INDICATORS OF DISTURBANCE AND RECOVERY OF A TALLGRASS PRAIRIE ECOSYSTEM FOLLOWING MILITARY VEHICLE TRAFFIC

by

PEGGY S. SHAW ALTHOFF

B.S., Oglala Lakota College, Kyle, South Dakota, 1999
M.S., Kansas State University, Manhattan, Kansas, 2005

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Agronomy
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2007

Abstract

Range and Training Land Assessment (RTLA) and Land Rehabilitation and Maintenance (LRAM) are key components of The United States Army's Integrated Training Area Management (ITAM) Program, which outlines its commitment to support the sustainable use of military training lands. The primary purpose of the RTLA Program is to provide information and recommendations regarding the condition of training lands to range managers for scheduling of training areas and monitoring the effectiveness of rehabilitation projects. The goal of the LRAM component of ITAM is to reduce the long-term impacts of training on installations through the implementation of improvements to vegetation cover and repairs to landscape damage in disturbed areas. Fort Riley Military Installation, located in the largest remaining expanse of tallgrass prairie in the Flint Hills of northeastern Kansas, is a major training reservation, with seventy percent of its 40,434 ha used for mechanized maneuvers. A randomized complete block design composed of M1A1 tank traffic in a figure-eight pattern during wet and dry soil conditions was established in each of two soil types, a silty clay loam and a silt loam, and recovery of physical, chemical, and biological indicator variables was monitored from 2005 through 2007. In a second study, the effectiveness of LRAM procedures, including leveling, mulching, and reseeding, was evaluated following wheeled vehicle disturbance. The goals of this study were to identify disturbance indicators appropriate for assessing soil quality and, based on the status of these indicators, develop a method for modeling the stage and rate of ecological degradation and potential response to remediation.

Disturbance increased significantly during wet compared to dry soil conditions, for increased traffic intensity, and for curve compared to straight-a-way areas in both soil types. The greatest impacts were on above- and belowground community structure, providing an effective bioindicator of ecosystem health for military training land mangers. Remediation of wheeled vehicle disturbance with leveling and mulching, but not reseeding, increased total vegetation production. The tallgrass prairie typically is considered to be among the most resilient of military training lands, but resiliency is dependent upon soil type and training conditions, and may require longer periods of recovery than previously thought.

INDICATORS OF DISTURBANCE AND RECOVERY OF A TALLGRASS PRAIRIE ECOSYSTEM FOLLOWING MILITARY TANK TRAFFIC

by

PEGGY S. SHAW ALTHOFF

B.S., Oglala Lakota College, Kyle, South Dakota, 1999
M.S., Kansas State University, Manhattan, Kansas, 2005

A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Agronomy
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2007

Approved by:

Major Professor
Stephen J. Thien

Abstract

Range and Training Land Assessment (RTLA) and Land Rehabilitation and Maintenance (LRAM) are key components of The United States Army's Integrated Training Area Management (ITAM) Program, which outlines its commitment to the sustainable use of military training lands. The primary purpose of the RTLA Program is to provide information and recommendations regarding the condition of training lands to range managers for scheduling of training areas and monitoring the effectiveness of rehabilitation projects. The goal of the LRAM component of ITAM is to reduce the long-term impacts of training on installations through the implementation of improvements to vegetation cover and repairs to landscape damage in disturbed areas. Fort Riley Military Installation, located in the largest remaining expanse of tallgrass prairie in the Flint Hills of northeastern Kansas, is a major training reservation, with seventy percent of its 40,434 ha used for mechanized maneuvers. A randomized complete block design composed of M1A1 tank traffic in a figure-eight pattern during wet and dry soil conditions was established in each of two soil types, a silty clay loam and a silt loam, and recovery of physical, chemical, and biological indicator variables was monitored from 2005 through 2007. In a second study, the effectiveness of LRAM procedures, including leveling, mulching, and reseeding, was evaluated following wheeled vehicle disturbance. The goals of this study were to identify disturbance indicators appropriate for assessing soil quality and, based on the status of these indicators, develop a method for modeling the stage and rate of degradation and potential response to remediation. Disturbance increased significantly during wet compared to dry soil conditions, for increased traffic

intensity, and for curve compared to straight-a-way areas in both soil types. The greatest impacts were on above- and belowground community structure, providing an effective bioindicator for military training land mangers. Remediation of wheeled vehicle disturbance with leveling and mulching, but not reseeding, increased total vegetation production. The tallgrass prairie typically is considered to be among the most resilient of military training lands, but resiliency is dependent upon soil type and training conditions, and may require longer periods of recovery than previously thought.

Table of Contents

List of Figures

List of Tables

Acknowledgements

Funding for my project was provided by the U.S. Army Military Installation, Integrated Training Area Management (ITAM) Program. Thank you to Philip B. Woodford (ITAM Coordinator), Chris Otto, (ITAM), Lee Breidenstein (Range Control), Tony Davis, Troy Livingston, (GIS, ITAM), Monte Cales (NRCS), Fred Siebe and staff (MPRC Gunnery Complex), M1A1 tank crews, and LMTV crew from Fort Riley Military Installation, for your efforts and support. Thank you to the Kansas State University Department of Agronomy for providing this opportunity to pursue my lifelong dream. A special thank you to Dr. Stephen J. Thien, my Major Professor, for your example of dedication to the pursuit of knowledge, my heartfelt thanks for your patience, understanding, support, and invaluable guidance. I am also indebted to the members of my committee: Philip S. Gipson, Mary Beth Kirkham, and Timothy C. Todd who made this possible, as well as providing instruction, words of encouragement, and excellent advice throughout this entire process.

There are numerous other faculty individuals, administrative staff, undergraduate and graduate students, and outside support who deserve my gratitude for their contributions: Drs. Carol Blocksome, Mickey Ransom, Walter Fick, Clenton Owensby, Paul White, Gerard Kluitenberg, Karina Fabrizzi, Elmer Fick, Joseph Thomasson, Robert Nicholson, Jerry Choate, Kent Jensen, Trudy Ecoffey, Karen Enterline, Lloyd Wright, Dennis Profant, Fred Caldwell, Jamie Loecker, Luke Baker, Meghan Buckley, Kevin Blecha, Jamie Aikins, Arline Novak, Roger Tacha, Terry Jo Litchfield, Pam and Will Lansing, Mary and Jeff Toliver, Brandy and

Matt Hanusosky, Jennifer and Greg Grove, Kim Wilson, DeAnn Upton, Patty Englebrecht, Karla Spence, Kitty Drake and Marty Courtois.

Dedication

To my parents, Harold and Evelyn and my sons, Craig and Eric for a lifetime of unconditional love and support as they continue to enrich my life with their lives. To my husband, Don for helping me realize that I am a stronger person than I ever realized. To all those who have served and fought under the flag of the United States of America and to those who have supported these men and women. Finally, in memory of Dr. Jeffrey S. Pontius.

Introduction

The Integrated Training Area Management Program

The United States Army's commitment to the sustainable use of military training lands is outlined in the Integrated Training Area Management (ITAM) Program. Key components of this program include Range and Training Land Assessment (RTLA) and Land Rehabilitation and Maintenance (LRAM). The primary purpose of the RTLA Program is to provide information and recommendations regarding the condition of training lands to range managers for scheduling of training areas and monitoring the effectiveness of rehabilitation projects (US Army Environmental Center, 2006). This is accomplished through the monitoring of land condition in training areas and the designation of benchmarks for sustainability. Collection and analysis of physical and biological resources data form the basis for decisions on training intensity and land rehabilitation requirements. Using a four-tiered classification system of training land's suitability for training, RTLA strives to avoid expensive maintenance and to promote its sustainable usage. For example, the system in use at Fort Riley (Fig. 1) classifies training areas based on vegetative cover as good (green), fair (amber), poor (red), and absent (black). A rating of "Poor" elicits a recommendation that training be conducted only when soils are dry. Absence of vegetation requires rehabilitation.

The goal of the LRAM component of ITAM is to reduce the long-term impacts of training on installations through the implementation of improvements to vegetation cover (e.g revegetation) and repairs to landscape damage (e.g. erosion control) in disturbed areas. Restriction of training activities in damaged areas to allow time for recovery is another important

LRAM technique. Together, these programs enable range managers to optimally match training areas with training needs.

Fort Riley

Fort Riley has been an important training installation since its establishment in 1853. Located in the Flint Hills of northeastern Kansas, Fort Riley encompasses 40,434 ha (100,656 acres), with seventy percent of the area used for maneuver training. Military vehicles commonly used on the fort include tracked vehicles such as the Abrams M1A1 (57.2 t) and the Bradley Fighting Vehicle (30.8 t), and wheeled vehicles such as the High Mobility Multipurpose Wheeled Vehicle (Humvee, 2.4 t), Heavy Expanded Mobility Tactical Truck (HEMTT, 18.8 t) and Light Medium Tactical Vehicle (LMTV, 5.4 t). Fort Riley's goal is to maintain its training lands in a condition that will accommodate long-term training. Land maintenance is currently guided by regulations set forth by the ITAM Program.

Maintenance of Fort Riley's training lands also has implications for one of the most endangered ecosystems in North America. The tallgrass prairie, which once extended from Texas to Canada and from Indiana to the central Great Plains (Fig. 2), survives on less than 4% of its historic 68,371,000 ha (Samson and Knopf, 1994). The largest remaining areas of untilled tallgrass prairie reside in the Flint Hills, which encompass more than 1.6 million ha, covering much of eastern Kansas from near the Kansas-Nebraska border south into northeastern Oklahoma (Knapp and Seastedt, 1998). Generally considered to be relatively resilient compared to other military lands (Schaeffer et al., 1990), recent research has shown that this system is sensitive to training activities, with the level of disturbance and recovery varying with soil type, environmental conditions, and training intensity (Althoff, 2005; Althoff and Thien, 2005; Althoff et al., 2007).

Fire is a natural occurrence in the tallgrass prairie ecosystem and represents an effective tool for land managers (Wright, 1974; Collins and Gibson, 1990). Prescribed burning stimulates vegetation biomass which provides greater cover for long-term sustainability. Approximately one-third of the Fort is burnt annually, including prescribed burns and both naturally-occurring and training-related wildfires, resulting in a mosaic of vegetation patterns at the landscape level. Fire enhances natural resources and it also protects soldiers by burning fuel that could erupt during training missions and damage soldiers' equipment and human life. It is also significant in cultural resources management. Many cultural artifacts are found close to the land's surface and following a fresh burn, archaeologist investigate the entire burned area looking for artifacts of Native Americans and past soldiers' activities. Fire is a natural occurrence in the tallgrass prairie environment as it brings back the development into early successional stages which many threatened and endangered species need to survive.

The USDA Soil Conservation Service (1975) mapped 36 soil series on Fort Riley and taxonomically categorized them into six soil associations; Eudora-Haynie-Sarpy, Reading-Kennebec-Ivan, Wymore-Irwin, Clime-Sogn, Benfield-Florence, and Smolan-Geary (Fig. 3). Eudora-Haynie-Sarpy and Reading-Kennebec-Ivan soil associations occupy small areas on the Post. The Eudora-Haynie-Sarpy associations are located on the southern boundary of the installation along the Republican and Kansas Rivers. These bottomland soils are vegetated by a mixture of trees and grasslands. The Reading-Kennebec-Ivan soil associations occur near the northeastern boundary of the installation along Wildcat Creek and its tributaries. These soils are typically forested. The Clime-Sogn soils are shallow to moderately deep, sloping and moderately steep silty clay loams on uplands. The lack of soil depth and slope position and these soils makes them subject to severe erosion if unprotected. These soils occur prominently in the

Impact Area and in Training Areas on the east, south, and west of Custer Hill. The Benfield-Florence soils are moderately deep, sloping and moderately steep, silty clay loams and cherty silt loams on uplands. Slopes up to 20% make these soils subject to severe erosion if left unprotected. These soils are most commonly found on the eastern side of the Fort. The Smolan-Geary soils are deep, gently sloping and sloping silt loams, on high terraces and uplands. These soils are subject to severe erosion if not protected. All of Maneuver Area C is included in the Smolan-Geary soil association.

The most abundant soils on the installation are the Wymore-Irwin, Clime-Sogn, Benfield-Florence, and Smolan-Geary associations. These soil associations represent greater than 85% of the land area on Fort Riley. The Wymore-Irwin soils are deep, nearly level to sloping silty clay loams on uplands. They are located along a corridor on either side of the old Highway 77 that transverse the installation from south to north and, thus, receive the bulk of vehicular traffic associated with the training mission at Fort Riley. The Wymore-Irwin soils tend to be droughty and are subject to water erosion if left unprotected. My study was conducted in Maneuver Area Q and is in the Wymore-Irwin soils association. The soil at the study plots was classified as a Wymore series consisting of very deep moderately drained, slowly or very slowly permeable soils that formed in loess (USDA, 1975). The taxonomic class is defined as: Fine, smectitic, mesic Aquertic Argiudolls (Fig. 3).

Rationale of present study

Long-term preservation has been identified as a priority for strategic military training sites. Assessing the impact of repeated disruptions of the type related to training activities (e.g., track and wheeled vehicles) is a necessary first step in managing military lands for maximum sustainability. The complexity of any ecosystem requires an evaluation to be based either on numerous individual features or a parameter that inherently integrates important benchmarks. Soil quality, defined as the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health (Doran and Parkin, 1994), integrates these criteria and serves as a primary indicator of an ecosystem's sustainability.

Soil degradation implies a loss of natural functions. Soils in military training areas suffer degradation mainly through displacement, compaction and erosion. Degradation impacts vegetative cover (a visual indicator) and critical soil functions (non-visual indicators). Compaction reduces porosity and leads to the attendant problems of reduced infiltration, increased runoff (erosion), lost aeration, and hindered root development (Doran and Jones, 1996; Elliot et al., 1999; Brady and Weil, 2002; Murphy et al., 2004). Disruption of the surface soil alters plant communities, associated carbon sequestration in the soil and soil profile integrity (Herrick et al., 1999). In combination, these changes represent degradation and lead to a loss of soil quality.

Soils possess a natural ability to recover from disruptions, a property called resilience and soil microbes play a significant role in promoting resilience. As soil quality deteriorates, though, undesirable consequences permeate the ecosystem, many of which impact microbial activity. For example, practices fostering erosion result in loss of topsoil at the erosion site and sedimentation problems at the deposition site. Topsoil contains most of the soil's stored carbon supply, the energy source essential for microbial remediation. Likewise, disturbance increases oxidative losses of stored carbon storage and further reduces microbial activity. Also, compaction and disturbance alter plant communities which in turn affect carbon storage patterns in the soil. The carbon storage-microbial activity relationship plays a significant role in assessing soil quality.

