix Table 11.

Column number	Variable description for 1995 raw data file
42	Soil surface cover of *Salix exigua* (%)
43	Soil surface cover of *Deschampsia caespitosa* (%)
44	Soil surface cover of *Carex nebrascensis* (%)
45	Soil surface cover of *Pascopyron smithii* (%)
46	Soil surface cover of *Calamagrostis canadensis* (%)
47	Soil texture sand (%)
48	Soil texture silt (%)
49	Soil texture clay (%)
50	Soil organic matter (%)
51	Control or treatment: 0 = no grazing; 1 = moderate grazing; 2 = heavy grazing.
52	Biomass of *Pascopyron smithii* (gm^{-2})
53	Biomass of *Artemisia tridentata* (gm^{-2})
54	Biomass of *Bromus inermis* (gm^{-2})
55	Biomass of *Carex aquatilis* (gm^{-2})
56	Biomass of *Calamagrostis canadensis* (gm^{-2})
57	Biomass of *Carex microptera* (gm^{-2})
58	Biomass of *Carex nebrascensis* (gm^{-2})
59	Biomass of *Carex utriculata* (gm^{-2})
60	Biomass of *Carex sp.* (gm^{-2})
61	Biomass of *Deschampsia caespitosa* (gm^{-2})
62	Biomass of *Equisetum arvense* (gm^{-2})
63	Biomass of *Fragaria virginiana* (gm^{-2})
64	Biomass of *Juncus arcticus* (gm^{-2})
65	Biomass of Litter (gm^{-2})
66	Biomass of Miscellaneous forbs (gm^{-2})
67	Biomass of *Phleum pratense* (gm^{-2})
68	Biomass of *Poa pratensis* (gm^{-2})
69	Biomass of *Salix exigua* (gm^{-2})
70	Biomass of *Salix sp.* (gm^{-2})
71	Biomass of *Salix planifolia* (gm^{-2})
72	Bank difference (cm) at position (1-2)
73	Bank difference (cm) at position (3-4)
74	Bank difference (absolute difference cm) at position (1-2)
75	Bank difference (absolute difference cm) at position (3-4)
76	Cluster groupings for vegetation group 3 (C3)
77	Cluster groupings for vegetation group 4 (C4)
78	Cluster groupings for vegetation group 2 (C2)
79	Control or treatment: 0 = no grazing; 1 = moderate grazing; 2 = heavy grazing; based on actual cover and biomass values rather than expected treatment.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix B Table 10. Columns defined in Table 9.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
E	A	3	16	12	45	12	7	2	0	0	0	0	0	0	0	0
E	B	6	10	23	0	13	0	0	5	13	2	2	0	0	0	0
E	C	0	21	6	29	15	1	1	18	1	0	0	4	4	0	0
E	D	7	8	9	21	11	0	0	19	0	0	0	16	0	0	0
E	E	1	8	0	2	1	0	45	18	0	0	0	0	9	16	0
E	F	1	22	4	15	0	1	4	12	0	0	0	0	0	0	5
E	G	7	19	22	0	0	1	0	7	0	0	2	0	1	0	0
E	H	4	16	30	0	10	1	2	3	0	0	0	0	7	23	0
E	I	7	12	18	14	3	0	5	1	0	0	0	0	19	2	0
E	J	2	21	4	32	8	0	7	1	0	0	0	0	15	1	0
E	K	5	46	31	7	6	4	0	0	0	0	0	0	0	0	0
O	L	1	4	1	15	9	0	16	8	0	0	0	0	34	7	0
O	M	1	1	5	70	0	0	0	7	0	0	15	0	0	0	0
O	N	0	3	0	75	12	0	4	1	3	0	0	0	0	0	0
O	O	1	1	2	63	10	13	6	0	0	0	0	0	0	0	0
O	P	1	0	4	80	5	0	6	0	4	0	0	0	0	0	0
O	Q	0	6	9	0	1	0	4	0	0	0	0	0	0	0	0
O	R	0	2	22	0	0	0	5	0	0	0	0	0	0	0	0
G	S	4	1	3	5	1	0	3	0	0	0	0	24	17	31	0
G	T	0	0	0	0	0	0	0	0	0	0	0	11	21	40	0
G	U	0	1	1	0	0	0	0	0	0	0	0	9	53	33	0
G	V	0	2	0	2	2	0	1	0	0	0	0	40	1	39	0
G	W	0	3	0	9	0	0	0	0	0	0	0	34	19	17	0
G	X	2	2	1	6	0	0	8	0	0	0	0	28	30	12	0
G	AA	1	2	1	55	0	0	0	0	0	0	0	12	2	15	0
G	AB	1	2	0	19	1	0	4	0	0	0	0	15	3	54	0
G	AC	7	5	0	0	0	0	0	0	0	0	0	31	7	39	0
G	AD	2	2	9	12	0	0	0	0	0	0	0	24	0	38	0
G	AE	1	0	2	0	1	0	2	0	0	0	0	17	0	41	0
G	AF	2	7	8	3	0	0	3	0	0	0	0	34	21	20	0

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix B Table 10. Columns defined in Table 9.

18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
0	0	0	0	0	0	0	0	0	0	41	23	21	8	0	4	3
0	0	0	0	0	0	0	0	0	0	57	24	7	7	0	2	1
0	0	0	0	0	0	0	0	0	0	71	18	0	5	0	0	1
0	0	0	0	0	0	0	0	0	0	81	7	0	0	0	1	0
0	0	0	0	0	0	0	0	0	0	65	26	0	3	0	0	0
1	1	0	0	0	0	0	0	0	0	57	23	6	5	0	2	1
1	0	38	1	1	0	0	0	0	0	52	29	3	0	0	14	0
0	0	4	0	0	0	0	0	0	0	43	21	1	2	0	25	0
0	0	0	0	0	1	16	0	0	0	82	8	0	0	0	4	1
0	0	0	0	0	0	9	0	0	0	76	22	0	0	0	0	3
0	0	1	0	0	0	0	0	0	0	40	33	18	8	0	1	0
0	0	0	0	0	2	0	3	0	0	75	7	2	6	0	0	0
0	0	0	0	0	0	0	0	1	0	69	11	14	0	1	3	1
0	0	0	0	0	0	0	2	0	0	34	17	0	47	0	0	2
0	0	0	0	0	0	0	1	0	2	37	16	16	26	0	0	1
0	0	0	0	0	0	0	0	0	0	58	11	0	29	2	0	0
0	0	0	0	0	0	0	80	0	0	51	10	1	12	0	1	0
0	0	0	0	0	0	0	71	0	0	53	19	7	0	0	1	0
0	0	0	0	0	0	0	11	0	0	72	7	0	14	0	0	0
0	0	0	0	0	0	0	28	0	0	57	17	11	6	0	0	0
0	0	0	0	0	0	0	3	0	0	69	8	9	5	0	0	0
0	0	0	0	0	0	0	6	0	7	54	10	19	8	0	0	0
0	0	0	0	0	0	0	10	0	8	53	7	1	29	0	0	0
0	0	0	0	0	0	0	1	0	10	51	5	4	32	0	0	0
0	0	0	0	0	0	0	0	0	0	62	18	1	14	0	0	0
0	0	0	0	0	0	0	0	0	0	54	14	1	24	0	0	0
0	0	0	0	0	0	0	1	0	6	53	17	1	21	0	0	0
0	0	0	0	0	0	0	13	0	0	34	18	21	11	0	0	2
0	0	0	0	0	0	0	36	0	0	48	7	9	11	0	1	0
0	0	0	0	0	0	0	2	0	0	62	16	9	6	0	0	0

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix B Table 10. Columns defined in Table 9.

35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
0	0	0	0	0	0	0	0	0	0	0	0	45	19	36	13.2
1	1	0	0	0	0	0	0	0	0	0	0	69	29	2	8.3
2	0	2	1	0	0	0	0	0	0	0	0	69	29	3	10.1
1	0	2	4	1	1	0	0	0	0	0	0	56	14	30	13.1
0	0	3	1	0	2	0	0	0	0	0	0	61	36	3	5.0
0	0	1	0	0	5	0	0	0	0	0	0	67	31	1	4.9
0	0	0	0	0	0	2	0	0	0	0	0	64	33	3	5.0
1	0	0	1	0	6	0	0	0	0	0	0	64	33	3	8.0
0	0	0	2	0	1	0	2	0	0	0	0	63	34	2	8.5
2	0	1	2	0	0	0	0	1	0	0	0	66	31	3	8.3
0	0	0	0	0	0	0	0	0	0	0	0	64	33	3	8.0
1	0	2	5	0	1	0	0	0	1	0	0	75	24	1	5.2
0	0	0	0	0	0	0	0	0	0	1	0	65	12	23	7.4
0	0	0	0	0	0	0	0	0	0	0	0	62	11	27	9.7
1	0	0	0	0	0	0	0	0	3	0	0	77	22	1	6.3
0	0	0	0	0	0	0	0	0	0	0	0	76	23	1	7.2
1	0	0	0	0	0	0	0	0	24	0	0	52	15	33	11.3
0	0	0	0	0	0	0	0	0	20	0	0	53	17	30	12.8
0	0	0	0	0	5	0	0	0	2	0	0	68	31	2	9.7
0	0	0	1	0	6	0	0	0	2	0	0	69	29	2	7.5
0	0	0	0	0	4	0	0	0	1	0	4	53	13	34	10.2
0	0	0	0	0	7	0	0	0	2	0	0	63	36	1	8.3
0	0	0	3	0	3	0	0	0	4	0	0	72	27	1	6.0
0	0	0	5	0	3	0	0	0	0	0	0	59	11	30	6.9
0	0	0	0	0	5	0	0	0	0	0	0	69	29	2	10.0
0	0	0	0	0	6	0	0	0	0	0	1	75	25	0	5.9
0	0	0	1	0	5	0	0	0	1	0	1	56	16	28	7.1
0	0	0	0	0	9	0	0	0	5	0	0	64	35	2	8.7
0	0	0	0	0	9	0	0	0	13	0	2	62	36	2	7.8
0	0	0	4	0	3	0	0	0	0	0	0	56	13	31	10.4

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix B Table 10. Columns defined in Table 9.