Training areas, by their very nature, when compared to most other uses, receive intensive use and degrade at accelerated rates. Addressing both rapid degradation and long-term use requires a systematic program of identifying, monitoring, and managing those indicators most appropriate for soil quality assessment. Preliminary studies have focused on evaluating short-term responses by soil physical, chemical and microbial indicators (Althoff, 2005; Althoff and Thien, 2005). This dissertation represents the culmination of a five-year study, focusing on monitoring longer-term trends in recovery of plant and soil communities and integrating these observations into management recommendations for improved sustainability. Chapters I through 3 summarize three years of recovery patterns for the plant community, soil physical and chemical structure, and soil biological communities, respectively. Chapter 4 reports preliminary (one growing season) results for a comparison of LRAM remediation procedures following wheeled vehicle disturbance. The final chapter introduces guidelines to assist land managers in their efforts to accommodate long-term training needs.

The goals of this study were to identify soil degradation indicators appropriate for assessing soil quality and, based on the status of these indicators, develop a method for modeling the stage and rate of degradation and potential response to remediation. Application of this site-assessment information should prove valuable in planning for the sustained use of military training areas.

Specific objectives:

1. Evaluate the soil quality status on lands subjected to military training by developing methods to monitor, evaluate, and predict changes of specific soil/environmental indicators.

2. Develop an information-based method of merging the composite status of a selected suite of indicators into a tool useful in assessing soil quality and predicting best management options for long-term sustainability of military training sites.

REFERENCES

Althoff, P.S. 2005. Evaluation of soil quality indicators following disturbance by an Abrams M1A1 Main Battle Tank. M.S. Thesis. Kansas State University, Manhattan, KS, 136 pp.

Althoff, P.S., and S.J. Thien. 2005. Impact of M1A1 main battle tank disturbance on soil quality, invertebrates, and vegetation characteristics. Journal of Terramechanics 42:159-176.

Althoff, D.P., P.S. Althoff, N.D. Lambrecht, P.S. Gipson, J.S. Pontius, and P.B. Woodford. 2007. Soil Properties and perceived disturbance of grasslands subjected to mechanized military training: evaluation of an index. Land Degradation and Development 18:269-288.

Brady, N.C., and R.R. Weil. 2002. The Nature and Properties of Soils. Thirteenth Edition. Prentice Hall, Upper Saddle Rive, New Jersey.

Collins, S.L., and D.J. Gibson. 1990. Effects of fire on community structure in tallgrass and mixed-grass prairie. Pp 81-98 *In* S.L. Collins and L.L. Wallace (ed.). Fire in North American tallgrass prairies. University of Oklahoma Press, Norman, Publishing Division of the University.

Doran, J.W., and T.B. Parkin. 1994. Defining and assessing soil quality. Pp 3-21 *In* J. W. Doran et al. (ed.). Defining soil quality for a sustainable environment. SSSA Special Publication 35. SSA, Madison, WI.

Doran, J.W., and A.J. Jones. 1996. Methods for assessing soil quality. SSSA Special Publication 49. Madison, WI. Soil Science Society America.

Elliott, E.T., J.W. Heil, E.F. Kelly, and H.C. Monger. 1999. Soil structural and other physical properties. Pp 74-85 *In* Robertson, G.P., Coleman, D.C., Bledsoe, C.S and Sollins, P. (eds.), Standard soil methods for long-term ecological research. Oxford University Press Inc, New York, NY.

Herrick, J.E., M.A. Weltz, J.D. Reeder, G.E. Schuman, and J.R. Simanton. 1999. Rangeland soil erosion and soil quality: role of soil resistance, resilience, and disturbance regime. Pp 209-233 *In* R. Lal. (ed.). Soil quality and soil erosion. Soil and water conservation society. Boca Raton, Florida.

Knapp, A.K., and T.R. Seastedt. 1998. Grasslands, Konza Prairie, and long-term ecological research. Pp 3-15 *In* A.K. Knapp, J.M. Briggs, D.C. Hartnet, and S.L. Collins (eds.), Grassland dynamics: long-term ecological research in tallgrass prairie. Oxford University Press, NY, NY, USA.

Murphy, C.A., B.L. Foster, M.E. Ramspott, and K.P. Price. 2004. Grassland management effects on soil bulk density. Transactions of the Kansas Academy of Science 107:45-54.

Samson, F. and F. Knopf. 1994. Prairie conservation in North America. Bioscience 44:418-421.

Schaeffer, DJ, Seastedt RR, Gibson DJ, Hartnett DC, James SW, Kaufman DW, Schwab AP, Herricks EE, Novak EW. 1990. Field bioassessments for selecting test systems to evaluate military training lands in tallgrass prairie. Ecosystem Health. V. Environmental Management. 14:81-93. Springer-Verlag New York Incorporated.

US Army Environmental Center. 2006. Sustainable range program: Range and training land assessment program. https://srp.army.mil/itam/rtla.

USDA, Soil Conservation Service in cooperation with Kansas Agricultural Experiment Station. 1975. Soil Survey of Riley and Part of Geary County, Kansas.

Wright, H.A. 1974. Range burning. Journal of Range Management 27:5-11.

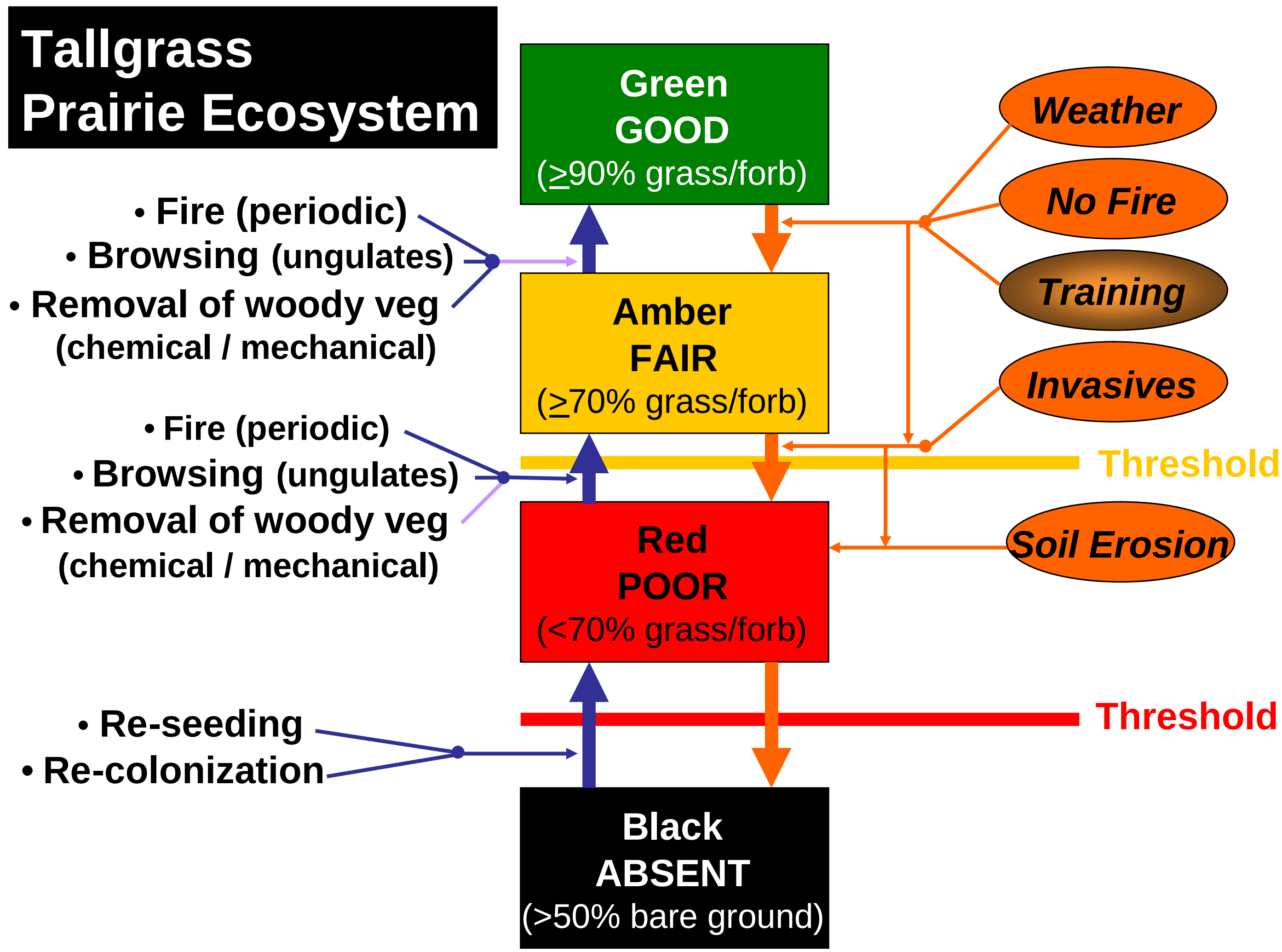
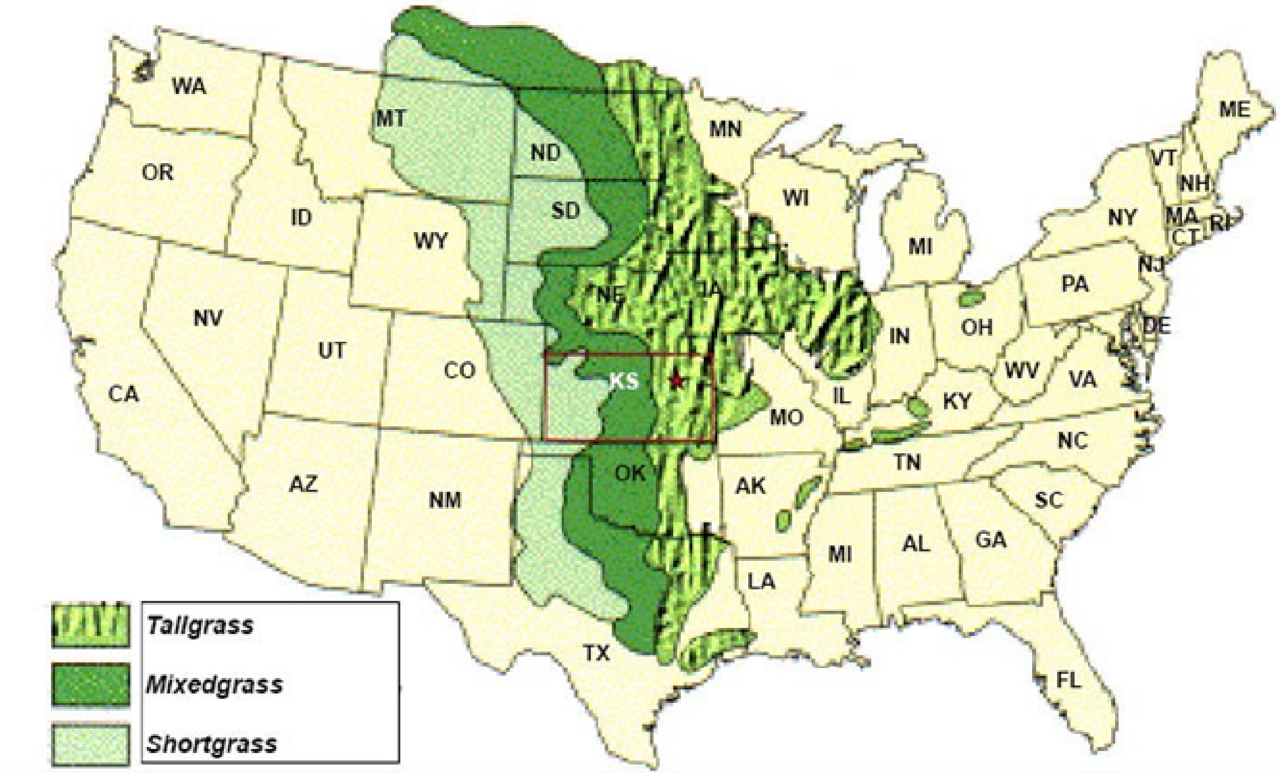


Figure I.1.1. Four-tiered classification system of training land's suitability for training to promote its sustainable usage (US Army Environmental Center, 2006).



http://people.uis.edu/braeb1/uisprairieproject/images/Prangeb4.gif

Figure I.1.2. Historic range of the tallgrass prairie, which once extended from Texas to Canada and from Indiana to the central Great Plains. The largest remaining areas of untilled tallgrass prairie reside in the Flint Hills, which encompass more than 1.6 million ha, covering much of eastern Kansas from near the Kansas-Nebraska border south into northeastern Oklahoma. The location of Fort Riley Military Installation is indicated by the red star.