51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67
0	0	0	0	0	0	0	0	0	0	0	11	11	0	.	27	38
1	0	0	0	0	0	0	0	0	12	21	0	0	21	.	12	4
2	0	0	1	6	0	0	0	0	9	0	0	0	37	.	43	0
0	0	0	0	39	0	0	0	0	5	2	0	0	23	.	14	7
1	0	0	0	8	57	0	0	11	4	0	0	0	0	.	19	0
2	0	0	0	13	13	0	0	39	0	0	0	0	19	.	15	1
0	4	4	5	0	0	0	0	0	1	0	0	0	0	.	72	0
0	0	0	0	31	9	1	0	15	0	0	0	0	0	.	27	4
2	0	0	0	27	4	0	0	0	1	4	0	0	4	.	51	2
1	0	0	0	14	22	0	0	0	1	0	0	0	29	.	15	6
0	0	0	1	0	0	0	0	0	0	0	0	0	0	.	87	7
2	0	0	0	52	14	0	0	8	4	0	0	0	6	.	2	12
0	17	0	0	0	0	0	0	0	0	0	0	0	45	.	10	0
0	0	0	0	0	0	0	0	5	2	19	0	0	51	.	16	6
2	0	0	0	0	15	0	7	0	5	0	0	0	56	.	12	6
1	0	0	0	4	7	0	0	0	11	0	0	0	58	.	6	7
0	0	0	0	0	0	0	78	0	0	0	0	0	0	.	12	0
0	0	0	0	0	0	0	70	0	0	1	0	0	0	.	10	0
1	0	0	0	4	29	0	5	51	0	0	0	0	9	.	1	1
2	0	0	0	33	33	0	19	11	0	0	0	0	0	.	4	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	.	0	0
1	0	0	0	0	26	18	1	46	0	6	0	0	1	.	2	0
2	0	0	0	57	10	3	3	0	0	3	0	0	16	.	7	0
0	0	0	0	49	21	1	0	20	0	1	0	0	1	.	3	4
2	0	0	0	13	11	0	0	0	0	0	0	0	65	.	10	0
1	0	0	0	70	14	2	0	0	0	4	0	0	0	.	11	0
0	0	0	0	45	28	5	0	12	0	0	0	0	0	.	10	1
1	0	0	0	9	26	0	5	57	0	0	0	0	1	.	2	0
2	0	0	0	46	13	0	10	28	0	1	0	0	0	.	1	1
0	0	0	0	65	16	1	0	5	0	1	0	0	0	.	10	0

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix B Table 10. Columns defined in Table 9.

68	69	70	71	72	73	74	75	76	77	78	79
13	0	0	0	-0.0115	.	0.0155	.	2	2	2	0
31	0	0	0	-0.0338	.	0.0544	.	3	3	2	1
4	0	0	0	-0.0477	0.0313	0.0523	0.0715	3	3	2	1
10	0	0	0	-0.0332	-0.0085	0.0332	0.0146	3	3	2	0
1	0	0	0	-0.0882	-0.0109	0.0882	0.0120	1	4	1	1
1	0	0	0	-0.0299	0.0459	0.1376	0.0549	3	3	2	1
14	0	0	0	-0.0175	-0.0345	0.0502	0.0545	3	3	2	0
13	0	0	0	-0.0231	-0.0105	0.0272	0.0276	3	4	1	0
3	4	0	0	-0.0212	0.0276	0.0310	0.0817	3	3	2	1
13	0	0	0	-0.0002	-0.0322	0.0205	0.0626	3	3	2	2
5	0	0	0	-0.0042	-0.0059	0.0476	0.0797	3	3	2	0
0	0	2	0	0.0011	-0.0073	0.0069	0.0082	1	4	1	1
28	0	0	0	0.0280	.	0.0280	.	2	2	2	0
0	0	0	0	-0.0089	-0.0092	0.0277	0.0190	2	2	2	0
0	0	0	0	0.0093	0.0163	0.0278	0.0252	2	2	2	2
0	0	0	7	0.0223	0.0205	0.0319	0.0282	2	2	2	2
10	0	0	0	0.0006	.	0.0042	.	1	1	1	0
19	0	0	0	-0.0094	.	0.0129	.	1	1	1	0
0	0	0	0	0.0139	-0.0091	0.0204	0.0118	1	4	1	2
0	0	0	0	-0.0071	-0.0277	0.0140	0.0288	1	1	1	2
0	0	0	0	-0.0023	0.0211	0.0134	0.0244	1	1	1	0
0	0	0	0	0.0082	.	0.0186	.	1	4	1	1
0	0	0	0	0.0215	.	0.0251	.	1	4	1	2
0	0	0	0	-0.1108	-0.0916	0.1137	0.0931	1	4	1	0
0	0	0	0	-0.0112	.	0.0270	.	2	2	2	2
0	0	0	0	-0.0082	.	0.0158	.	1	4	1	1
0	0	0	0	-0.0157	.	0.0294	.	1	4	1	0
0	0	0	0	-0.0192	.	0.0305	.	1	4	1	1
0	0	0	0	0.0040	.	0.0371	.	1	1	1	2
1	0	0	0	-0.0175	.	0.0249	.	1	4	1	0

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

APPENDIX C CHAPTERS III & IV

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix C Table 1. Means and standard errors of variables used in Chapter III data analyses.

Characteristic	Exclosure mean	Standard error	Opened to grazing in 1988 mean	Standard error	Continuous grazing mean	Standard error
Total root length (cm)	5643	2110	3356	677	3392	507
Root biomass (g/cm^3)	0.01	0.01	0.01	0.01	0.01	0.01
Root length density (cm/cm^3)	15.10	1.02	17.90	1.70	18.10	2.10
Root length A (cm) for root widths < 0.5 mm	4622	1876	1726	273	1951	184
Root length B (cm) for root widths 0.51 – 1.00 mm	989	348	1308	333	1183	305
Root length C (cm) for root widths > 1.00 mm	32	14.8	349	111	259	96
Soil organic matter (%)	12.5	0.23	9.6	0.49	8.1	0.35
Sand (%)	75	0.76	67	1.38	72	1.44
Silt (%)	12.5	0.95	16.0	1.48	15.0	0.99
Clay (%)	12.5	0.19	17.0	1.20	13.0	0.84
Soil surface moisture (%)	40	3.10	51	5.35	45	2.09
Soil bulk density (g/cm^3)	0.73	0.04	0.83	0.04	0.90	0.02
Hoof simulator impact (cm)	2.8	1.16	4.5	2.97	5.0	1.22
No hoof simulator impact (cm)	2.80	0.76	-0.46	2.65	1.90	0.96
Soil shear strength (kN/m^2)	23.6	7.72	40.9	6.98	50.5	7.17
Carex aquatilis canopy (%)	0.38	0.26	0.13	0.13	9.80	2.20
Carex utriculata canopy (%)	3.50	1.27	0.13	0.13	13.60	2.25
Grass canopy (%)	55.4	7.53	42.5	3.3	32.5	2.12
Juncus arcticus canopy (%)	17.0	4.35	20.1	5.50	5.4	1.45
Forb canopy (%)	14.9	1.43	6.8	0.81	14.7	2.00
Poa spp. canopy (%)	0.63	0.50	0.00	0.00	2.90	1.78
Carex canopy (%)	3.9	1.25	21.7	5.74	25.1	3.86
Salix canopy (%)	0.25	0.25	1.75	1.32	11.36	3.05

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix C Table 2. Results of General Linear Model analysis of variance procedure for hoof simulator impact on areas with three different past grazing histories at Sheep Creek, Colorado. The dependent variable is hoof simulator impact (cm).

	DF	Sum of Squares	Mean Square	F-Value	Prob>F	R-Square
Model	2	7.48	3.74	0.18	0.84	0.04
Error	10	205.76	20.58			
Corrected Total	12	213.24				

	DF	Type I SS	Mean Square	F-Value	Prob>F
HISTORY	2	7.48	3.74	0.18	0.84

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix C Table 3. Results of General Linear Model analysis of variance procedure for soil shear strength on areas with three different past grazing histories at Sheep Creek, Colorado. The dependent variable is soil shear strength (kN/m^2).

	DF	Sum of Squares	Mean Square	F-Value	Prob>F	R-Square
Model	2	1156.93	578.46	0.85	0.46	0.15
Error	10	6821.90	682.19			
Corrected Total	12	7978.83				

	DF	Type I SS	Mean Square	F-Value	Prob>F
HISTORY	2	1156.93	578.46	0.85	0.46

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix C Table 4. Results of General Linear Model analysis of variance procedure for hoof simulator impact on areas with three different past grazing histories at Sheep Creek, Colorado and two soil treatment conditions. The dependent variable is hoof simulator impact (cm). Least Significant Difference (LSD) tests show differences.

	DF	Sum of Squares	Mean Square	F-Value	Prob>F	R-Square
Model	3	278.64	92.88	2.59	0.08	0.26
Error	22	787.82	35.81			
Corrected Total	25	1066.46				

	DF	Type I SS	Mean Square	F-Value	Prob>F
HISTORY	2	14.95	7.48	0.21	0.81
WET PreWET	1	263.69	263.69	7.36	0.01

T Grouping	Mean	N	Treatment
A	7.67	13	Wet
B	1.30	13	Pre-Wet

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix C Table 5. Results of stepwise multiple linear regression analysis for hoof simulator impact for the complete data set. This table includes the last step of the analysis and summary of the SAS output (SAS 1988). The dependent variable, hoof, is simulator impact (cm).

	DF	Sum of Squares	Mean Square	F-Value	Prob>F	R-square	C(p)
Regression	1	271.94	271.94	4.33	0.04	0.08	-4.99
Error	49	3078.70	62.83				
Total	50	3350.64					

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	-2.74	3.66	35.24	0.56	0.46
SURFSM	0.16	0.08	271.94	4.33	0.04

Summary of stepwise procedure for dependent variable Hoof simulator impact.