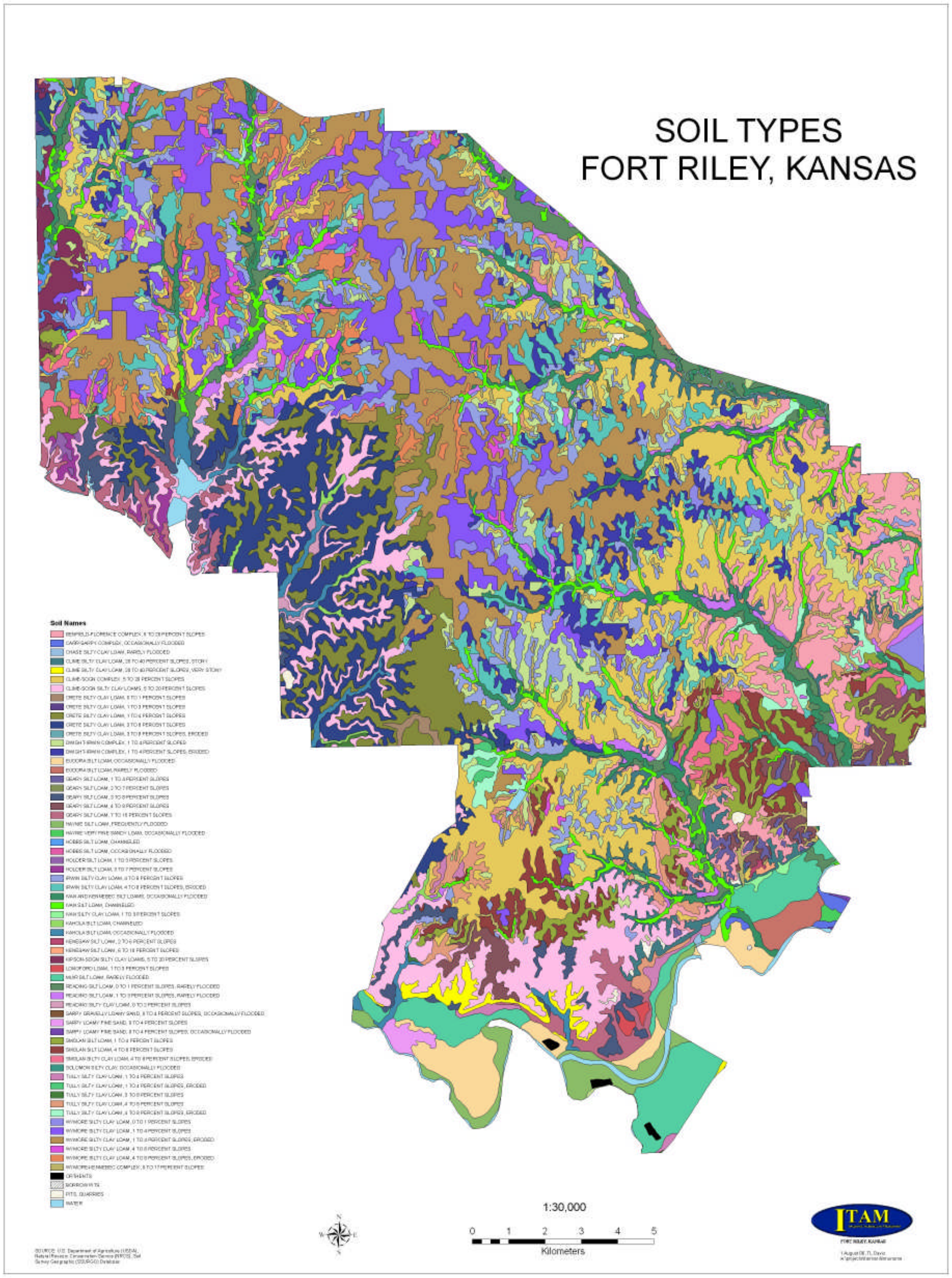


Figure I.1.3. Soil types located on Fort Riley Military Installation, Kansas.

CHAPTER 1 - Influence of an Abrams M1A1 Main Battle Tank Disturbance on Plant Community Structure

Peggy S. Althoff, M.B. Kirkham, T.C. Todd, S.J. Thien, and P.S. Gipson.

Peggy S. Althoff, M.B. Kirkham, and S.J. Thien, Dept. Of Agronomy; T.C. Todd, Dept. Of Plant Pathology; P.S. Gipson, U.S.G.S. Kansas Cooperative Fish and Wildlife Research Unit, Kansas State University; Manhattan, KS, 66506.

For submission to Journal of Range Management

ABSTRACT

Range and Training Land Assessment (RTLA) program provides information and recommendations regarding the condition of training lands to range managers to assist scheduling of training areas and monitoring of the effectiveness of rehabilitation projects. Fort Riley Military Installation, located in the largest remaining expanse of tallgrass prairie in the Flint Hills of northeastern Kansas, is a major training reservation, with seventy percent of its 40,434 ha used for mechanized maneuvers. A randomized complete block design composed of three treatments (M1A1 Abrams tank traffic during wet and dry soil conditions, and a non-trafficked control) and three replications was established in each of two soil types, a silty clay loam and a silt loam soil on Fort Riley in 2003. Additional tank passes were added to one-half of each figure eight in 2004 and burning was added as an experimental treatment in 2006. Two areas, a curve and straight-a-way, within each traffic intensity-burn treatment subplot were designated for sampling in 2005-2007. Vegetation biomass, species composition, and ground cover were measured during each growing season. In general, biomass in disturbed areas was lower for grasses and higher for forbs relative to undisturbed control plots through 2006. Disturbance was greatest on curve areas and with repeated traffic in both soil types. In contrast, species composition and ground cover were more strongly affected by soil moisture conditions at the time of disturbance, with greatest damage severity observed for repeated traffic under wet soil conditions. Fire effects varied with year and soil type, with the strongest recovery response observed for grass biomass in silty clay loam soil in 2007. Recovery of plant species composition lagged behind that of plant biomass and ground cover. The tallgrass prairie

typically is considered to be among the most resilient of military training lands, but, for the vegetation of this ecosystem, resiliency is dependent upon soil type and training conditions, and may require longer periods of recovery than previously thought.

INTRODUCTION

Environmental impacts of military vehicle use have been reviewed recently by Anderson et al. (2005). The intensity of military training makes resilience of vegetation an important consideration. Stand establishment and the ability to produce rhizomes are associated with recovery (Palazzo et al., 2005), and for this reason, the tallgrass prairie, which is dominated by rhizomatous grasses, is considered to be relatively resilient compared to other military lands. Fort Riley Military Installation, located in the largest remaining expanse of tallgrass prairie in the Flint Hills of northeastern Kansas, is a major training reservation, with seventy percent of its 40,434 ha used for mechanized maneuvers. In a preliminary assessment of training sites on Fort Riley, plant biomass displayed no discernible trends related to training activities, with values well within the range observed for native tallgrass prairie (Schaeffer et al., 1990). Species composition, in contrast, was negatively impacted on Fort Riley, with abundance of the dominant grass *Andropogon gerardii* (big bluestem) greatly reduced compared to the native site. Subsequent monitoring showed little change in plant species diversity in training areas, further supporting the argument for resiliency of grassland ecosystems (Althoff et al., 2006). Negative effects were observed, however, with invasive species and bare ground both increasing over time in areas of concentrated mechanized training. In a subsequent Fort Riley study, vegetation biomass remained significantly reduced one year after M1A1 tank traffic during wet and dry soil conditions in two soil types (Althoff, 2005). Traffic intensity also impacts vegetation recovery patterns, with target species declining as traffic intensity increases (Palazzo et al., 2005). Anderson et al., (2005) developed a model predicting decreased ground and aerial vegetative cover associated with increased training intensity.

Land maintenance on military training lands is currently guided by regulations set forth by the Integrated Training Area Management (ITAM) Program, which outlines procedures for achieving sustainable use of training lands (Army Regulation 350-4, 1988). A key component of this program, Range and Training Land Assessment (RTLA), provides information and recommendations regarding the condition of training lands to range managers to assist scheduling of training areas and monitoring of the effectiveness of rehabilitation projects (US Army Environmental Center, 2006). Fort Riley started implementing portions of the assessment protocol under the Land Condition Trend Analysis (LCTA) Program, monitoring trends in plant communities related to military vehicle traffic patterns during 1994-2001 (Althoff et al., 2006). Assessment of soil quality indices, including physical, chemical, and biological properties began in 2002 (Althoff, 2005; Althoff and Thien, 2005; Althoff et al., 2007).

A replicated small-plot study of tracked vehicle disturbance effects on tallgrass prairie soils and communities was initiated on Fort Riley in 2003. In 2006, fire was added as a management variable. Fire is a natural occurrence in the tallgrass prairie ecosystem and represents an effective tool for land managers (Wright, 1974; Collins and Gibson, 1990). Prescribed burning stimulates vegetation biomass which provides greater cover for long-term sustainability. Approximately one-third of the Fort is burned annually, including prescribed burns and both naturally-occurring and training-related wildfires, resulting in a mosaic of vegetation patterns at the landscape level.

The objectives were to evaluate rates of recovery in a suite of plant and soil-quality indicators over a range of disturbances encompassing soil type, environmental conditions, and traffic intensity. Results from the first two years are reported in Althoff (2005) and Althoff and

Thien (2005). This manuscript reports longer-term trends in plant community responses following the first and second years of disturbance.

MATERIALS AND METHODS

Site Description

Research was conducted at Fort Riley Military Installation, an Army base in operation since 1853, located in Clay, Geary, and Riley counties in the Flint Hills of northeastern Kansas (39°15'N, 96°50'W) (Pride, 1997; McCale and Young, 2000). The installation, located in a mesic, tallgrass-prairie ecosystem, uses 29,542 ha (70,926 ac) of its 40,434 ha (100,656 ac) for maneuver training. The Flint Hills grasslands encompass more than 1.6 million ha, covering much of eastern Kansas from near the Kansas-Nebraska border south into northeastern Oklahoma, and contain the largest remaining areas of untilled tallgrass prairie in North America (Knapp and Seastedt, 1998). Hot summers and cold, dry winters characterize the climate. Mean monthly temperatures range from -2.7°C in January to 26.6°C in July. Annual precipitation averages 83.5 cm, with 75% of precipitation occurring during the growing season (Hayden, 1998). Fort Riley lands host three major vegetation communities: grasslands (ca. 32,200 ha), shrublands (ca. 6, 000 ha), and woodlands (ca. 1,600 ha). The soil at the study plots was classified as a Wymore series consisting of very deep, moderately drained, slowly or very slowly permeable soils that formed in loess (USDA, 1975). This soil series is found on most of the fort's training area. Wymore soils are classified as fine, smectitic, mesic Aquertic Argiudolls.

Experimental Treatments

A randomized complete block design composed of three treatments (a non-trafficked control, tank traffic during wet soil conditions, and tank traffic during dry soil conditions) and three replications (blocks) was established in each of two soil types, a silty clay loam and a silt loam, in 2003 (Althoff and Thien, 2005). An Abrams M1A1 main battle tank created disturbances by driving 5 circuits around a figure eight pattern in designated plots either during wet or dry soil conditions. The M1A1 weighs 57.2 t with a ground pressure of 0.00626 t/cm (13.8 pounds/sq inch). The tracks are approximately 63.5 cm (25 inches) wide and 4.57 m (15 feet) long. It has a maximum cross country speed of 48 km/h (30 mph). Tank speed was maintained at approximately 8 km/h (5 mph).

In 2004, one-half of each of the previously disturbed plots received 5 additional tank passes during wet or dry conditions similar to 2003. On a randomly selected half of the original figure eight, 5 additional passes were made with an M1A1 tank, producing a S-shaped pattern (Althoff, 2005). The second year of treatments allowed comparison of different levels of traffic intensity (one-time-traffic with 5 passes versus repeated traffic with a total of 10 passes). Two areas, a curve and straight-a-way, within each traffic intensity subplot were designated for sampling in 2005. Data from the first and second years of disturbance are reported in Althoff (2005) and Althoff and Thien (2005).

In April 2006, each whole plot was again split and a randomly selected half received a burn treatment (Fig. 1.1). Curve and straight-a-way areas within each burn-intensity subplot were designated for sampling in 2006 and 2007 (Figs. 1.2, 1.3).

Field Sampling and Laboratory Methods

Vegetation Biomass

Vegetation biomass was sampled on 8 June 2005, 1 October 2006, and 2 July 2007, using the Daubenmire frame (20 cm x 50 cm) technique (Daubenmire, 1959). Living plant biomass was clipped, sorted into grass or forb categories, dried 48 hours at 40^{o}C, and weighed (Althoff and Thien, 2005).

Step-point

Plant species composition and basal area were determined from transects comprised of 100 points for each figure-eight (whole plot) using the modified step-point technique (Evans and Love, 1957). Data were recorded separately for the eight most abundant grass species [*Andropogon gerardii* (big bluestem), *Schizachyrium scoparium* (little bluestem), *Panicum virgatum* (switchgrass), *Sorghastrum nutans* (indiangrass), *Sporobolus asper* (dropseed), *Bromus* spp. (brome), *Koeleria macrantha* (prairie junegrass), *Carex* spp. (sedge)] and the five most abundant forb species [*Aster ericoides* (heath aster), *Desmanthus illinoensis* (Illinois bundleflower), *Ambrosia* spp. (ragweed), *Solidago* spp. (goldenrod), *Erigeron strigosus* (daisy fleabane)]. All other species were grouped into “other grasses” or “other forb” categories. Percentage bare ground and litter cover also were estimated with this technique.

Bare Ground Analysis Using Aerial Photographs

Field Procedure—High quality digital images of plots were obtained using a low-level aerial photography system (LLAPS) consisting of a remotely controlled aerial photography platform suspended below an 18 ft. helium filled blimp tethered to/and controlled by personnel

(Kansas Cooperative Fish and Wildlife Research Unit) on the ground (Fig. 1.4). A 5.0 mega-pixel Nikon digital camera was used in 2004, 2005, and 2006 and a 10 mega-pixel Sony DSC-R1 camera was used in 2007. Prior to conducting the aerial photography, highly-visible white markers, 25 cm x 25 cm in size where placed within the photographed area to provide scale and mark plot corners to facilitate photo analysis. The LLAPS was typically centered 60-70 meters above the center of the targeted area.

Photo Selection and Analysis--Series of images for each plot were downloaded from the digital camera to a desktop computer in the lab. A trained technician (Kansas Cooperative Fish and Wildlife Research Unit) then selected a single photograph for each plot for each year to be analyzed. The single photograph used for each plot in a given year was chosen for overall clarity of the image, visibility of corner markers, and positioning of the plot in the photograph. After geo-referencing using GPS coordinates obtained with a Trimble GeoXT handheld unit, photographs were then loaded in ArcMap (ESRI, Redlands, California) as a raster layer. Using the editor tool within ArcMap, the technician traced the visible bare ground areas for each plot resulting in separate layers for all areas of bare ground $\geq 1\text{m}^2$. HAWTHS tools (Beyer, 2004) was used to calculate the area of bare ground (m^2) for each plot. Percentage of bare ground in each plot was calculated by dividing the area of bare ground by the total area in a 35 meter by 70 meter (~2450 m^2) plot arbitrarily placed to contain the impacted area in each figure eight treatment (Althoff and Blecha, 2007).

Statistical Analyses

A disturbance effect index was calculated for all variables using the following formula:

(*disturbed measurement-undisturbed measurement)/ (undisturbed measurement*).

This disturbance effect index was expressed as a percentage of the control and subjected to mixed-model analysis of variance using SAS (SAS Institute, Cary, NC, 2000). The data were analyzed as a split-split plot with correlated subplots (5 passes vs. 10 passes) and correlated sub-subplots (curved vs. straight areas) with each subplot. The significance of the disturbance index was tested for individual treatment combinations using Least Squares Means (H_0: mean = 0). Principal components analysis (PCA) was used to analyze disturbance-related patterns in plant community composition.

RESULTS

Weather Patterns

Monthly averages, as well as long-term patterns in precipitation and evapotranspiration are presented in Fig.1.5. Spring months, especially April and May, generally were drier than average throughout the present study, while summer months, particularly August were wetter than average. Evapotranspiration values in all years were typical of long-term averages.