Step	Variable[1]	Number in	Partial r^2	Model r^2	C(p)	F-Value	Prob>F
1	SURFSM	1	0.08	0.08	-4.99	4.33	0.04
2	ROOTLD	2	0.05	0.13	-5.26	2.75	0.10
3	ROOTLD	1	0.05	0.08	-4.99	2.75	0.10

[1]Variable SURFSM = Surface soil moisture (%); ROOTLD = root length density (cm/cm^3). All variables in the model were significant at the 0.10 level. No other variables met the 0.15 significant level for entry into the model.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix C Table 6. Results of stepwise multiple linear regression analysis for hoof simulator impact. This table includes the last step of the analysis and summary of the SAS output (SAS 1988). The dependent variable hoof simulator impact (cm) and results showed no variable met the 0.15 significance level for entry into the model. No model was produced for this EXCLOSURE data.

Summary of stepwise procedure for dependent variable HOOFSIM.

Step	Variable [1/]	Number in	Partial r^2	Model r^2	F-Value	Prob>F
1	ROOTBIO	1	0.32	0.32	2.80	0.15
2	ROOTBIO	0	0.32	0.00	2.80	0.15

[1/] ROOTBIO = root biomass (g/cm^3).
All variables in the model were significant at the 0.10 level. No other variables met the 0.15 significant level for entry into the model.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix C Table 7. Results of stepwise multiple linear regression analysis for hoof simulator impact. This table includes the last step of the analysis and summary of the SAS output (SAS 1988). The model produced was for data for areas opened to grazing in 1988. The dependent variable was hoof simulator impact (cm).

	DF	Sum of Squares	Mean Square	F-Value	Prob>F	R-square	C(p)
Regression	2	872.02	436.01	4.55	0.03	0.41	8.75
Error	13	1246.15	95.86				
Total	15	2118.17					

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	131.69	42.28	929.83	9.70	0.01
SAND	-1.66	0.55	860.80	8.98	0.01
ROOTLD	-0.91	0.46	374.24	3.90	0.07

Summary of stepwise procedure for dependent variable Hoof simulator impact.

Step	Variable[1]	Number in	Partial r^2	Model r^2	C(p)	F-Value	Prob>F
1	SAND	1	0.24	0.24	12.37	4.30	0.06
2	ROOTLD	2	0.18	0.41	8.75	3.90	0.07

[1]Variable SAND = percent sand in soil; ROOTLD = root length density (cm/cm^3). All variables in the model were significant at the 0.10 level. No other variables met the 0.15 significant level for entry into the model.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix C Table 8. Results of stepwise multiple linear regression analysis for hoof simulator impact. This table includes the last step of the analysis and summary of the SAS output (SAS 1988). No model was produced for continuous grazing since 1956. The dependent variable hoof simulator impact (cm).

Summary of stepwise procedure for dependent variable HOOFSIM.

Step	Variable[1]	Number in	Partial r^2	Model r^2	C(p)	F-Value	Prob>F
1	GRAS	1	0.09	0.09	-7.61	2.48	0.13
2	GRAS	0	0.09	0.00	-8.08	2.48	0.13

[1]Variable GRAS = grass canopy cover by percent. All variables in the model were significant at the 0.10 level. No other variables met the 0.15 significant level for entry into the model.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix C Table 9. Results of stepwise multiple linear regression analysis for soil shear strength. This table includes the last step of the analysis and summary of the SAS output (SAS 1988). The model produced was for the complete data set. The dependent variable was soil shear strength (kN/m^2).

	DF	Sum of Squares	Mean Square	F-Value	Prob>F	R-square	C(p)
Regression	2	20305.99	10153.00	12.91	0.0001	0.35	-4.32
Error	48	37746.63	786.39				
Total	50	58052.63					

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	0.25	10.91	0.43	0.00	0.98
CAREX	0.67	0.19	9444.51	12.01	0.01
SHEARSM	0.59	0.20	6532.16	8.31	0.01

Summary of stepwise procedure for dependent variable HOOFSIM.

Step	Variable[1]	Number in	Partial r^2	Model r^2	C(p)	F-Value	Prob>F
1	CAREX	1	0.24	0.24	0.72	15.24	0.01
2	SHEARSM	2	0.11	0.35	-4.32	8.31	0.01

[1]Variable CAREX = percent canopy of *Carex* sp.; SHEARSM = percent soil moisture for shear soil samples. All variables in the model were significant at the 0.10 level. No other variables met the 0.15 significant level for entry into the model.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix C Table 10. Results of stepwise multiple linear regression analysis for soil shear strength. This table includes the last step of the analysis and summary of the SAS output (SAS 1988). No model was produced for the exclosure data set. The dependent variable was soil shear strength (KN/m^2).

Step	Variable[1]	Number in	Partial r^2	Model r^2	F-Value	Prob>F
1	CATC	1	0.36	0.36	3.36	0.12
2	CATC	0	0.36	0.00	3.36	0.12

[1]Variable CATC = Category C root lengths (root length (in cm) for root diameters greater than 1.0 mm). All variables in the model were significant at the 0.10 level. No other variables met the 0.15 significant level for entry into the model.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix C Table 11. Results of stepwise multiple linear regression analysis for soil shear strength. This table includes the last step of the analysis and summary of the SAS output (SAS 1988). The model produced was for the opened to grazing in 1988 data set. The dependent variable was soil shear strength (kN/m^2).

	DF	Sum of Squares	Mean Square	F-Value	Prob>F	R-square	C(p)
Regression	2	9531.44	4765.72	28.73	0.0001	0.82	-8.21
Error	13	2156.31	165.87				
Total	13	11687.75					

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	181.20	64.81	1296.61	7.82	0.02
SAND	-2.43	0.88	1256.41	7.57	0.02
SHEARSM	0.45	0.16	1302.26	7.85	0.02

Summary of stepwise procedure for dependent variable soil shear strength.

Step	Variable[1]	Number in	Partial r^2	Model r^2	C(p)	F-Value	Prob>F
1	SHEARSM	1	0.71	0.71	-9.16	33.95	0.00
2	SAND	2	0.11	0.82	-8.21	7.57	0.02

[1]Variable SHEARSM = percent soil moisture for shear soil samples; SAND = percent sand in soil. All variables in the model were significant at the 0.10 level. No other variables met the 0.15 significant level for entry into the model.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix C Table 12. Results of stepwise multiple linear regression analysis for soil shear strength. This table includes the last step of the analysis and summary of the SAS output (SAS 1988). The model produced was for the continuous grazing since 1956 data set. The dependent variable was soil shear strength (kN/m2).

	DF	Sum of Squares	Mean Square	F-Value	Prob>F	R-square	C(p)
Regression	1	12305.56	2305.56	11.95	0.002	0.32	-1.59
Error	25	25733.18	1029.33				
Total	26	38038.74					

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	24.83	9.88	6509.20	6.32	0.02
CAREX	1.05	0.30	12305.56	11.95	≤0.01

Summary of stepwise procedure for dependent variable soil shear strength.

Step	Variable[1]	Number in	Partial r^2	Model r^2	C(p)	F-Value	Prob>F
1	CAREX	1	0.32	0.32	-1.59	11.95	≤0.01

[1]Variable CAREX = percent canopy of *Carex* spp. All variables in the model were significant at the 0.10 level. No other variables met the 0.15 significant level for entry into the model.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix C Table 13. Data for 1996 field season. Variables correspond for each column number at top of each column in Appendix Table 14.

Column number	Variable description for 1996 raw data file
1	Plot identifier
2	Season: 1 = irrigated to field capacity; 2 = not irrigated
3	Date sampled
4	Treatment: Cnt = no mechanical hoof treatment; Trt = mechanical hoof treatment
5	Use code: E = Exclosure; O = Open to grazing in 1988 (was an exclosure); G = Long term grazing
6	Canopy cover of *Alnus incana* (%)
7	Canopy cover of *Carex aquatilis* (%)
8	Canopy cover of *Carex utriculata* (%)
9	Canopy cover of grass species combined (%)
10	Percent cover recorded as holes (%)
11	Canopy cover of *Juncus arcticus* (%)
12	Canopy cover of *Pinus contorta* (%)
13	Canopy cover of combined forb species (%)
14	No data
15	Canopy cover of *Poa* species (%)
16	Canopy cover of *Salix lutea* (%)
17	Canopy cover of *Salix* species (%)
18	Canopy cover of *Salix planifolia* (%)
19	Canopy cover of *Salix exigua* (%)
20	Canopy cover of *Carex microptera* (%)
21	Canopy cover of *Carex nebrascensis* (%)
22	Canopy cover of *Carex* sp. (%)
23	Canopy cover of *Salix glauca* (%)
24	Canopy cover of litter (%)
25	Canopy cover of combined forb species (%)
26	Soil surface cover of bare ground (%)
27	Soil surface cover of grass species combined (%)
28	Soil surface cover of moss species combined (%)
29	Soil surface cover of *Carex utriculata* (%)
30	Soil surface cover of rock (%)
31	Soil surface cover of pin table leg (%)
32	Soil surface cover of *Salix planifolia* (%)
33	No data
34	Soil surface cover of *Carex* sp.
35	Soil surface cover of *Carex aquatilis* (%)
36	Percent cover recorded as holes (%)
37	Soil surface cover of *Carex microptera* (%)
38	Soil surface cover of *Juncus arcticus* (%)
39	Soil surface cover of *Salix glauca* (%)
40	Soil surface cover of *Salix exigua* (%)
41	Percent soil moisture at position 1-2, depth 0-10cm

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix C Table 13. Data for 1996 field season. Variables correspond for each column number at top of each column in Appendix Table 14.

Column number	Variable description for 1996 raw data file
42	Percent soil moisture at position 1-2, depth 10-20cm
43	Percent soil moisture at position 1-2, depth 20-30cm
44	Percent soil moisture at position 3-4, depth 0-10cm
45	Percent soil moisture at position 3-4, depth 10-20cm
46	Percent soil moisture at position 3-4, depth 20-30cm
47	Percent soil moisture at position 5-6, depth 0-10cm
48	Percent soil moisture at position 5-6, depth 10-20cm
49	Percent soil moisture at position 5-6, depth 20-30cm
50	Soil bulk density (gcm^{-3}) at position 1-2, depth 0-10cm
51	Soil bulk density (gcm^{-3}) at position 1-2, depth 10-20cm
52	Soil bulk density (gcm^{-3}) at position 1-2, depth 20-30cm
53	Soil bulk density (gcm^{-3}) at position 3-4, depth 0-10cm
54	Soil bulk density (gcm^{-3}) at position 3-4, depth 10-20cm
55	Soil bulk density (gcm^{-3}) at position 3-4, depth 20-30cm
56	Soil bulk density (gcm^{-3}) at position 5-6, depth 0-10cm
57	Soil bulk density (gcm^{-3}) at position 5-6, depth 10-20cm
58	Soil bulk density (gcm^{-3}) at position 5-6, depth 20-30cm
59	Soil organic matter (%) at position 1-2, depth 0-10cm
60	Soil organic matter (%) at position 1-2, depth 10-20cm
61	Soil organic matter (%) at position 1-2, depth 20-30cm
62	Soil organic matter (%) at position 3-4, depth 0-10cm
63	Soil organic matter (%) at position 3-4, depth 10-20cm
64	Soil organic matter (%) at position 3-4, depth 20-30cm
65	Soil organic matter (%) at position 5-6, depth 0-10cm
66	Soil organic matter (%) at position 5-6, depth 10-20cm
67	Soil organic matter (%) at position 5-6, depth 20-30cm
68	Soil texture sand (%)
69	Soil texture silt (%)
70	Soil texture clay (%)
71	Average soil organic matter content (%)
72	Soil moisture measured in soil surface (%)
73	Soil bulk density measured in soil surface (gcm^{-3})
74	Hoof impression from mechanical hoof simulator (mm)
75	Difference in soil created by mechanical hoof simulator (mm)
76	Difference in soil surface level with no mechanical hoof simulator (mm)
77	Soil shear strength (kNm^{-2})
78	Soil moisture content in shear soil sample (%)
79	Cluster groupings for three vegetation groups
80	Cluster groupings for different three vegetation groups

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix C Table 14.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
A	2	6/10/96	Cnt	E	9	0	10	27	0	22	0	14	18	0	0
A	2	6/10/96	Trt	E	6	0	7	24	0	38	0	16	9	0	0
AC	2	6/26/96	Cnt	G	4	10	5	21	0	0	0	23	1	36	0
AC	2	6/26/96	Trt	G	3	12	9	44	0	0	0	26	1	5	0
AF	2	6/20/96	Cnt	G	6	16	12	24	0	20	0	12	5	0	0
AF	2	6/20/96	Trt	G	4	10	5	21	0	0	0	23	1	36	0
BA	2	6/25/96	Cnt	G	4	0	13	34	0	0	0	18	1	0	0
BA	2	6/25/96	Trt	G	6	0	15	36	0	0	0	0	3	0	0
BB	2	6/29/96	Cnt	G	4	0	3	20	0	12	4	19	7	4	0
BB	2	6/29/96	Trt	G	14	1	4	15	0	21	0	13	1	0	0
BC	2	6/27/96	Cnt	G	3	2	5	32	0	29	0	10	2	0	0
BC	2	6/27/96	Trt	G	4	2	1	37	0	6	0	24	0	0	0
D	2	7/22/96	Cnt	E	1	0	2	61	0	24	0	12	0	0	0
D	2	7/22/96	Trt	E	2	1	5	50	0	26	0	16	0	0	0
M	2	6/11/96	Cnt	O	13	0	0	27	0	53	0	4	3	0	0
M	2	6/11/96	Trt	O	13	0	0	49	0	24	0	9	5	0	0
N	2	6/13/96	Cnt	O	5	0	0	18	0	49	0	13	7	0	8
N	2	6/13/96	Trt	O	13	0	0	14	1	58	0	6	1	0	0
Q	2	6/14/96	Cnt	O	15	0	0	47	0	0	0	8	1	0	0
Q	2	6/14/96	Trt	O	3	0	0	55	0	1	0	6	1	0	0
R	2	6/17/96	Cnt	O	8	0	0	38	0	0	0	9	0	0	0
R	2	6/17/96	Trt	O	8	0	0	38	0	0	0	5	1	0	0
U	2	6/18/96	Cnt	G	10	28	20	19	0	5	0	9	9	0	0
U	2	6/18/96	Trt	G	9	31	23	24	0	0	0	5	8	0	0
X	2	6/19/96	Cnt	G	17	23	8	22	0	8	0	11	11	0	0
X	2	6/19/96	Trt	G	7	28	11	23	0	13	0	10	8	0	0
A	1	8/9/96	Cnt	E	6	0	0	58	0	9	0	22	1	4	0
A	1	8/9/96	Trt	E	2	0	0	62	0	8	0	18	9	1	0
AC	1	7/29/96	Cnt	G	2	5	5	50	0	0	0	19	1	0	0
AC	1	7/29/96	Trt	G	5	8	19	51	0	0	0	13	2	0	0
AF	1	7/30/96	Cnt	G	2	4	25	54	0	0	0	9	0	0	0
AF	1	7/30/96	Trt	G	1	0	53	38	0	0	0	8	0	0	0
BA	1	8/9/06	Cnt	G	2	0	0	22	0	7	0	9	1	0	0
BA	1	8/9/96	Trt	G	1	0	0	37	0	1	0	12	3	0	0
BB	1	8/19/96	Cnt	G	5	0	26	32	0	1	0	19	1	0	0
BB	1	8/19/96	Trt	G	1	0	0	57	0	12	0	17	0	0	0
BC	1	8/16/96	Cnt	G	5	0	17	28	0	0	0	41	2	0	0
BC	1	8/16/96	Trt	G	3	0	9	33	0	2	0	45	0	0	0
D	1	8/7/96	Cnt	E	1	2	1	78	0	6	0	12	0	0	0
D	1	8/7/96	Trt	E	0	0	3	83	0	3	0	9	0	0	0
M	1	8/6/96	Cnt	O	6	0	0	52	0	29	0	12	1	0	0
M	1	8/6/96	Trt	O	0	0	0	57	0	36	0	7	0	0	0
N	1	8/5/96	Cnt	O	2	0	0	43	0	33	0	2	0	0	0
N	1	8/5/96	Trt	O	0	0	2	49	0	38	0	10	1	0	0
Q	1	8/3/96	Cnt	O	1	2	0	47	0	0	0	3	0	0	0
Q	1	8/3/96	Trt	O	0	0	0	60	0	0	0	4	0	0	0
R	1	8/2/96	Cnt	O	0	0	0	39	0	0	0	7	0	0	0
R	1	8/2/96	Trt	O	0	0	0	47	0	0	0	3	0	0	0
U	1	8/1/96	Cnt	G	1	23	27	31	0	3	0	7	0	0	0
U	1	8/1/96	Trt	G	1	35	31	29	0	2	0	0	0	0	0
X	1	7/31/96	Cnt	G	2	23	19	35	0	1	0	7	0	0	0
X	1	7/31/96	Trt	G	0	13	15	41	0	8	0	3	0	0	0

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix C Table 14.

17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
0	0	0	0	0	0	0	64	18	13	3	0	2	0	0	0	0
0	0	0	0	0	0	0	62	23	11	2	1	1	0	0	0	0
0	0	0	0	0	0	0	50	35	10	0	5	0	0	0	0	0
0	0	0	0	0	0	0	58	30	10	0	2	0	0	0	0	0
5	0	0	0	0	0	0	74	26	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	50	35	10	0	5	0	0	0	0	0
0	21	9	0	0	0	0	40	35	4	1	20	0	0	0	0	0
0	25	5	0	0	0	0	46	16	28	2	7	1	0	0	0	0
0	24	3	0	0	0	0	69	30	0	0	0	0	0	0	1	0
0	20	11	0	0	0	0	64	26	0	0	8	1	0	0	1	0
0	4	13	0	0	0	0	56	41	2	0	0	0	0	0	0	10
0	19	7	0	0	0	0	74	12	6	3	0	0	0	0	5	0
0	0	0	0	0	0	0	94	6	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	85	14	0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	92	6	2	0	0	0	0	0	0	0
0	0	0	0	0	0	0	56	7	36	1	0	0	0	0	0	0
0	0	0	0	0	0	0	36	10	2	0	52	0	0	0	0	0
0	0	0	0	0	0	0	44	20	0	1	32	0	2	1	0	0
0	0	0	0	29	0	0	95	5	0	0	0	0	0	0	0	0
0	0	0	0	0	34	0	88	11	0	1	0	0	0	0	0	0
0	0	0	0	0	45	0	84	11	1	0	0	0	0	0	0	0
0	0	0	0	0	48	0	70	23	0	1	0	0	0	0	0	0
0	0	0	0	0	0	0	79	20	0	0	1	0	0	0	0	0
0	0	0	0	0	0	0	89	8	0	0	3	0	0	0	0	0
0	0	0	0	0	0	0	80	16	2	0	2	0	0	0	0	0
0	0	0	0	0	0	0	71	28	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	33	50	11	5	0	0	0	0	0	0
0	0	0	0	0	0	0	38	35	22	5	0	0	0	0	0	0
0	1	0	0	2	0	0	49	38	4	0	9	0	0	0	0	0
0	0	0	2	0	0	0	58	30	10	0	2	0	0	0	0	0
0	2	0	0	4	0	0	41	53	3	0	0	0	0	0	0	0
0	0	0	0	0	0	0	66	34	0	0	0	0	0	0	0	0
0	11	11	0	0	0	37	25	43	0	5	22	0	0	0	0	0
0	0	10	0	0	0	36	17	42	4	4	32	0	0	0	0	0
0	7	9	0	0	0	0	57	7	8	4	20	2	0	0	2	0
0	0	13	0	0	0	0	63	10	5	3	19	0	0	0	0	0
0	0	7	0	0	0	0	80	2	4	0	14	0	0	0	0	0
0	0	8	0	0	0	0	71	3	2	1	23	0	0	0	0	0
0	0	0	0	0	0	0	81	14	0	5	0	0	0	0	0	0
0	2	0	0	0	0	0	76	17	0	7	0	0	0	0	0	0
0	0	0	0	0	0	0	58	29	9	4	0	0	0	0	0	0
0	0	0	0	0	0	0	68	21	5	6	0	0	0	0	0	0
0	20	0	0	0	0	0	33	34	5	5	20	0	2	0	1	0
0	0	0	0	0	0	0	16	46	5	2	28	0	2	0	0	0
0	0	0	0	47	0	0	57	36	0	3	0	0	0	0	0	0
0	0	0	0	36	0	0	51	40	0	2	0	0	0	0	0	0
0	0	0	0	54	0	0	65	29	0	4	0	0	0	0	0	0
0	0	0	0	50	0	0	70	23	0	2	0	0	0	0	0	0
0	0	0	0	8	0	0	76	22	0	0	0	0	0	0	0	0
0	0	0	0	2	0	0	78	22	0	0	0	0	0	0	0	0
0	0	0	0	12	0	0	67	33	0	0	0	0	0	0	0	0
0	0	0	0	19	0	0	66	19	0	0	14	0	0	0	0	0

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix C Table 14.