Vegetation Biomass

Biomass of grasses continued to be severely impacted in both soil types in 2005 (1-2 years post treatment), with repeated tank traffic (10 passes) displaying greater reductions than single traffic (5 passes; Table 1.1, Fig 1.6). Reductions were generally less severe in 2006, with less biomass produced ($p \leq 0.10$) on curves and under burned conditions relative to control plots in silty clay loam soil (Table 1.2, Fig. 1.7 A, B). Recovery did not vary with any treatment in the silt loam soil in 2006, but significant reductions in grass biomass were observed only for curve areas under burned conditions (Table 1.3, Fig. 1.7 C, D). By 2007 (3-4 years post treatment), recovery in silty clay loam soil was significantly greater in single traffic plots and under burned conditions, with grass biomass in these plots greater than that of control plots (Table 1.4, Fig. 1.8 A, B). Recovery again did not vary with treatment in silt loam soil in 2007 (Table 1.5, Fig. 1.8 C, D)

Forb biomass tended to increase following disturbance but there were no consistent trends in treatment responses across years (Tables 1.1-1.5, Figs. 1.9-1.11. Significant increases ($p \leq 0.10$) in forb biomass relative to control plots generally occurred on curve areas and were more frequently observed in silty clay loam than in silt loam soil. By 2007, none of the disturbed plots were significantly different from control plots in forb biomass (Fig. 1.11).

Total vegetation biomass exhibited trends similar to those described for grass biomass (Tables 1.1-1.5, Figs. 1.12-1.14). Most treatments displayed significant reductions ($p \leq 0.10$) relative to control plots in 2005, and these reductions were more severe for repeated than for single tank traffic (Table 1.1, Fig. 1.12). Fewer treatments with significant biomass reductions were observed in subsequent years, although vegetation biomass remained significantly reduced in curve areas three years after repeated traffic under wet soil conditions in silty clay loam soil (Fig. 1.14).

Community Analysis

Reductions in litter cover and increases in bare ground relative to control plots in 2005 were greater ($p \leq 0.10$) for disturbance during wet compared to dry soil conditions but were unaffected by traffic intensity (Table 1.1, Figs. 1.15, 1.17). In 2007, residual treatment effects on these variables were consistently observed only for plots with repeated traffic under wet soil conditions in silty clay loam soil (Figs. 1.16, 1.18).

The first two principal components from a principal components analysis (PCA) of vegetation community structure in 2005 and 2007 are shown in Table 1.6. These components explained 34%-43% of the total variation in the data set. Separation of individual treatments primarily occurred on the first principal component, with repeated traffic under wet soil conditions consistently plotted to the left of control plots (Figs. 1.19, 1.20). The weightings for individual plant taxa were similar across soil types and years for this component (Table 1.6), which can loosely be interpreted as a contrast of the relative abundance of typically dominant prairie grasses and forbs (particularly switchgrass, indiangrass, prairie junegrass and/or goldenrod, generally positively weighted) vs. that of other, normally subdominant, grasses and forbs (negatively weighted).

Aerial Image Analysis

Bare ground in aerial images of M1A1 figure-8 tracks decreased from a May 2004 (one year after initial disturbance) average of 337 m^2 and 45 m^2 for silty clay loam and silt loam soil, respectively, to a June 2007 average of 11 m^2 and 1 m^2, respectively. This represented a 97%-98% decrease in bare ground in both soil types during a 3-year period, suggesting an equivalent amount of recovery in vegetative cover as measured with aerial imagery. No moisture treatment effects were discernible for either the amount of bare ground or recovery.

DISCUSSION

Destruction of vegetation is one of the primary impacts of tracked vehicle maneuvers and can result in significant secondary effects such as soil loss through erosion (Grantham et al., 2001). From this perspective, ground cover is a key indicator of ecosystem health and revegetation of disturbed areas is an essential first step in the recovery process. Grasslands are considered to be relatively resilient compared to other military training lands (Yorks et al., 1997), but prairie plant species show differential responses to disturbance, often resulting in significant shifts in species composition even in the absence of measurable effects on plant biomass (Schaeffer et al., 1990; Hartnett and Fay, 1998). In this study, perennial warm-season grasses were largely replaced by annual cool-season grasses and forbs during the recovery process, a pattern also observed following military tracked vehicle maneuvers in Colorado grasslands (Shaw and Diersing, 1990; Milchunas et al., 1999). Invasive exotic species are an additional concern following tank traffic in grassland ecosystems (Wilson, 1988; Milchunas et al., 1999; Althoff et al., 2006).

Althoff (2005), however, reported that vegetation biomass remained severely impacted (45%-49% lower in disturbed areas compared to undisturbed controls) across two soil types (silty clay loam and silt loam soils) one year following tank maneuvers, with recovery patterns of grasses and forbs varying with soil moisture condition at the time of disturbance. Greater soil moisture at the time of trafficking has been observed to magnify vegetation impacts (Yorks et al., 1997) and this was confirmed in this study. Patterns of recovery subsequent to those reported by Althoff (2005), indicates that reductions in net primary production (current year's biomass) continued through 2007 for areas with the greatest disturbance (i.e. curves, wet soil conditions). As expected, the relative abundance of plant species was a better indicator of disturbance and recovery for both grasses and forbs, with dominant species replaced by subdominant species.

The effects of traffic intensity (5 vs. 10 passes) on plant biomass and cover were still detectable in 2007, 3-4 years after disturbance. Since traffic intensity effects are confounded with years since disturbance in the present study, however, it is difficult to attribute how much of this effect is in fact due to intensity. Traffic intensity did differentially impact range grasses at the Yakima Training Center, with relative abundance of target species declining with increasing traffic intensity (Palazzo et al., 2005). Similarly, species composition and the amount of bare ground were found to vary with traffic frequency in a mixed-grass prairie (Wilson, 1988). In contrast, moderate and heavy use by tracked vehicles increased bare ground but did not affect plant species composition in a transitional grassland in North Dakota (Prosser et al., 2000). Even when there are differences due to traffic intensity, it is important to note that the greatest losses to vegetation occur with the first few passes (Yorks et al., 1997; Althoff, 2005).

In addition to intensity, turning during vehicle maneuvers had a residual effect on vegetation recovery, with only vegetation on curve areas displaying significant disturbance at the end of the study (2007). Ayers (1994) reported that sharper turns by tracked vehicles produced more severe vegetation damage, but this pattern was not observed early in the present study (2005), where reductions in vegetation biomass were equivalent between curve and straight-a-way areas. Soil surface disturbance, however, was noticeably more severe for curve areas compared to straight-a-ways, and the displacement of topsoil and associated rutting (see Chapter 2) appears to have reduced the seed/rhizome bank and limited vegetative recovery in these areas.

Fire interacts with other disturbances to alter plant community structure in the tallgrass prairie (Collins and Gibson, 1990). Burning also represents an effective tool for land managers (Wright, 1974). In mesic grasslands such as the tallgrass prairie, burning typically enhances production of the dominant C_4 grasses and increases nitrogen limitation, allowing the grasses to out-compete forbs (Knapp and Seastedt ,1986; Seastedt et al., 1991). Therefore, burning would be expected to enhance recovery of native vegetation following disturbance by tracked vehicles. This pattern eventually was observed for the silty clay loam soil in 2007, but was never observed for the silt loam soil. Additionally, recovery of vegetation biomass in disturbed plots relative to control plots was initially lower in burned compared to unburned plots due to disturbance-related limitations in fuel supply. Nonetheless, fire was demonstrated to sufficiently enhance the later stages of vegetation recovery following tracked vehicle disturbance in tallgrass prairie to warrant its use as a management tool.

Aerial image analysis indicated nearly total recovery of vegetation in tank tracks in 2007. Although low-level aerial photography for bare ground analysis is not capable of assessing basal bare ground area, the results obtained with this system generally were supported by step-point estimates of basal bare ground. Additionally, aerial coverage of vegetation is important for controlling erosion resulting from rain droplet force. Image analysis for measuring ground cover has been noted for its capabilities to assess large numbers of samples, reduces biases possibly induced by human subjectivity, and leaves researchers in the future with a permanent data record (Booth et al., 2005). Aerial image analysis for quantification of vegetative cover have been conducted with an extremity of sampling scales ranging from heights of 2-100 m (Bennett et al., 2000; Booth et al., 2003).

Data resulting from the analysis of bare ground for each plot should be interpreted with caution. Many improvements in field protocols were made as the study progressed. The importance of positioning the photography system directly over the center of the plot must be stressed. Using the camera tilting feature of the aerial photography system creates distortion in the image, thus leading to problems with processing steps in the lab, such as geo-referencing. If images are not accurately geo-referenced, analysis of bare ground areas are then not representative of what is actually on the plot. Other problems existed in the early onset of this aerial photography system, and therefore year-to-year comparisons could not be dependably characterized. These problems involve the switching of camera gear to a higher resolution camera in 2007, the incorrect placement of highly-visible white markers prior to taking a photograph, and the suspicion that permanent plot markers may have been slightly moved by uncontrolled events of military training.

Ground-based methods, such as the step-point technique, complement aerial image analysis, and are necessary to fully evaluate the recovery status of the plant community. By the end of the present study, for instance, plant community structure remained significantly disturbed, even though vegetative cover and biomass displayed few residual disturbance effects. While this may be sufficient for military training needs, it does not fulfill the requirements for sustainability originally outlined by the LCTA Program (Diersing et al., 1992). Replacement of the dominant tallgrass prairie plants with species that are less resilient will lengthen recovery periods, resulting in less suitable lands for training.

Climate change models predict declines to moderate increases in precipitation for the central Great Plains, with increases in the form of less frequent but heavier rainfall events (CAST, 2004). The weather patterns observed during this study largely match these predictions. Spring precipitation, in particular, was frequently well below the long-term average, but there were months of extreme rainfall in three of the five years. Fortunately, the tallgrass prairie, in addition to being relatively resilient to disturbance, is less sensitive to variations in precipitation than many ecosystems (Seastedt et al., 1998). Persistent drought, however, could reduce the dominance of the resilient tallgrass species, thus necessitating changes in land management practices.

The tallgrass prairie typically is considered to be among the most resilient of military training lands, but, for the vegetation of this ecosystem, resiliency is dependent upon soil type and training conditions, and may require longer periods of recovery than previously thought.

Dominant tallgrass species, in particular, failed to recover completely by 4-5 years following initial disturbance. As resiliency of this system largely is dependent upon these rhizomatous grasses, their lack of recovery has significant implications for long-term training sustainability.

ACKNOWLEDGMENTS

Funding for this project was provided by the U.S. Army Military Installation, Integrated Training Area Management (ITAM) Program. I thank Philip B. Woodford (ITAM) Coordinator, Chris Otto, (ITAM), Lee Breidenstein (Range Control), Tony Davis, Troy Livingston, (GPS), Monte Cales (NRCS), Fred Siebe and staff (MPRC Gunnery Complex), and M1A1 tank crews from Fort Riley Military Installation, for their effort and support. I am indebted to Dr. Carol Blocksome, Dr. Walter Fick, Dr. Clenton Owensby, Rebecca Lyons (NRCS, Manhattan), and Alex Miller (NRCS, Westmoreland), for assistance in step-point analysis, including collecting and identifying the plant species. Finally, I appreciate Dr. Donald Althoff, Kevin Blecha and staff (U.S.G.S. Kansas Cooperative Fish and Wildlife Research Unit) for their assistance in collecting blimp images and data and Dr. Mary Knapp (State Climatologist, Weather Data Library), Jamey Duesterhaus, and Stephen Arnold for weather data contributions.

REFERENCES

Althoff, D.P., and K.A. Blecha. 2007. Personal communications. Kansas Cooperative Fish and Wildlife Research Unit.

Althoff, P.S. 2005. Evaluation of soil quality indicators following disturbance by an Abrams M1A1 Main Battle Tank. M.S. Thesis. Kansas State University, Manhattan, KS, 136 pp.

Althoff, P.S., and S.J. Thien. 2005. Impact of M1A1 main battle tank disturbance on soil quality, invertebrates, and vegetation characteristics. Journal of Terramechanics 42:159-176.

Althoff, D.P., P.S. Althoff, N.D. Lambrecht, P.S. Gipson, J.S. Pontius, and P.B. Woodford. 2007. Soil Properties and perceived disturbance of grasslands subjected to mechanized military training: evaluation of an index. Land Degradation and Development 18:269-288.

Althoff, D.P., P.S. Gipson, J.S. Pontius, and P.B. Woodford. 2006. Plant community and bare ground trends on Fort Riley, Kansas: Implications for monitoring of a highly disturbed landscape. Transactions of the Kansas Academy of Science 109:101-106.

Anderson, A.B., G. Wang, S. Fang, G.Z. Gertner, B. Guneralp, and D. Jones. 2005. Assessing and predicting changes in vegetation cover associated with military land use activities using field monitoring data at Fort Hood, Texas. Journal of Terramechanics 42:207-229.

Army Regulation 350-4. 1988. Integrated Training Area Management (ITAM). Unclassified. Headquarters Department of the Army Washington, DC.

Ayers, P. 1994. Environmental damage from tracked vehicle operation. Journal of Terramechanics 31:173-183.

Bennett, L.T., T.S. Judd, and M.A. Adams. 2000. Close-range vertical photography for measuring cover changes in perennial grassland. Journal of Range Managemen. 53:634-641.

Beyer, H.L. 2004. Hawth's analysis tools for ArcGIS. Available at http://www.spatialecology.com/htools.

Booth, D.T., D. Glenn, B. Keating, S.E. Cox, J. Nance, J. Barrier. 2003. Monitoring rangeland watersheds with very-large scale aerial imagery. Pp. 212-215 *In* First interagency conference on research in the watersheds proceedings.

Booth, D.T., S.E. Cox, C. Fifield, M. Phillips, and N. Williamson. 2005. Image analysis compared with other methods for measuring ground cover. Arid Land Research and Management 19:91-100.

Collins, S.L., and D.J. Gibson. 1990. Effects of fire on community structure in tallgrass and mixed-grass prairie. Pp 81-98 *In* S.L. Collins and L.L. Wallace (ed.). Fire in North American tallgrass prairies. University of Oklahoma Press, Norman, Publishing Division of the University.

Council for Agriclutural Science and Technology (CAST). 2004. Climate change and greenhouse gas mitigation: Challenges and opportunities for agriculture. Task Force Report no. 141. Pp 120.

Daubenmire, R. 1959. Measurement of species diversity using canopy coverage classes. Northwest Science. 33:43-66. Diersing, V.E., R.B Shaw, and D.J. Tazik. 1992.

US Army Land Condition-Trend Analysis (LCTA) Program. Environmental Management 16:405-414.

Engle, D.M., and T.G. Bidwell. 2001. The response of central North American prairies to seasonal fire. Journal of Range Management 54:2-10.

Evans, R.A., and R.M. Love. 1957. The step-point method of sampling—A Practical tool in range research. Journal of Range Management 10:208-212.

Grantham, W.P., E.F. Redente, C.F. Bagley, and M.W. Paschke. 2001. Tracked vehicle impacts to vegetation structure and soil erodibility. Journal of Range Management 54:711-716.

Hartnet D.C., and P.A. Fay. 1998. Plant populations: Patterns and process. Pp 81-100 *In* A.K. Knapp, J.M. Briggs, D.C. Hartnet, and S.L. Collins (eds.), Grassland dynamics: long-term ecological research in tallgrass prairie. Oxford University Press, NY, NY, USA.

Hayden, B.P. 1998. Regional climate and the distribution of tallgrass prairies. Pp 19-34 *In* A.K. Knapp, J.M. Briggs, D.C. Hartnet, and S.L. Collins (eds.), Grassland dynamics: long-term ecological research in tallgrass prairie. Oxford University Press, NY, NY, USA.

Knapp, A.K., and T.R. Seastedt. 1986. Detritus accumulation limits productivity of tallgrass prairie. Bioscience 36:662-668.

Knapp, A.K., and T.R. Seastedt. 1998. Grasslands, Konza Prairie, and long-term ecological research. Pp 3-15 *In* A.K. Knapp, J.M. Briggs, D.C. Hartnet, and S.L. Collins (eds.), Grassland dynamics: long-term ecological research in tallgrass prairie. Oxford University Press, NY, NY, USA.

McKale, W., and W.D. Young. 2000. Fort Riley Citadel of the Frontier West, Kansas State Historical Society Topeka, Kansas.

Milchunas, D.G., K.A. Schulz, and R.B. Shaw. 1999. Plant Community responses to disturbance by mechanized military maneuvers. Journal of Environmental Quality 28:1533-1547.

Palazzo, A.J., K.B. Jensen, B.L. Waldron, and T.J. Cary. 2005. Effect of tank tracking on range grasses. J. Terramechanics 42:177-191.

Pride, W.F. The History of Fort Riley. 1997. Manhattan, KS: U.S. Cavalry Museum and Fort Riley Historical and Archaeology Society.

Prosser, C.W., K.K. Sedivec, and W.T. Barker. 2000. Tracked vehicle effects on vegetation and soil characteristics. Journal of Range Management 53:666-670.

SAS Institute Inc. 2000. SAS/STAT user's guide. Version 9.01. SAS Institute Inc., Cary NC, USA.

Schaeffer, DJ, Seastedt RR, Gibson DJ, Hartnett DC, James SW, Kaufman DW, Schwab AP, Herricks EE, Novak EW. 1990. Field bioassessments for selecting test systems to evaluate military training lands in tallgrass prairie. Ecosystem Health. V. Environmental Management. 14:81-93. Springer-Verlag New York Incorporated.

Seastedt, T.R., B.P. Hayden, C.E. Owensby, and A.K. Knapp. 1998. Climate change, elevated Co_2 and predictive modeling: Past and future climate change scenarios for the tallgrass prairie. Pp 283-300 *In* A.K. Knapp, J.M. Briggs, D.C. Hartnet, and S.L. Collins (eds.), Grassland dynamics: long-term ecological research in tallgrass prairie. Oxford University Press, NY, NY, USA.

Seastedt, T.R., M. Briggs, and D.J. Gipson. 1991. Controls of nitrogen limitation in tallgrass prairie. Oecologia 87:72-79.

Shaw, R.B. and V.E Diersing. 1990. Tracked vehicle impacts on vegetation at the Pinyon Canyon Maneuver Site, Colorado. Journal of Environmental Quality 19:234-243.

US Army Environmental Center. 2006. Sustainable range program: Range and training land assessment program. https://srp.army.mil/itam/rtla.

USDA, Soil Conservation Service in cooperation with Kansas Agricultural Experiment Station. 1975. Soil Survey of Riley and Part of Geary County, Kansas.

Wilson, S.D. 1988. The effects of military tank traffic on prairie: a management model. Environmental Management 12:397-403.

Wright, H.A. 1974. Range burning. Journal of Range Management 27:5-11.

Yorks, T.P., N.E. West, R.J. Mueller, and S.D. Warren. 1997. Toleration of traffic by vegetation: Life form conclusions and summary extracts from a comprehensive data base. Environmental Management 21:121-131.

A

B

Figure 1.1. Whole plots were split in 2006 and one-half of each plot received a burn treatment. (A) Ground image of fire intensity. (B) Aerial image of experimental design showing the three blocks in silty clay loam soil in the foreground and the three blocks in silt loam soil in the background.

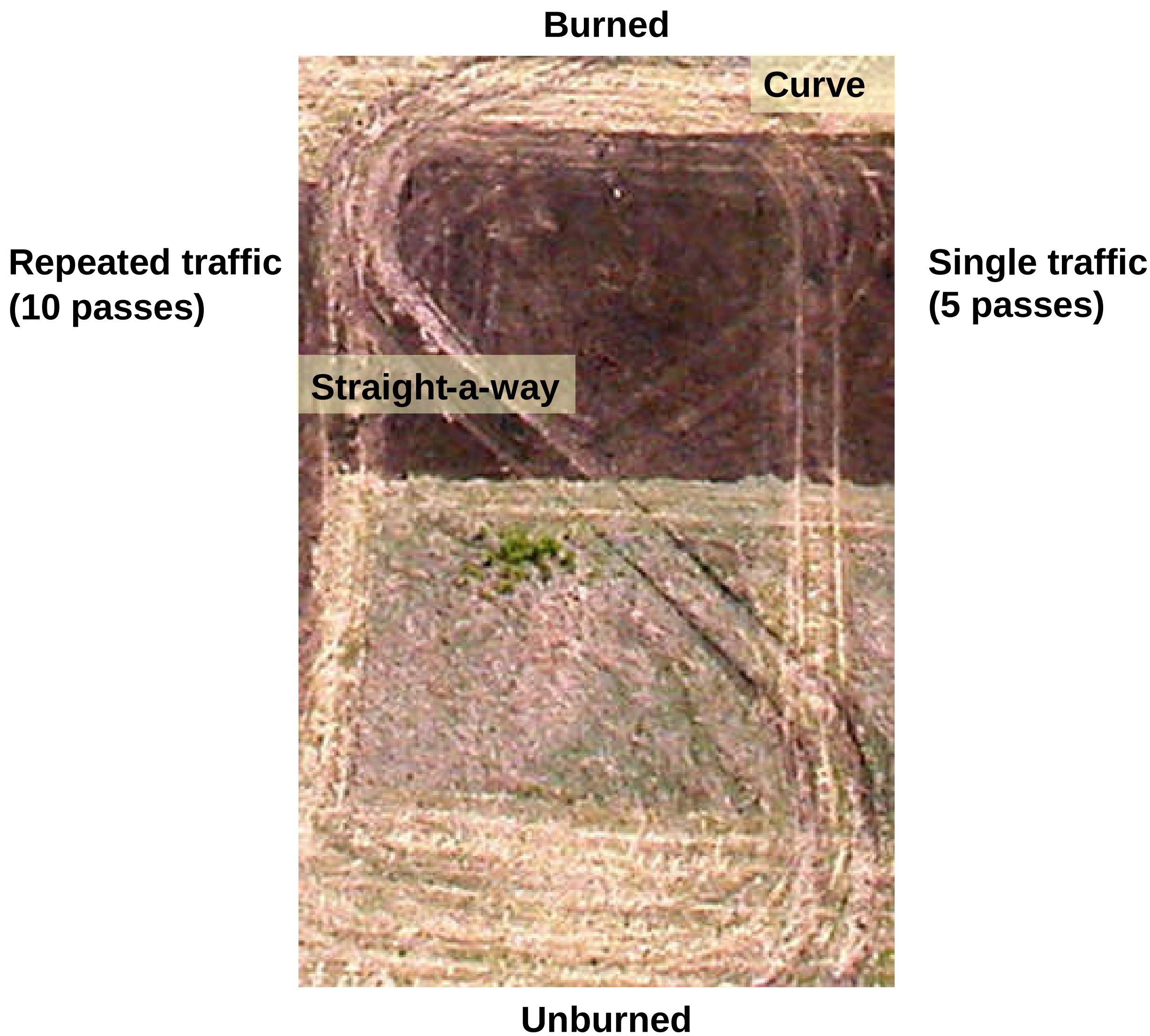


Figure 1.2. Arial image of an individual plot in silty clay loam soil depicting the burned and unburned subplots, single and repeated traffic intensity during wet soil conditions, and curve and straight-a-way sampling areas. Samples were collected from all four curve and straight-a-way areas.

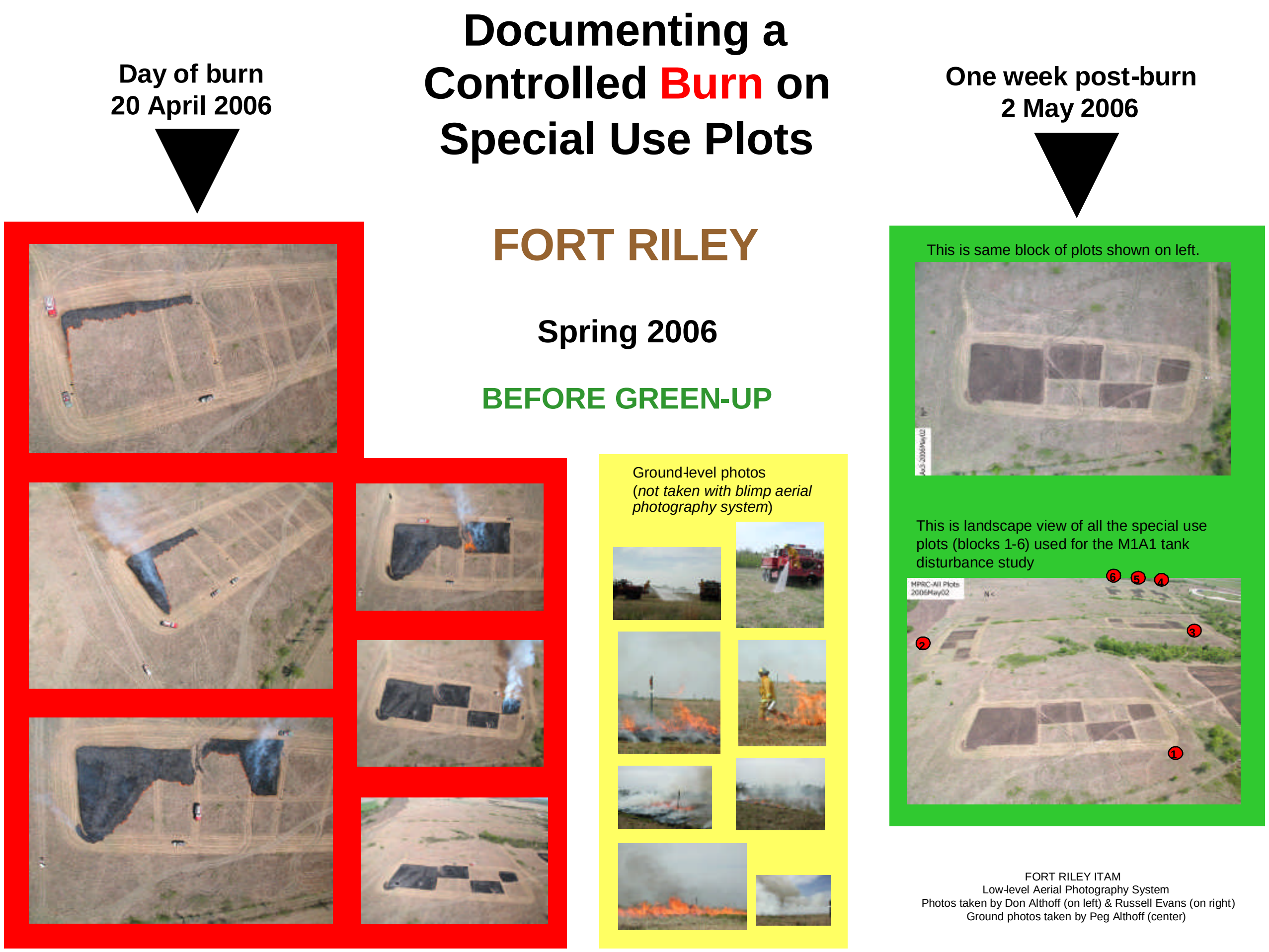


Figure 1.3. All plots pre and post burn. Digital image taken with a remotely-controlled low-level aerial photography system, courtesy of the Kansas Cooperative Fish and Wildlife Research Unit.

Figure 1.4. Aerial images provided by (A) 5.0 meg-pixel Nikon digital cameral and (B) ITAM blimp system.