34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
0	0	0	0	0	0	0	46	39	34	46	42	34	45	43	36
0	0	0	0	0	0	0	46	41	34	44	39	34	42	32	32
0	0	0	0	0	0	0	40	33	35	31	30	34	23	31	26
0	0	0	0	0	0	0	44	41	37	42	29	34	34	34	32
0	0	0	0	0	0	0	56	38	21	64	38	35	62	43	34
0	0	0	0	0	0	0	48	39	36	74	42	37	59	41	25
0	0	0	0	0	0	0	51	38	35	37	29	31	22	13	23
0	0	0	0	0	0	0	47	47	40	39	36	34	43	20	27
0	0	0	0	0	0	0	37	35	35	30	18	32	28	10	33
0	0	0	0	0	0	0	29	31	27	43	38	31	21	13	5
0	0	1	0	0	0	0	44	23	47	39	16	17	35	30	32
0	0	0	0	0	0	0	33	26	26	33	28	19	30	28	31
0	0	0	0	0	0	0	38	41	25	28	25	35	28	21	28
0	0	0	0	0	0	0	23	26	31	24	24	30	25	19	29
0	0	0	0	0	0	0	26	17	25	28	20	20	23	15	16
0	0	0	0	0	0	0	20	14	23	20	15	14	24	18	17
0	0	0	0	0	0	0	67	67	50	66	38	26	63	34	29
0	0	0	0	0	0	0	44	51	40	52	46	39	60	30	32
0	0	0	0	0	0	0	46	37	39	50	39	46	51	41	39
0	0	0	0	0	0	0	48	35	34	54	40	43	49	40	37
4	0	0	0	0	0	0	56	48	40	57	51	43	64	45	50
6	0	0	0	0	0	0	59	41	44	61	43	34	61	45	44
0	0	0	0	0	0	0	69	52	43	47	31	27	48	30	49
0	0	0	0	0	0	0	59	24	28	47	44	39	53	33	37
0	0	0	0	0	0	0	44	35	34	44	37	39	66	36	35
0	1	0	0	0	0	0	47	32	32	52	39	31	50	35	31
0	0	0	0	1	0	0	46	42	39	44	44	37	41	40	41
0	0	0	0	0	0	0	45	36	35	46	41	33	43	38	32
0	0	0	0	0	0	0	57	42	37	41	32	32	37	32	36
0	0	0	0	0	0	0	57	43	38	39	18	34	34	30	33
0	0	0	3	0	0	0	52	41	37	60	56	43	42	40	37
0	0	0	0	0	0	0	61	42	37	66	45	38	62	54	45
0	0	0	0	2	2	1	57	19	26	48	22	28	34	18	26
0	0	0	1	0	0	0	60	29	31	44	18	26	26	17	25
0	0	0	0	0	0	0	37	31	50	27	14	37	27	15	37
0	0	0	0	0	0	0	38	36	19	35	19	41	23	13	35
0	0	0	0	0	0	0	32	31	33	23	12	22	26	9	29
0	0	0	0	0	0	0	29	25	45	34	20	27	33	28	22
0	0	0	0	0	0	0	52	50	50	50	49	49	50	43	47
0	0	0	0	0	0	0	39	70	52	40	42	53	41	41	44
0	0	0	0	0	0	0	22	16	13	23	15	15	23	15	14
0	0	0	0	0	0	0	20	13	14	17	19	16	20	13	17
0	0	0	0	0	0	0	127	59	46	72	37	26	68	35	35
0	0	0	0	1	0	0	114	69	51	90	37	35	59	44	30
0	0	1	3	3	0	0	56	49	46	57	44	44	54	49	42
0	0	0	7	7	0	0	51	47	41	50	53	51	50	46	40
0	0	0	2	2	0	0	43	42	38	52	39	38	48	36	37
0	0	0	5	5	0	0	60	43	38	62	48	40	58	66	51
0	0	0	2	2	0	0	59	49	41	63	46	35	56	41	32
0	0	0	0	0	0	0	70	43	38	60	46	25	46	31	36
0	0	0	0	0	0	0	19	45	39	50	62	32	59	36	37
0	0	0	1	1	0	0	55	42	26	62	46	39	58	37	32

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix C Table 14.

50	51	52	53	54	55	56	57	58	59	60	61	62	63	64
0.88	0.89	1.06	0.89	0.94	1.21	0.89	0.98	1.02	12.80	12.40	7.50	13.60	11.50	9.80
0.65	0.78	1.00	0.74	0.83	1.06	0.88	1.00	1.07	13.20	11.95	8.65	14.20	11.70	8.95
0.91	1.26	1.21	0.94	1.29	1.19	1.10	1.10	1.03	7.10	4.60	4.90	9.80	5.40	6.60
0.87	0.98	1.19	0.93	1.18	1.21	0.98	1.30	1.22	10.10	7.10	5.70	9.10	4.30	3.80
0.79	1.11	0.98	0.75	1.12	1.17	0.78	1.11	1.17	10.50	6.20	1.30	9.30	5.40	2.50
0.96	1.04	1.12	0.63	1.17	1.20	0.70	1.10	1.24	10.50	6.20	2.45	11.60	7.00	6.30
0.85	1.25	1.20	1.14	1.34	1.29	1.30	1.32	1.17	7.20	2.40	2.10	7.20	2.40	2.10
0.95	1.00	1.10	1.05	1.24	1.23	1.06	1.25	1.14	7.20	2.40	2.10	7.20	2.40	2.10
0.94	0.95	1.18	0.73	0.93	1.24	0.86	1.22	1.14	7.60	6.60	4.30	8.30	4.50	4.50
1.04	1.21	1.14	0.92	0.93	1.06	0.89	1.33	1.36	5.10	4.10	2.50	10.30	5.00	2.60
0.91	1.18	1.07	0.91	1.13	1.35	0.93	1.13	1.10	7.80	2.10	4.80	8.20	2.00	1.82
0.98	1.18	1.31	0.95	1.24	1.11	0.82	1.05	0.85	6.60	4.20	2.70	9.00	4.10	1.60
0.68	0.89	1.81	0.69	1.07	0.99	0.73	0.98	0.95	11.60	8.20	8.90	13.40	7.90	11.50
0.62	0.94	1.01	0.79	0.91	0.94	0.72	0.95	0.96	12.20	9.50	7.90	12.60	12.20	11.90
1.10	1.16	1.16	1.10	0.93	1.13	1.31	1.27	1.30	9.50	5.30	4.80	8.70	5.90	3.90
1.09	1.10	1.14	1.08	1.08	1.12	1.11	1.21	1.09	7.25	2.95	3.60	6.55	4.60	3.90
0.81	0.81	0.92	0.67	1.22	1.50	0.67	1.12	1.16	10.50	6.70	4.70	11.80	5.40	2.10
0.99	1.05	1.16	0.95	1.10	1.16	0.87	1.36	1.18	6.90	6.50	3.20	8.10	6.70	6.00
0.96	1.07	1.16	0.76	1.14	1.04	0.95	1.05	1.17	9.90	6.70	7.10	11.50	4.70	8.10
0.88	1.19	1.18	0.85	1.11	1.10	1.00	1.12	1.10	9.70	6.10	5.20	12.30	7.70	8.80
0.84	1.03	1.11	0.79	1.01	1.15	0.71	1.11	1.13	9.70	6.45	5.40	11.90	9.50	7.10
0.79	1.06	1.08	0.81	1.09	1.23	0.81	1.06	1.12	13.50	6.90	7.00	13.80	10.00	6.20
0.64	0.99	1.10	0.86	1.10	1.27	0.87	1.22	1.05	11.00	7.10	5.70	8.70	3.60	3.20
0.81	1.27	1.21	0.97	0.99	1.17	0.80	1.24	1.20	9.40	6.30	5.20	10.20	6.00	6.60
0.92	1.21	1.18	1.00	1.17	1.37	0.69	1.16	1.11	6.90	4.40	3.30	9.60	5.00	3.10
0.81	1.24	1.20	0.83	1.07	1.33	0.78	1.33	1.33	5.95	4.25	3.30	6.00	4.30	3.30
0.58	0.72	0.86	0.70	0.83	0.91	0.62	0.83	0.97	12.80	12.40	7.50	13.60	11.50	9.80
0.50	0.74	1.08	0.62	0.73	1.07	0.69	0.88	1.11	13.20	11.95	8.70	14.20	11.70	9.00
0.75	1.08	1.13	1.08	1.37	1.31	1.00	1.18	1.11	7.10	4.60	4.90	9.80	5.40	6.60
0.82	0.98	1.24	0.91	1.50	1.16	1.00	1.30	0.97	10.10	7.10	5.70	9.20	4.30	3.80
1.04	1.00	1.10	0.85	0.94	1.07	1.17	1.21	1.13	10.50	6.20	1.30	9.30	5.40	2.50
0.94	1.03	1.11	0.73	1.01	1.11	0.85	0.87	1.01	10.50	6.20	2.45	11.60	7.00	6.30
0.74	1.53	1.31	0.58	1.26	1.25	1.14	1.25	1.14	7.20	2.40	2.10	7.20	2.40	2.10
0.91	1.05	1.12	0.93	1.88	1.59	0.96	1.08	1.08	7.20	2.40	2.10	7.20	2.40	2.10
0.78	0.96	0.96	0.96	0.80	0.96	0.94	1.15	0.86	7.60	6.60	4.30	8.30	4.50	4.50
1.01	0.92	0.94	0.76	1.05	1.08	0.94	1.16	1.02	5.10	4.10	2.50	10.30	5.00	2.60
0.68	0.97	0.93	0.73	0.97	0.94	0.80	1.08	1.25	7.80	2.10	4.80	8.20	2.00	1.80
0.85	0.18	0.91	0.87	0.97	1.11	0.73	1.09	0.95	6.60	4.20	2.70	9.00	4.10	1.60
0.64	0.85	0.80	0.77	0.81	0.94	0.52	0.86	0.87	11.60	8.20	8.90	13.40	7.90	11.50
0.91	0.78	0.82	0.80	0.90	0.76	0.55	0.85	0.78	12.20	9.50	7.90	12.60	12.20	11.90
0.62	0.57	1.01	0.79	0.83	0.78	0.86	0.87	0.73	9.50	5.30	4.80	8.70	5.90	3.90
0.60	0.63	0.70	0.48	0.85	0.75	0.86	0.62	1.28	7.25	2.95	3.60	6.55	4.60	3.90
0.51	0.91	1.07	0.66	1.11	1.21	0.57	1.07	1.08	10.50	6.70	4.70	11.80	5.40	2.10
0.49	0.61	0.95	0.54	1.11	1.16	0.57	0.93	1.21	6.90	6.50	3.20	8.10	6.70	6.00
0.76	0.91	1.01	0.80	1.10	1.06	0.76	0.96	1.04	9.90	6.70	7.10	11.50	4.70	8.10
0.82	0.98	1.09	0.89	0.92	0.94	0.85	1.02	1.06	9.70	6.10	5.20	12.30	7.70	8.80
0.97	1.02	1.22	0.91	1.09	1.21	0.87	1.18	0.81	9.70	6.45	5.40	11.90	9.50	7.10
0.90	0.97	1.09	0.82	0.83	1.12	0.80	0.86	1.01	13.50	6.90	7.00	13.80	10.00	6.20
0.83	0.99	1.10	0.97	1.04	1.24	0.91	1.16	1.15	11.00	7.10	5.70	8.70	3.60	3.20
0.76	1.07	1.13	0.78	1.04	1.29	1.06	1.03	1.20	9.40	6.30	5.20	10.20	6.00	6.60
1.12	1.09	1.14	1.05	0.81	1.22	1.02	1.13	1.22	6.90	4.40	3.30	9.60	5.00	3.10
0.83	1.08	1.28	0.82	1.03	1.18	0.89	1.09	1.28	5.95	4.25	3.30	6.00	4.30	3.30