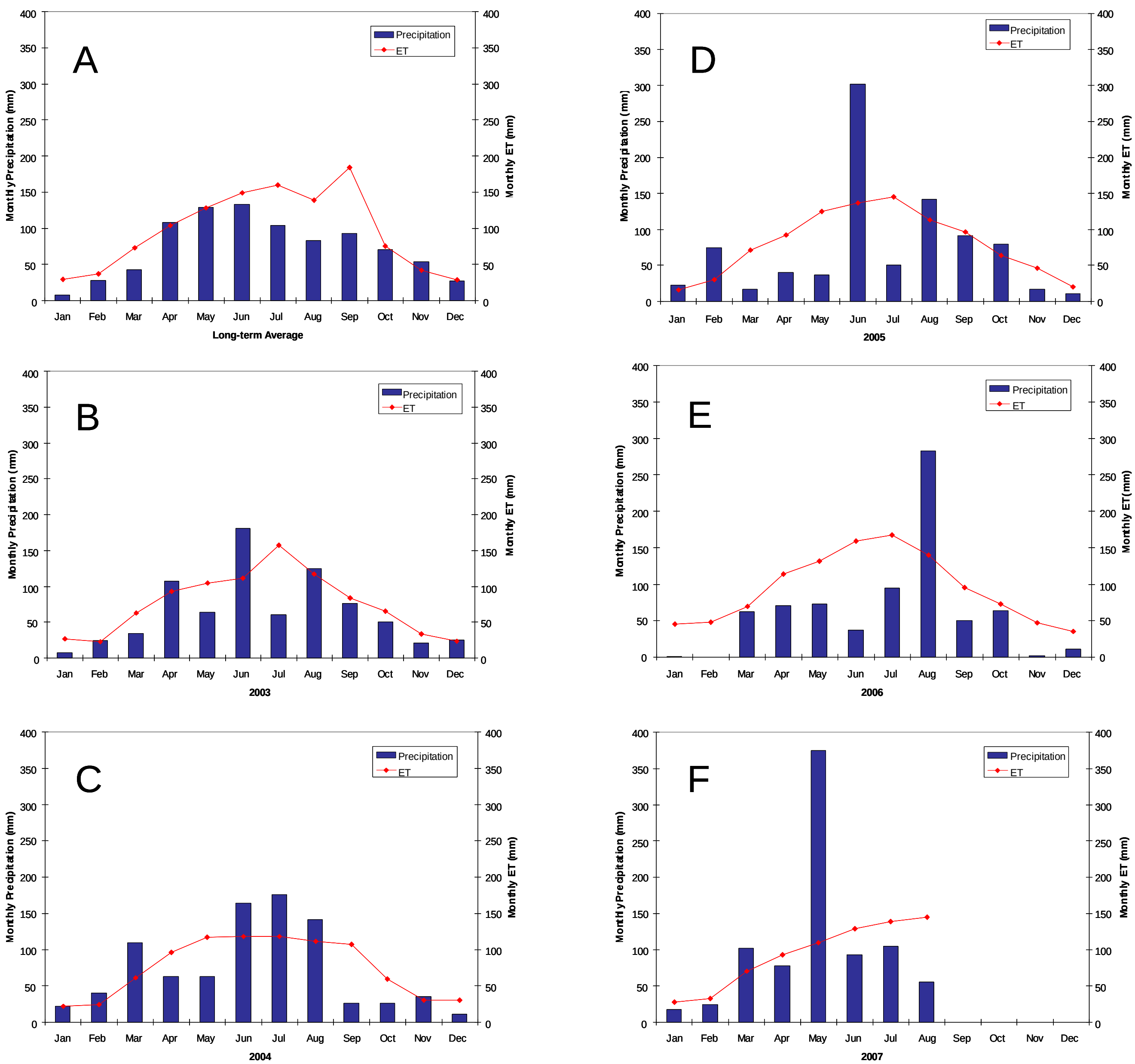


Figure 1.5. Monthly precipitation and evapotranspiration (ET) for (A) long-term average, (B) 2003, (C) 2004, (D) 2005, (E) 2006, and (F) 2007.

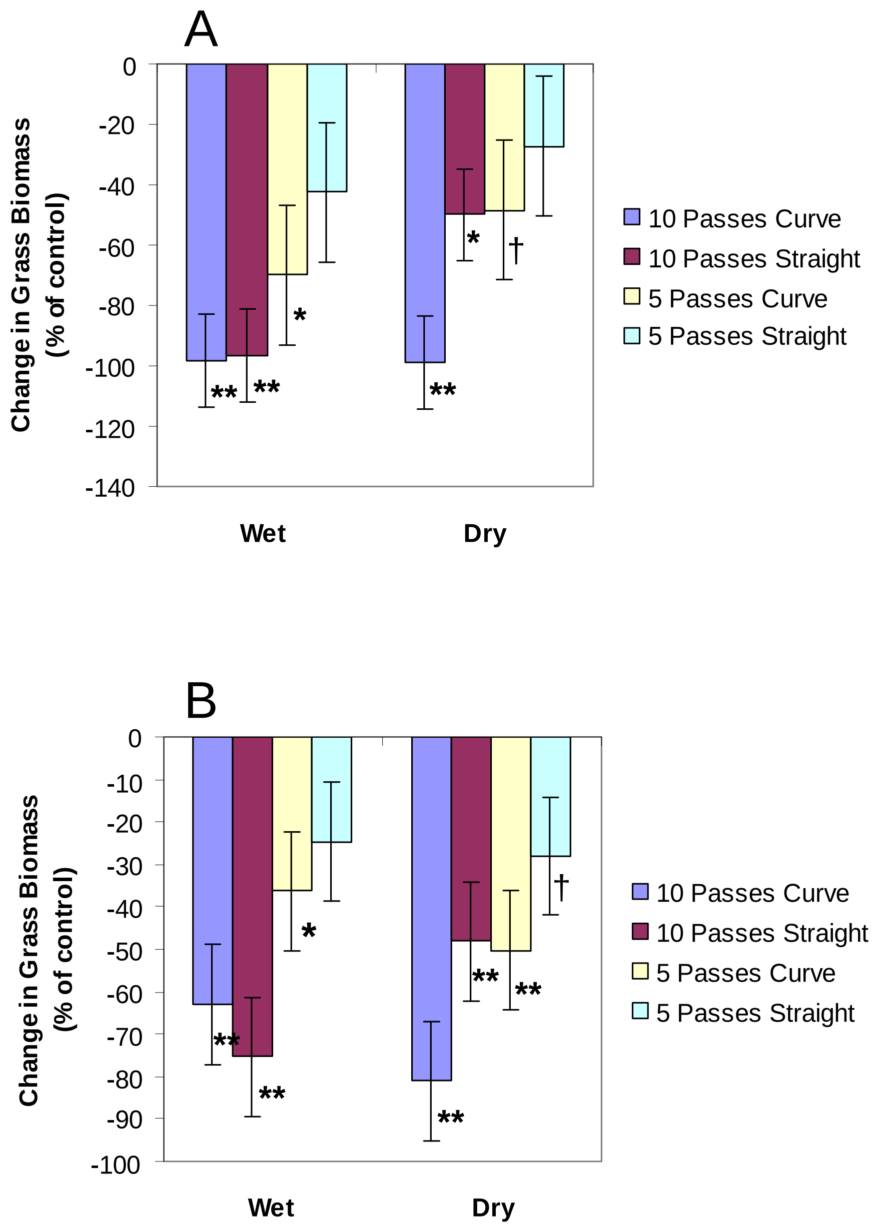


Figure 1.6. Disturbance response for grass biomass in (A) silty clay loam soil and (B) silt loam soil, 2005. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, *, ** indicate $p \leq 0.10$, 0.05, 0.01, respectively. Grass biomass averaged 86 and 194 g m^{-2} for controls in silty clay loam soil and silt loam soil, respectively.

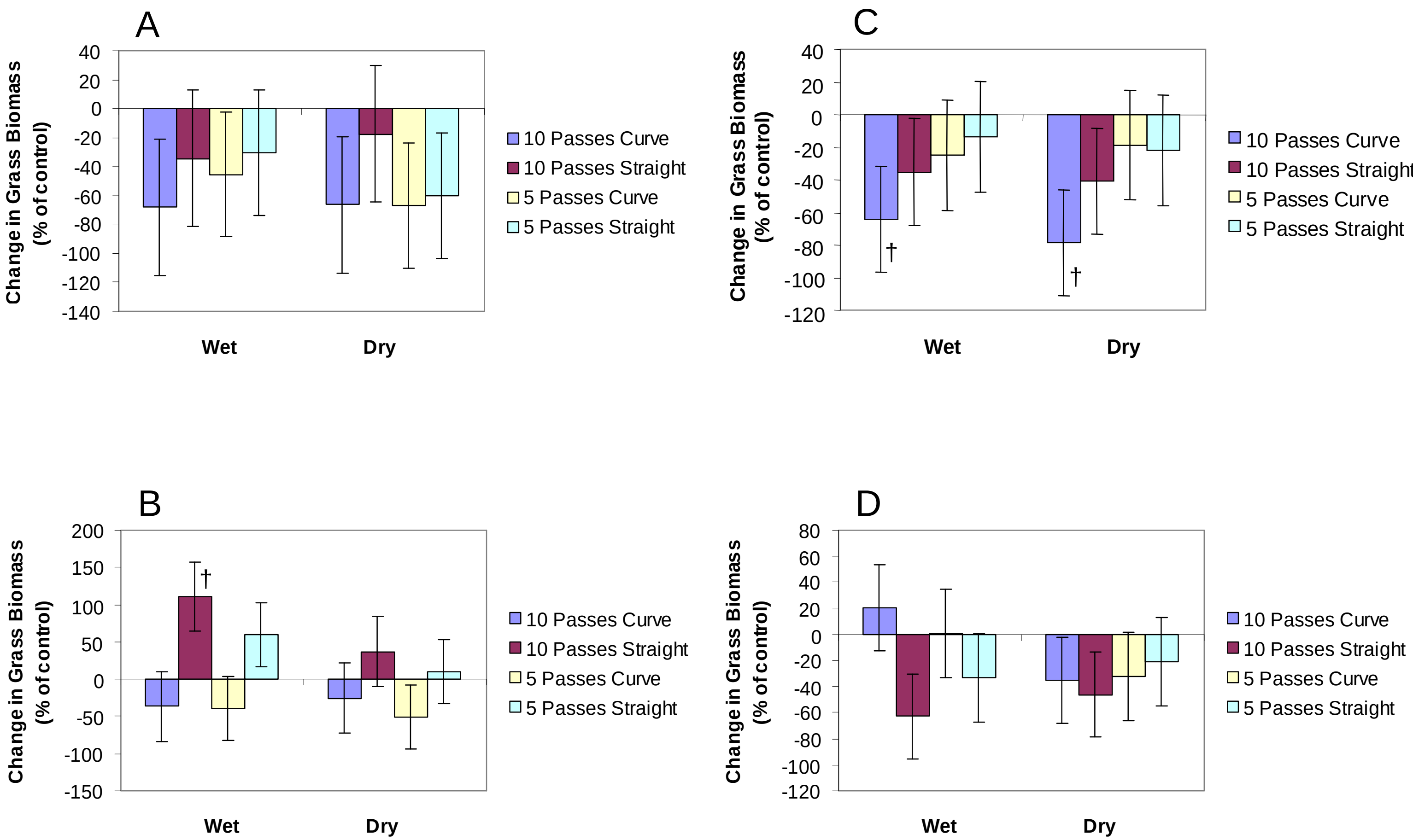


Figure 1.7. Disturbance response for grass biomass in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2006. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. † indicates $p \leq 0.10$. Grass biomass averaged 217 and 86 g m^{-2} for burned and unburned controls, respectively, in silty clay loam soil and 272 and 231 g m^{-2} for burned and unburned controls, respectively, in silt loam soil.

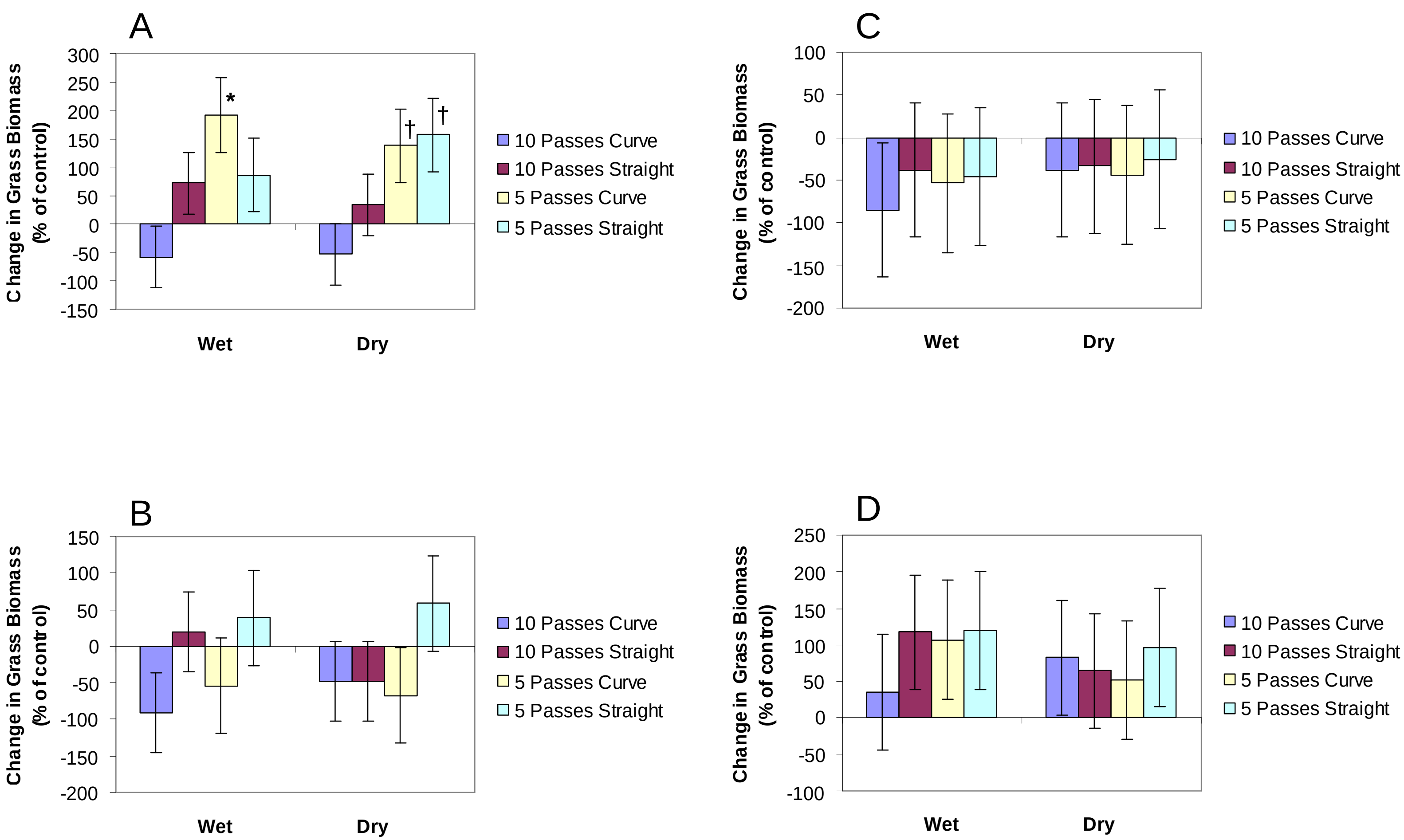


Figure 1.8. Disturbance response for grass biomass in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2007. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, * indicate $p \leq 0.10$, 0.05, respectively. Grass biomass averaged 70 and 127 g m^{-2} for burned and unburned controls, respectively, in silty clay loam soil and 500 and 174 g m^{-2} for burned and unburned controls, respectively, in silt loam soil.

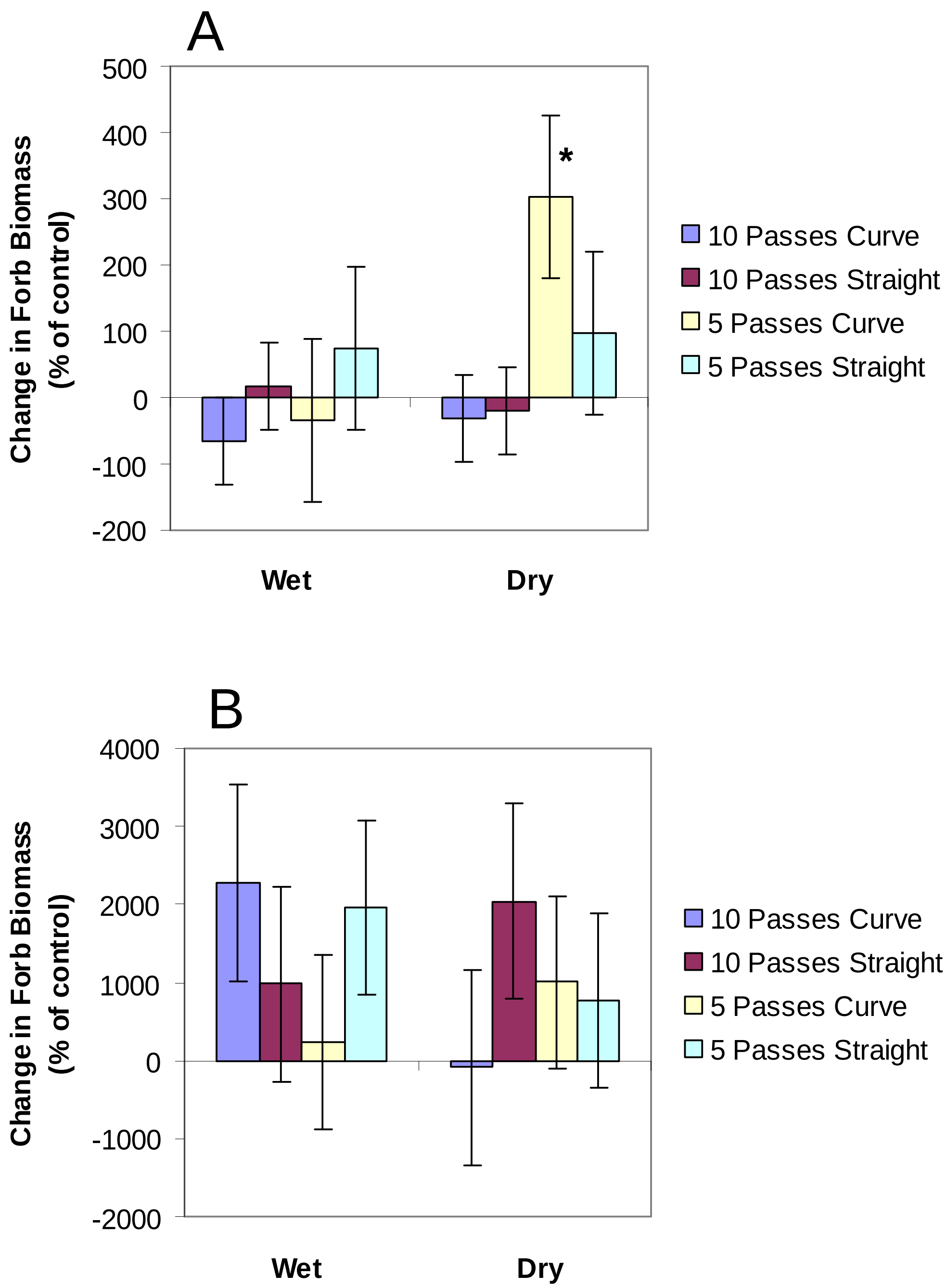


Figure 1.9. Disturbance response for forb biomass in (A) silty clay loam soil and (B) silt loam soil, 2005. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, *, ** indicate $p \leq 0.10$, 0.05, 0.01, respectively. Forb biomass averaged 42 and 35 g m^{-2} for controls in silty clay loam soil and silt loam soil, respectively.

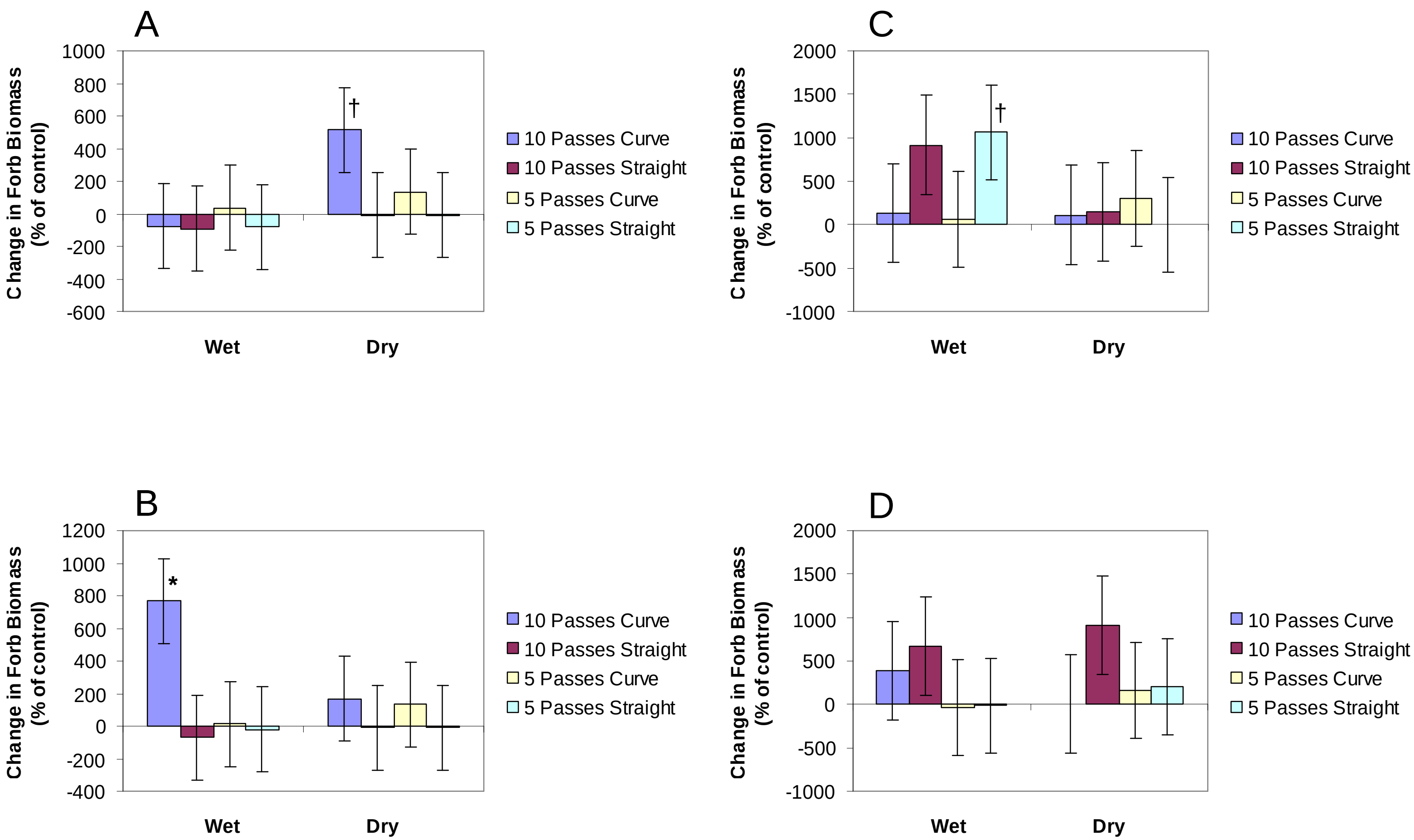


Figure 1.10. Disturbance response for forb biomass in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2006. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, * indicate $p \leq 0.10$, 0.05, respectively. Forb biomass averaged 50 and 55 g m^{-2} for burned and unburned controls, respectively, in silty clay loam soil and 71 and 91 g m^{-2} for burned and unburned controls, respectively, in silt loam soil.

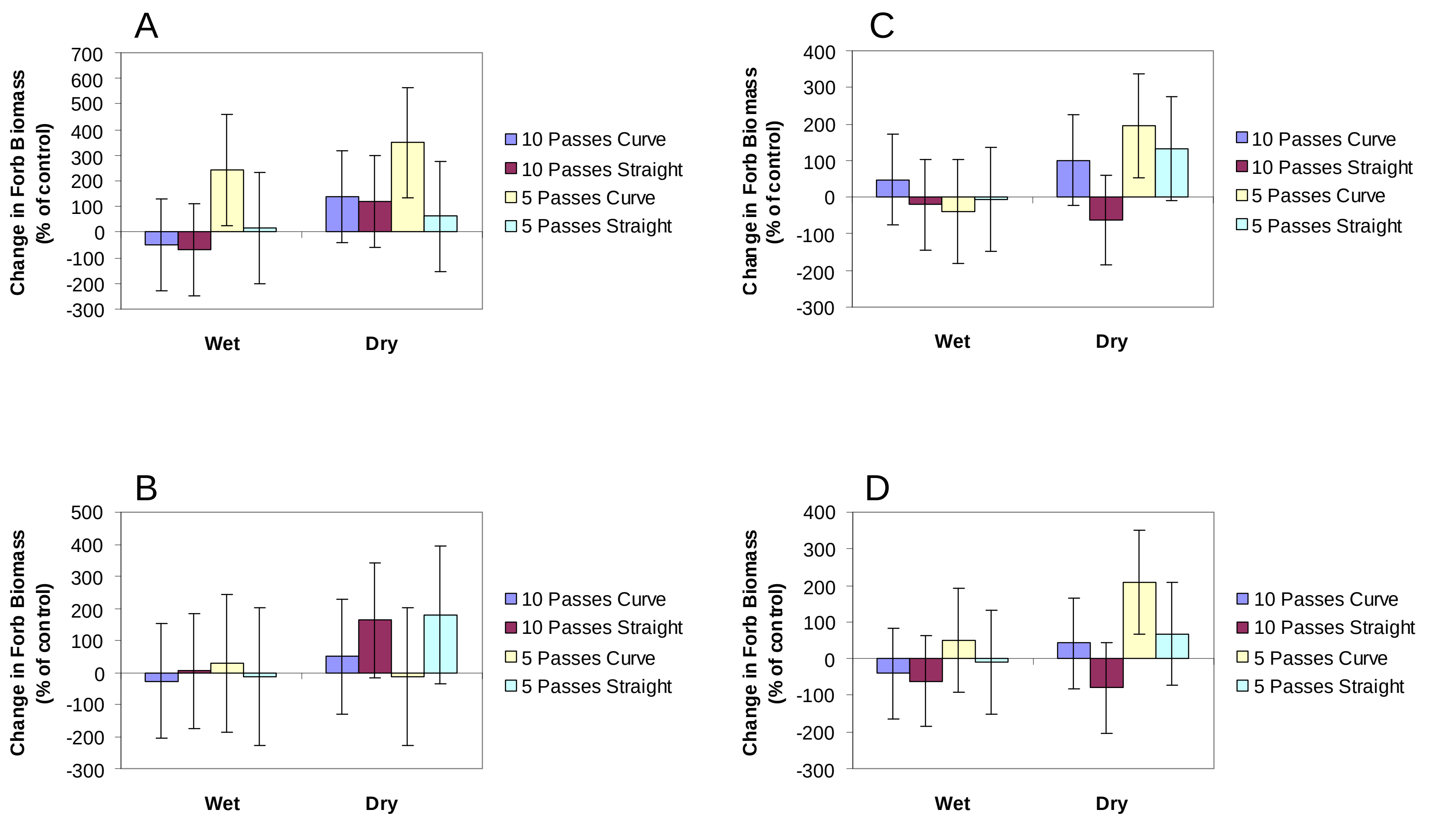


Figure 1.11. Disturbance response for forb biomass in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2007. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. Forb biomass averaged 169 and 58 g m^{-2} for burned and unburned controls, respectively, in silty clay loam soil and 93 and 138 g m^{-2} for burned and unburned controls, respectively, in silt loam soil.

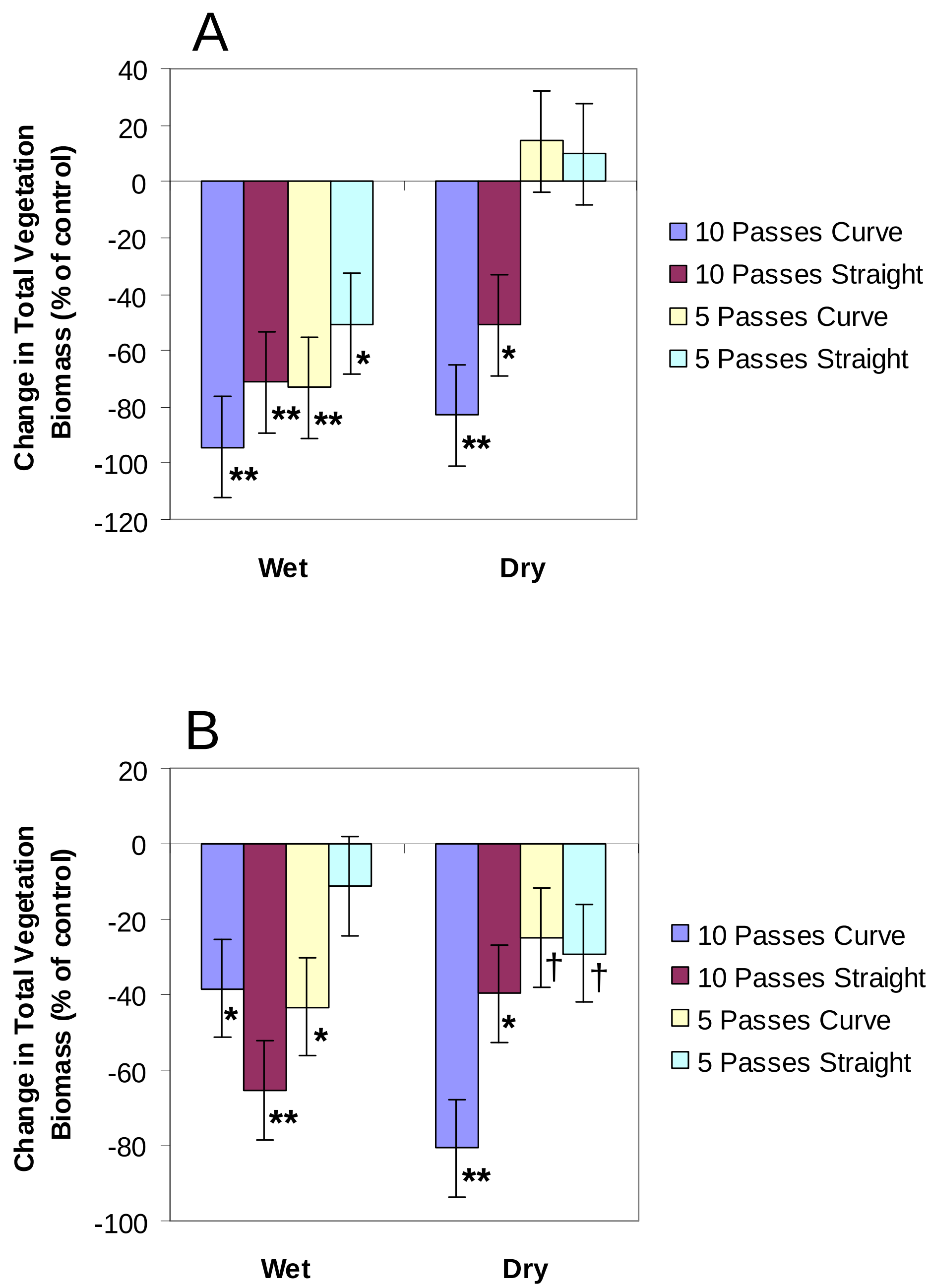


Figure 1.12. Disturbance response for total vegetation biomass in (A) silty clay loam soil and (B) silt loam soil, 2005. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, *, ** indicate $p \leq 0.10, 0.05, 0.01$, respectively. Total biomass averaged 128 and 230 g m^{-2} for controls in silty clay loam soil and silt loam soil, respectively.