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix C Table 14.

65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
16.20	11.10	9.60	43	39	17	13.2	42	0.88	1.1	0.1	1.1	11	25	3	2
10.00	10.60	19.00	46	33	21	13.2	46	0.89	10.1	9.3	0.8	8	28	3	2
10.40	5.50	4.50	57	28	15	7.1	31	0.98	1.7	-0.8	2.5	14	52	3	3
9.60	5.70	5.80	55	29	16	7.1	40	0.93	7.6	5.1	2.5	68	60	3	3
10.50	6.20	2.50	53	33	14	10.4	61	0.77	2.0	0.3	1.7	58	47	3	1
10.50	6.20	3.60	58	29	13	10.4	60	0.76	12.4	6.8	5.6	60	46	3	3
7.20	2.40	2.10	68	22	10	.	37	1.10	2.3	-3.2	5.5	40	51	2	3
7.20	2.40	2.10	65	25	11	.	43	1.02	17.1	12.2	4.9	32	53	3	3
10.10	1.60	4.20	61	27	12	.	32	0.84	-1.2	-7.1	5.9	48	44	2	3
5.70	3.00	0.50	64	25	12	.	31	0.95	8.0	7.0	1.0	44	39	2	3
7.60	4.00	4.10	59	28	13	.	39	0.92	2.8	-0.6	3.4	41	44	3	2
7.80	4.20	4.30	65	23	13	.	32	0.92	4.9	8.7	-3.9	36	42	3	3
13.80	7.90	11.50	55	32	13	13.1	31	0.70	0.3	-4.9	5.2	42	49	3	2
14.70	9.10	11.60	57	29	14	13.1	24	0.71	6.4	4.2	2.2	17	43	3	2
6.70	3.50	3.40	66	22	12	7.4	26	1.17	1.1	-0.1	1.2	0	10	3	2
7.25	4.55	4.15	64	24	12	7.4	18	1.11	9.6	8.2	1.4	4	5	3	2
9.50	5.30	4.00	62	27	11	9.7	67	0.74	3.6	0.7	2.9	61	66	2	2
11.10	2.80	2.60	62	27	12	9.7	52	0.94	32.3	9.8	22.5	61	55	2	2
13.80	7.00	9.40	52	33	15	11.3	49	0.89	3.7	1.6	2.1	32	48	2	1
10.70	8.30	9.50	52	33	15	11.3	50	0.91	9.1	7.1	2.1	43	46	2	1
15.00	8.50	5.90	55	28	17	12.8	59	0.78	1.1	0.2	0.9	52	48	3	1
13.00	8.50	6.40	50	33	17	12.8	60	0.80	6.7	4.4	2.3	52	52	3	1
9.80	5.60	5.20	54	33	13	10.2	55	0.79	-18.4	2.3	-20.8	41	70	2	1
9.80	5.60	5.20	52	35	13	10.2	53	0.86	12.3	13.1	-0.9	56	46	2	1
8.90	3.50	3.50	57	32	11	6.9	51	0.87	-0.4	-0.3	-0.2	52	38	2	1
6.00	4.30	3.30	60	29	11	6.9	50	0.81	5.8	5.1	0.8	49	40	2	1
16.20	11.10	9.60	43	39	17	13.2	44	0.63	0.6	0.1	0.5	66	32	3	2
10.00	10.60	19.00	46	33	21	13.2	45	0.60	8.4	4.8	3.6	0	39	3	2
10.40	5.50	4.50	57	28	15	7.1	45	0.94	4.9	-0.6	5.5	23	60	3	3
9.60	5.70	5.80	55	29	16	7.1	43	0.91	13.7	6.3	7.5	26	62	3	1
10.50	6.20	2.50	53	33	14	10.4	51	1.02	2.6	0.8	1.8	44	69	3	1
10.50	6.20	3.60	58	29	13	10.4	63	0.84	7.1	1.5	5.6	74	62	3	1
7.20	2.40	2.10	68	22	10	.	46	0.82	3.6	1.4	2.2	11	63	2	3
7.20	2.40	2.10	65	25	11	.	43	0.93	14.9	14.5	0.4	75	67	3	3
10.10	1.60	4.20	61	27	12	.	30	0.89	1.7	-1.4	3.2	21	52	2	3
5.70	3.00	0.50	64	25	12	.	32	0.90	5.1	5.5	-0.3	27	53	2	2
7.60	4.00	4.10	59	28	13	.	27	0.74	2.7	0.6	2.1	23	42	3	3
7.80	4.20	4.30	65	23	13	.	32	0.82	6.9	1.9	4.9	26	41	3	3
13.80	7.90	11.50	55	32	13	13.1	51	0.64	1.9	0.3	1.5	19	63	3	2
14.70	9.10	11.60	57	29	14	13.1	40	0.75	5.0	3.8	1.3	29	40	3	2
6.70	3.50	3.40	66	22	12	7.4	23	0.76	2.7	0.3	2.5	0	9	3	2
7.25	4.55	4.15	64	24	12	7.4	19	0.65	7.9	5.2	2.7	8	15	3	2
9.50	5.30	3.95	62	27	11	9.7	89	0.58	3.4	-1.0	4.5	72	99	2	2
11.10	2.80	2.60	62	27	12	9.7	88	0.53	17.7	9.3	8.4	75	118	2	2
13.80	7.00	9.40	52	33	15	11.3	56	0.84	2.1	0.5	1.7	30	57	2	1
10.70	8.30	9.50	52	33	15	11.3	50	0.85	15.4	13.5	1.9	83	54	2	1
15.00	8.50	5.90	55	28	17	12.8	48	0.92	3.3	-0.4	3.7	48	41	3	1
13.00	8.50	6.40	50	33	17	12.8	60	0.84	6.7	3.9	2.9	41	51	3	1
9.80	5.60	5.20	54	33	13	10.2	49	0.99	3.3	-0.2	3.5	194	53	3	1
9.80	5.60	5.20	52	35	13	10.2	59	0.87	7.3	3.9	3.4	141	63	3	1
8.90	3.50	3.45	57	32	11	6.9	55	1.06	3.3	-0.6	3.9	58	84	2	1
6.00	4.30	3.30	60	29	11	6.9	58	0.85	7.7	3.9	3.8	31	58	2	1

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix C Table 15. Data for 1996 field season with results from ROOTEDGE - Root length analyses. Variables correspond for each column number at top of each column in Appendix B Table 16.

Column number	Variable description for Rootedge data file.
1	Identification code
2	Plot identification letter
3	Date (month)
4	Season: 1 = irrigated to field capacity; 2 = not irrigated
5	Treatment: Cnt = no hoof simulator applied; Trt = hoof simulator applied
6	Use code: E = Exclosure; O = Open to grazing in 1988 (was an exclosure); G = Long term grazing
7	Root length category 1 (<0.1 root width mm) cm
8	Root length category 2 (0.1<0.2 root width mm) cm
9	Root length category 3 (0.2<0.3 root width mm) cm
10	Root length category 4 (0.3<0.4 root width mm) cm
11	Root length category 5 (0.4<0.5 root width mm) cm
12	Root length category 6 (0.5<0.6 root width mm) cm
13	Root length category 7 (0.6<0.7 root width mm) cm
14	Root length category 8 (0.7<0.8 root width mm) cm
15	Root length category 9 (0.8<0.9 root width mm) cm
16	Root length category 10 (0.9<1.0 root width mm) cm
17	Root length category 11 (1.0<1.2 root width mm) cm
18	Root length category 12 (2.0<3.0 root width mm) cm
19	Root length category 13 (>3.0 root width mm) cm
20	Total root length (all categories (1-13) combined) cm
21	Soil moisture at 0-10 cm depth (%)
22	Soil bulk density at 0-10 cm depth (gcm^{-3})
23	Soil organic matter content at 0-10 cm depth (%)
24	Soil texture sand (%)
25	Soil texture silt (%)
26	Soil texture clay (%)
27	Average soil organic matter content (all sample combined) (%)
28	Soil moisture near soil surface (%)
29	Soil bulk density near soil surface (gcm^{-3})
30	Hoof impression from mechanical hoof simulator (mm)
31	Difference in soil surface level with no mechanical hoof simulator (mm)
32	Difference in soil created by mechanical hoof simulator (mm)
33	Soil shear strength (kNm^{-2})
34	Soil moisture content in shear soil sample (%)
35	Soil type: 1 = sands; 2 = loamy sand; 3 = sandy loam
36	Soil shear strength pressure (initial value, lb in^{-2})
37	Soil shear strength measured in Pascals

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix C Table 15. Data for 1996 field season with results from ROOTEDGE - Root length analyses. Variables correspond for each column number at top of each column in Appendix B Table 16.

Column number	Variable description for Rootedge data file.
38	Soil shear strength measured (lb in^{-2})
39	Soil shear strength measured in K Pascals
40	Canopy cover of *Alnus incana* (%)
41	Canopy cover of *Carex aquatilis* (%)
42	Canopy cover of *Carex utriculata* (%)
43	Canopy cover of grass species combined (%)
44	Canopy cover of *Juncus arcticus* (%)
45	Canopy cover of combined forb species (%)
46	No canopy cover recorded (%)
47	Canopy cover of *Poa* species (%)
48	Canopy cover of *Salix lutea* (%)
49	Canopy cover of *Salix* species (%)
50	Canopy cover of *Salix planifolia*
51	Canopy cover of *Salix exigua* (%)
52	Canopy cover of *Carex microptera* (%)
53	Canopy cover of *Carex nebrascensis* (%)
54	Canopy cover of *Carex* sp. (%)
55	Canopy cover of *Salix glauca* (%)
56	Root biomass (g/cm^3)
57	Root length density (cm/cm^3)
58	Clusters of vegetation groups number 1
59	Clusters of vegetation groups number 2

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix C Table 16.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
267	A	6	2	Cnt	E	49	427	492	1303	1839	176	576	81	3	35
268	A	8	1	Cnt	E	423	2533	3967	5697	2874	413	202	106	453	146
269	A	6	2	Trt	E	19	251	330	638	677	267	17	17	66	1
270	A	8	1	Trt	E	161	1770	1953	2837	3238	1636	1290	99	54	15
271	AC	6	2	Cnt	G	44	414	496	527	621	425	312	1513	343	173
272	AC	7	1	Cnt	G	60	484	490	626	565	279	475	200	239	83
273	AC	6	2	Trt	G	57	520	606	769	608	357	326	577	241	248
274	AC	7	1	Trt	G	40	355	409	605	343	220	315	109	172	61
275	AF	6	2	Cnt	G	2	182	241	300	570	366	71	123	14	47
276	AF	7	1	Cnt	G	10	160	123	94	85	214	70	249	43	34
277	AF	6	2	Trt	G	2	224	222	421	474	541	219	112	70	102
278	AF	7	1	Trt	G	2	233	336	532	313	221	86	16	33	0
279	BA	6	2	Cnt	G	36	332	303	441	527	223	92	134	3	12
280	BA	8	1	Cnt	G	31	225	342	374	192	222	46	14	4	2
281	BA	6	2	Trt	G	39	288	681	751	401	200	33	131	27	7
282	BA	8	1	Trt	G	15	134	102	162	203	254	458	168	69	14
283	BB	6	2	Cnt	G	12	183	214	221	358	181	287	39	52	6
284	BB	8	1	Cnt	G	176	1005	741	1338	1858	1428	918	2357	1138	1137
285	BB	6	2	Trt	G	17	175	171	430	422	686	315	20	13	0
286	BB	8	1	Trt	G	109	871	562	514	505	369	771	1053	666	289
287	BC	6	2	Cnt	G	35	324	339	364	359	335	209	75	5	9
288	BC	8	1	Cnt	G	.	.	.	.	.	.	.	.	.	.
289	BC	6	2	Trt	G	2	229	276	350	561	130	119	16	26	0
290	BC	8	1	Trt	G	163	1042	746	739	1085	1485	1818	915	365	431
291	D	7	2	Cnt	E	41	342	450	536	381	108	15	1	2	7
292	D	8	1	Cnt	E	49	218	233	139	103	191	484	10	21	771
293	D	7	2	Trt	E	25	185	176	768	518	181	52	2	132	23
294	D	8	1	Trt	E	38	279	329	396	291	160	59	24	18	0
295	M	6	2	Cnt	O	53	705	893	910	915	717	681	444	111	131
296	M	8	1	Cnt	O	31	503	667	666	578	553	608	218	700	259
297	M	6	2	Trt	O	28	420	546	557	673	672	659	490	221	140
298	M	8	1	Trt	O	27	279	307	263	277	438	292	369	172	172
299	N	6	2	Cnt	O	61	666	797	1077	1345	1382	1196	501	274	111
300	N	8	1	Cnt	O	41	653	819	836	893	1258	1080	743	644	1021
301	N	6	2	Trt	O	4	89	124	241	27	37	27	14	2	11
302	N	8	1	Trt	O	2	49	119	101	36	37	28	4	13	9
303	Q	6	2	Cnt	O	26	300	291	698	246	248	39	35	55	154
304	Q	8	1	Cnt	O	19	267	307	415	728	560	63	37	29	2
305	Q	6	2	Trt	O	26	225	215	254	210	475	115	32	257	36
306	Q	8	1	Trt	O	17	158	162	148	345	236	118	18	142	267
307	R	6	2	Cnt	O	2	255	409	508	352	81	66	3	48	45
308	R	8	1	Cnt	O	1	260	388	561	615	146	144	10	7	47
309	R	6	2	Trt	O	1	266	314	359	434	289	59	28	1	108
310	R	8	1	Trt	O	3	162	137	148	108	188	146	20	47	84
311	U	6	2	Cnt	G	22	188	244	476	1230	134	89	12	65	9
312	U	8	1	Cnt	G	30	246	314	1877	400	355	45	23	9	2
313	U	6	2	Trt	G	26	259	293	770	1085	209	73	68	1	6
314	U	8	1	Trt	G	46	250	439	472	397	186	89	142	4	4
315	X	6	2	Cnt	G	23	297	292	993	653	238	92	18	67	2
316	X	7	1	Cnt	G	41	329	510	925	691	258	122	13	9	3
317	X	6	2	Trt	G	22	245	348	568	378	132	41	7	7	11
318	X	7	1	Trt	G	24	306	355	706	674	144	74	67	13	14

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix C Table 16.

17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
57	0	0	5038	46	0.88	12.80	77	10	13	13.2	42	0.88	1.0	1.1	-0.1
126	0	0	16940	46	0.58	12.80	77	10	13	13.2	44	0.63	0.6	0.5	0.0
11	0	0	2293	46	0.65	13.20	77	10	13	13.2	46	0.89	-0.5	6.5	-7.0
20	0	0	13073	45	0.50	13.20	77	10	13	13.2	45	0.60	8.3	3.6	4.7
557	185	111	5719	40	0.91	7.10	65	13	22	7.1	31	0.98	1.6	2.6	-1.0
539	51	0	4088	57	0.75	7.10	65	13	22	7.1	45	0.94	4.8	5.4	-0.6
1465	20	12	5805	44	0.87	10.10	59	22	19	7.1	40	0.93	7.5	2.5	5.0
318	61	0	3006	57	0.82	10.10	59	22	19	7.1	43	0.91	13.7	7.5	6.2
152	0	0	2066	56	0.79	10.50	77	10	13	10.4	61	0.77	1.8	1.6	0.2
139	0	0	1219	52	1.04	10.50	77	10	13	10.4	51	1.02	2.5	1.8	0.7
70	13	0	2469	48	0.96	10.50	77	10	13	10.4	60	0.76	12.4	5.7	6.7
56	0	0	1827	61	0.94	10.50	77	10	13	10.4	63	0.84	7.1	5.4	1.6
20	10	0	2133	51	0.85	7.20	81	11	8	.	37	1.10	2.3	5.5	-3.2
1	0	0	1451	57	0.74	7.20	81	11	8	.	46	0.82	3.7	2.2	1.5
6	0	0	2565	47	0.95	7.20	75	11	14	.	43	1.02	17.2	5.0	12.1
44	0	0	1624	60	0.91	7.20	75	11	14	.	43	0.93	14.7	0.5	14.2
19	24	0	1595	37	0.94	7.60	82	11	7	.	32	0.84	-0.7	5.0	-5.6
335	1	0	12431	37	0.78	7.60	82	11	7	.	30	0.89	1.7	3.2	-1.4
87	0	0	2336	29	1.04	5.10	82	11	7	.	31	0.95	6.9	0.8	6.1
2115	30	0	7856	38	1.01	5.10	82	11	7	.	32	0.90	5.1	-0.3	5.5
2	0	0	2056	44	0.91	7.80	72	17	11	.	39	0.92	2.5	3.4	-0.9
.	.	.	.	32	0.68	7.80	72	17	11	.	27	0.74	2.7	3.9	-1.1
32	0	1	1741	33	0.98	6.60	76	15	9	.	32	0.92	4.6	-3.8	8.5
260	15	0	9063	29	0.85	6.60	76	15	9	.	32	0.82	6.8	4.9	1.9
5	0	0	1889	38	0.68	11.60	73	15	12	13.1	31	0.70	0.2	5.1	-4.9
7	0	0	2225	52	0.64	11.60	73	15	12	13.1	51	0.64	1.2	1.6	-0.4
25	0	0	2085	23	0.62	12.20	73	15	12	13.1	24	0.71	6.4	2.4	4.0
2	2	0	1599	39	0.91	12.20	73	15	12	13.1	40	0.75	4.9	1.2	3.8
276	0	0	5836	26	1.10	9.50	76	10	14	7.4	26	1.17	1.1	1.2	-0.1
619	137	16	5555	22	0.62	9.50	76	10	14	7.4	23	0.76	2.7	2.4	0.4
643	208	0	5257	20	1.09	7.25	76	10	14	7.4	18	1.11	-33.3	-38.3	5.0
255	34	0	2883	20	0.60	7.25	76	10	14	7.4	19	0.65	7.7	2.6	5.0
349	55	22	7836	67	0.81	10.50	64	11	25	9.7	67	0.74	3.6	2.8	0.7
1678	61	14	9741	127	0.51	10.50	64	11	25	9.7	89	0.58	3.4	4.5	-1.0
52	38	0	663	44	0.99	6.90	64	11	25	9.7	52	0.94	22.3	-8.3	30.7
21	65	0	65	114	0.49	6.90	64	11	25	9.7	88	0.53	17.7	8.4	9.3
144	0	0	2236	46	0.96	9.90	64	22	14	11.3	49	0.89	3.5	2.1	1.5
127	4	0	2558	56	0.76	9.90	64	22	14	11.3	56	0.84	1.9	1.6	0.4
188	1	0	2034	48	0.88	9.70	64	22	14	11.3	50	0.91	9.1	2.0	7.1
109	21	0	1742	51	0.82	9.70	64	22	14	11.3	50	0.85	15.4	1.9	13.5
24	0	0	1793	56	0.84	9.70	63	22	15	12.8	59	0.78	0.9	0.8	0.1
82	2	0	2263	43	0.97	9.70	63	22	15	12.8	48	0.92	3.2	3.7	-0.5
140	0	0	1998	59	0.79	13.50	63	22	15	12.8	60	0.80	6.6	2.3	4.3
201	0	0	1243	60	0.90	13.50	63	22	15	12.8	60	0.84	6.6	2.9	3.8
18	0	0	2488	69	0.64	11.00	67	16	17	10.2	55	0.79	-18.4	-20.7	2.3
7	0	0	3307	59	0.83	11.00	67	16	17	10.2	49	0.99	3.2	3.6	-0.4
37	0	0	2825	59	0.81	9.40	67	16	17	10.2	53	0.86	12.2	-0.9	13.1
50	0	0	2079	70	0.76	9.40	67	16	17	10.2	59	0.87	7.3	3.3	4.0
34	0	0	2708	44	0.92	6.90	63	25	12	6.9	51	0.87	-0.3	-0.1	-0.2
0	0	0	2902	19	1.12	6.90	63	25	12	6.9	55	1.06	3.1	4.0	-0.9
2	0	0	1761	47	0.81	5.95	63	25	12	6.9	50	0.81	5.0	0.9	4.1
83	0	0	2458	55	0.83	5.95	63	25	12	6.9	58	0.85	7.7	0.1	7.6

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix C Table 16.

33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
11	25	3	12	80500	1.5361	11	9	0	10	27	22	14	18	0	0
66	32	3	73	500250	9.5459	66	6	0	0	58	9	22	1	4	0
8	28	3	8	57500	1.0972	8	6	0	7	24	38	16	9	0	0
-3	39	3	-4	-25875	-0.4938	-3	2	0	0	62	8	18	9	1	0
14	52	3	15	103500	1.9750	14	4	10	5	21	0	23	1	36	0
23	60	3	25	172500	3.2917	23	2	5	5	50	0	19	1	0	0
68	60	3	75	517500	9.8751	68	3	12	9	44	0	26	1	5	0
26	62	3	28	195500	3.7306	26	5	8	19	51	0	13	2	0	0
58	47	3	48	331200	6.3201	44	6	16	12	24	20	12	5	0	0
44	69	3	64	439875	8.3938	58	2	4	25	54	0	9	0	0	0
60	46	3	81	558900	10.6651	74	4	10	5	21	0	23	1	36	0
74	62	3	66	457125	8.7230	60	1	0	53	38	0	8	0	0	0
40	51	2	44	301875	5.7605	40	4	0	13	34	0	18	1	0	0
11	63	2	13	86250	1.6459	11	2	0	0	22	7	9	1	0	0
32	53	3	35	241500	4.6084	32	6	0	15	36	0	0	3	0	0
75	67	3	83	572700	10.9284	75	1	0	0	37	1	12	3	0	0
48	44	2	53	362250	6.9126	48	4	0	3	20	12	19	7	4	0
21	52	2	23	158700	3.0284	21	5	0	26	32	1	19	1	0	0
44	39	2	49	336375	6.4188	44	14	1	4	15	21	13	1	0	0
27	53	2	30	207000	3.9500	27	1	0	0	57	12	17	0	0	0
41	44	3	45	310500	5.9251	41	3	2	5	32	29	10	2	0	0
23	42	3	25	172500	3.2917	23	5	0	17	28	0	41	2	0	0
36	42	3	40	276000	5.2667	36	4	2	1	37	6	24	0	0	0
26	41	3	29	198375	3.7855	26	3	0	9	33	2	45	0	0	0
42	49	3	46	316250	6.0348	42	1	0	2	61	24	12	0	0	0
19	63	3	21	144900	2.7650	19	1	2	1	78	6	12	0	0	0
17	43	3	19	132250	2.5236	17	2	1	5	50	26	16	0	0	0
29	40	3	32	217350	4.1475	29	0	0	3	83	3	9	0	0	0
-3	10	3	-3	-23000	-0.4389	-3	13	0	0	27	53	4	3	0	0
-5	9	3	-6	-40250	-0.7681	-5	6	0	0	52	29	12	1	0	0
4	5	3	4	28750	0.5486	4	13	0	0	49	24	9	5	0	0
8	15	3	9	63250	1.2070	8	0	0	0	57	36	7	0	0	0
61	66	2	68	465750	8.8876	61	5	0	0	18	49	13	7	0	8
72	99	2	79	545100	10.4018	72	2	0	0	43	33	2	0	0	0
61	55	2	68	465750	8.8876	61	13	0	0	14	58	6	1	0	0
75	118	2	83	572700	10.9284	75	0	0	2	49	38	10	1	0	0
32	48	2	35	241500	4.6084	32	15	0	0	47	0	8	1	0	0
30	57	2	33	227700	4.3450	30	1	2	0	47	0	3	0	0	0
43	46	2	48	327750	6.2542	43	3	0	0	55	1	6	1	0	0
83	54	2	91	627900	11.9818	83	0	0	0	60	0	4	0	0	0
52	48	3	58	396750	7.5709	52	8	0	0	38	0	9	0	0	0
48	41	3	53	365700	6.9784	48	0	0	0	39	0	7	0	0	0
52	52	3	58	396750	7.5709	52	8	0	0	38	0	5	1	0	0
41	51	3	45	310500	5.9251	41	0	0	0	47	0	3	0	0	0
41	70	2	45	310500	5.9251	41	10	28	20	19	5	9	9	0	0
194	53	3	213	146970	28.0453	194	1	23	27	31	3	7	0	0	0
56	46	2	61	422625	8.0647	56	9	31	23	24	0	5	8	0	0
141	63	3	155	106720	20.3647	141	1	35	31	29	2	0	0	0	0
52	38	2	57	393875	7.5161	52	17	23	8	22	8	11	11	0	0
58	84	2	64	441600	8.4268	58	2	23	19	35	1	7	0	0	0
49	40	2	54	373750	7.1320	49	7	28	11	23	13	10	8	0	0
31	58	2	35	239200	4.5645	31	0	13	15	41	8	3	0	0	0

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Appendix C Table 16.

49	50	51	52	53	54	55	56	57	58	59
0	0	0	0	0	0	0	0.0128	19.458	J	2
0	0	0	0	0	0	0	0.0081	11.848	J	2
0	0	0	0	0	0	0	0.0099	16.064	J	2
0	0	0	0	0	0	0	0.0056	12.307	J	2
0	0	0	0	0	0	0	0.0040	6.525	G	3
0	1	0	0	2	0	0	0.0064	12.477	G	3
0	0	0	0	0	0	0	0.0089	10.920	G	3
0	0	0	2	0	0	0	0.0057	9.203	G	1
5	0	0	0	0	0	0	0.0224	39.058	G	1
0	2	0	0	4	0	0	0.0096	13.324	G	1
0	0	0	0	0	0	0	0.0152	38.512	G	3
0	0	0	0	0	0	0	0.0100	26.984	G	1
0	21	9	0	0	0	0	0.0070	4.802	G	3
0	11	11	0	0	0	37	0.0052	5.168	G	3
0	25	5	0	0	0	0	0.0076	5.898	G	3
0	0	10	0	0	0	36	0.0027	4.412	G	3
0	24	3	0	0	0	0	0.0079	11.056	G	3
0	7	9	0	0	0	0	0.0038	9.157	G	3
0	20	11	0	0	0	0	0.0092	13.055	G	3
0	0	13	0	0	0	0	0.0075	13.563	G	2
0	4	13	0	0	0	0	0.0073	15.703	G	2
0	0	7	0	0	0	0	0.0091	13.463	G	3
0	19	7	0	0	0	0	0.0099	17.344	G	3
0	0	8	0	0	0	0	0.0123	9.188	G	3
0	0	0	0	0	0	0	0.0109	18.490	G	2
0	0	0	0	0	0	0	0.0109	13.339	G	2
0	0	0	0	0	0	0	0.0110	16.407	G	2
0	2	0	0	0	0	0	0.0061	13.114	G	2
0	0	0	0	0	0	0	0.0190	14.447	J	2
0	0	0	0	0	0	0	0.0127	11.561	J	2
0	0	0	0	0	0	0	0.0131	12.243	J	2
0	0	0	0	0	0	0	0.0137	9.285	J	2
0	0	0	0	0	0	0	0.0158	30.363	J	2
0	20	0	0	0	0	0	0.0121	21.263	J	2
0	0	0	0	0	0	0	0.0121	9.366	J	2
0	0	0	0	0	0	0	0.0106	9.965	J	2
0	0	0	0	29	0	0	0.0129	15.421	G	1
0	0	0	0	47	0	0	0.0124	22.442	G	1
0	0	0	0	0	34	0	0.0160	17.783	G	1
0	0	0	0	36	0	0	0.0139	19.049	G	1
0	0	0	0	0	45	0	0.0144	29.328	C	1
0	0	0	0	54	0	0	0.0106	19.931	C	1
0	0	0	0	0	48	0	0.0165	21.330	C	1
0	0	0	0	50	0	0	0.0162	22.711	C	1
0	0	0	0	0	0	0	0.0112	20.820	C	1
0	0	0	0	8	0	0	0.0078	21.440	C	1
0	0	0	0	0	0	0	0.0143	32.288	C	1
0	0	0	0	2	0	0	0.0165	20.598	C	1
0	0	0	0	0	0	0	0.0139	29.344	C	1
0	0	0	0	12	0	0	0.0149	38.584	C	1
0	0	0	0	0	0	0	0.0115	28.037	C	1
0	0	0	0	19	0	0	0.0169	35.747	C	1

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.