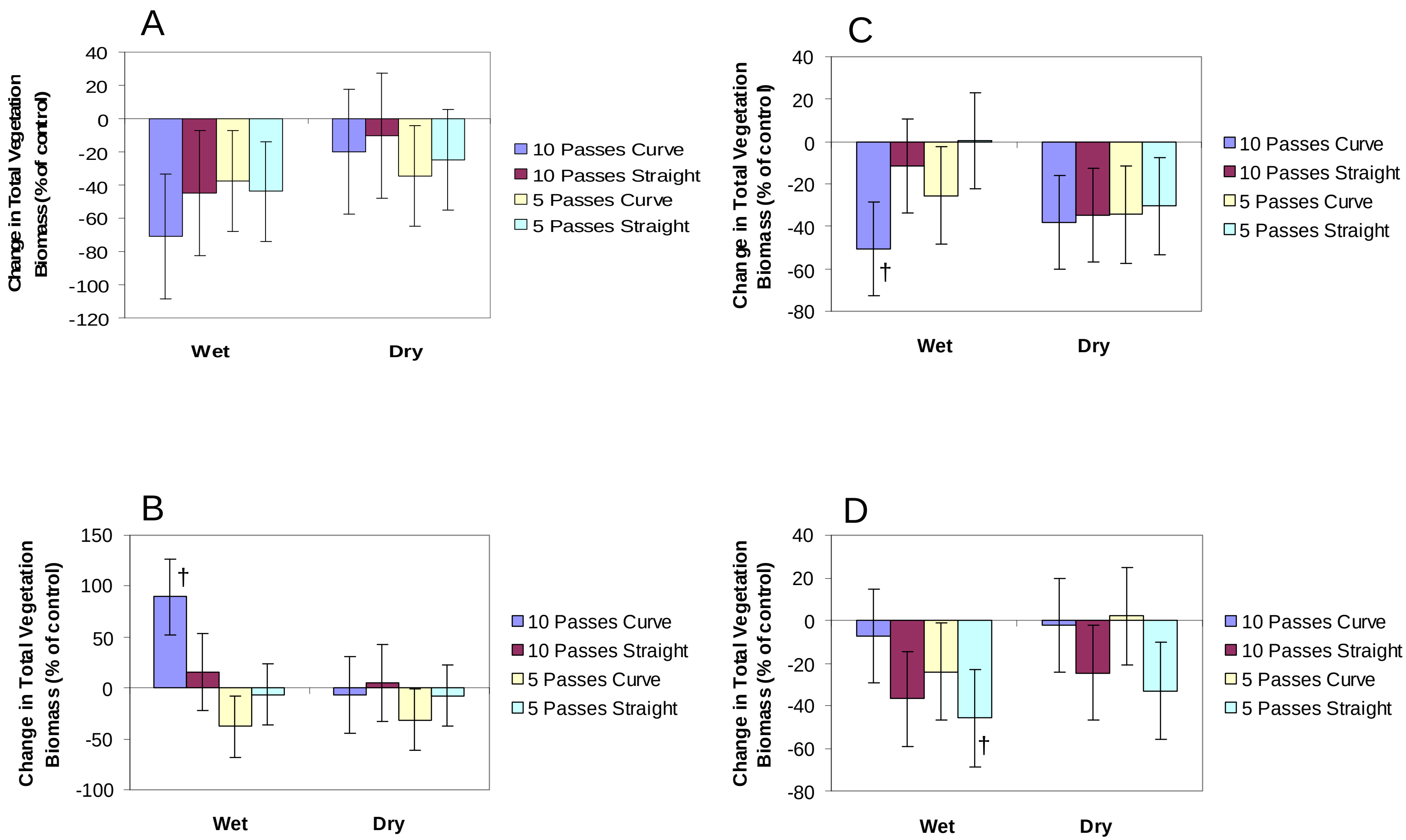


Figure 1.13. Disturbance response for total vegetation biomass in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2006. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. † indicates $p \leq 0.10$. Total biomass averaged 267 and 141 g m^{-2} for burned and unburned controls, respectively, in silty clay loam soil and 343 and 322 g m^{-2} for burned and unburned controls, respectively, in silt loam soil.

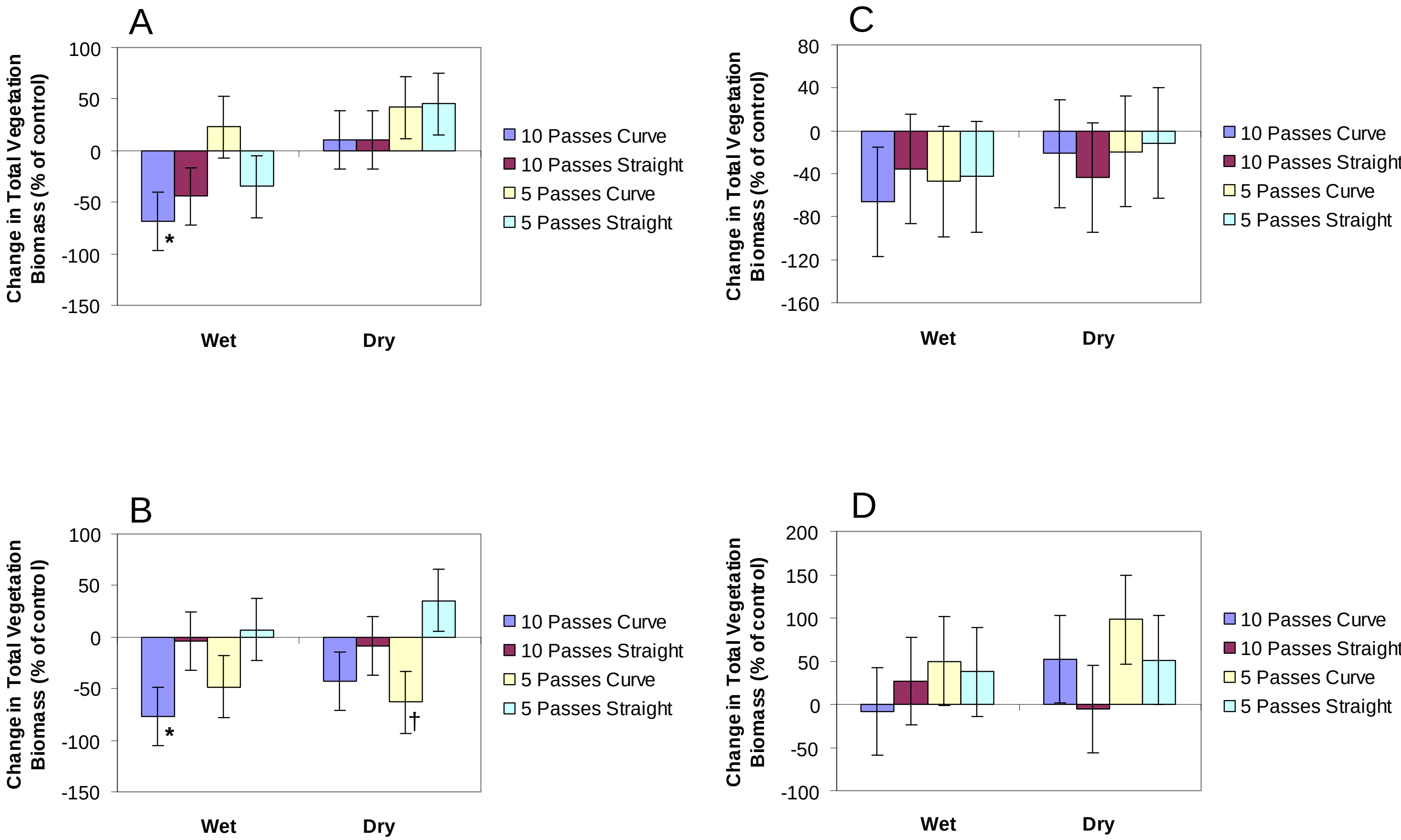
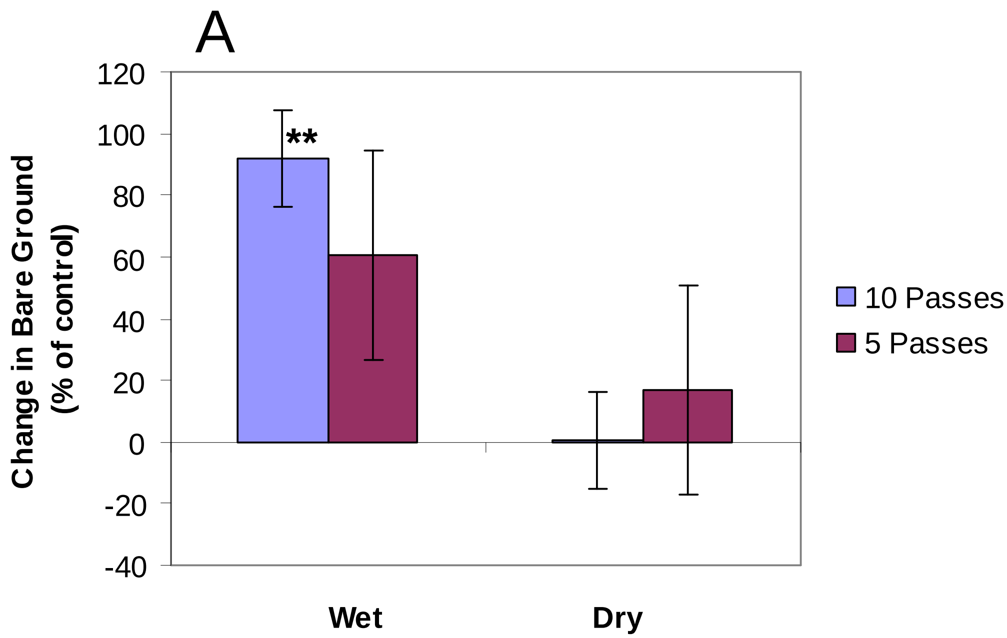


Figure 1.14. Disturbance response for total vegetation biomass in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2007. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, * indicate $p \leq 0.10, 0.05$, respectively. Total biomass averaged 239 and 185 g m^{-2} for burned and unburned controls, respectively, in silty clay loam soil and 592 and 312 g m^{-2} for burned and unburned controls, respectively, in silt loam soil.



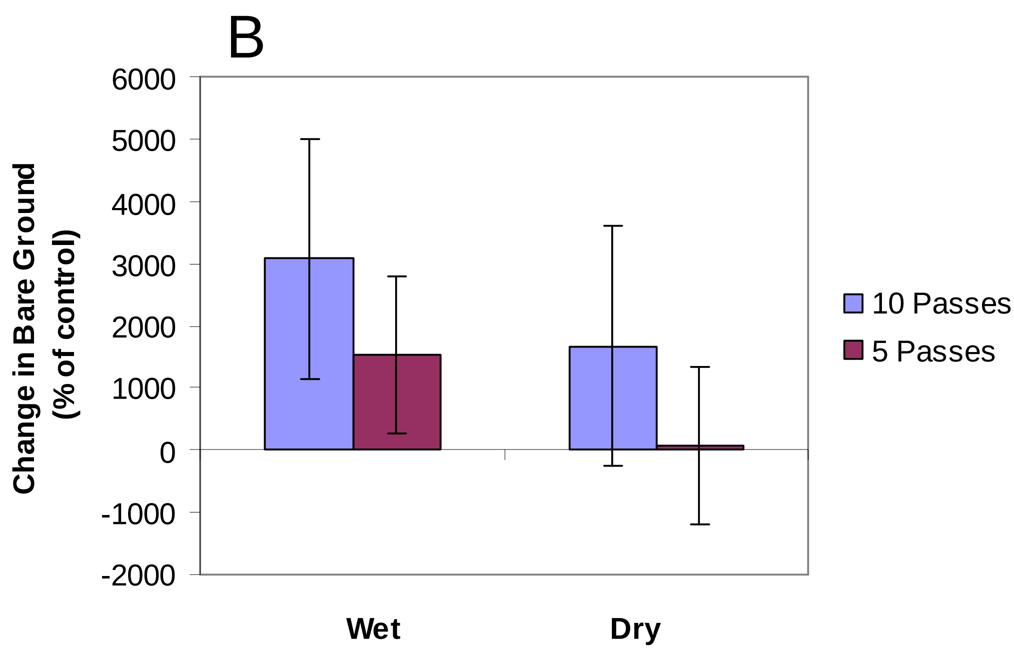


Figure 1.15. Disturbance response for bare ground in (A) silty clay loam soil and (B) silt loam soil, 2005. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. ** indicates $p \leq 0.01$. Bare ground averaged 48 and 7 % for controls in silty clay loam soil and silt loam soil, respectively.

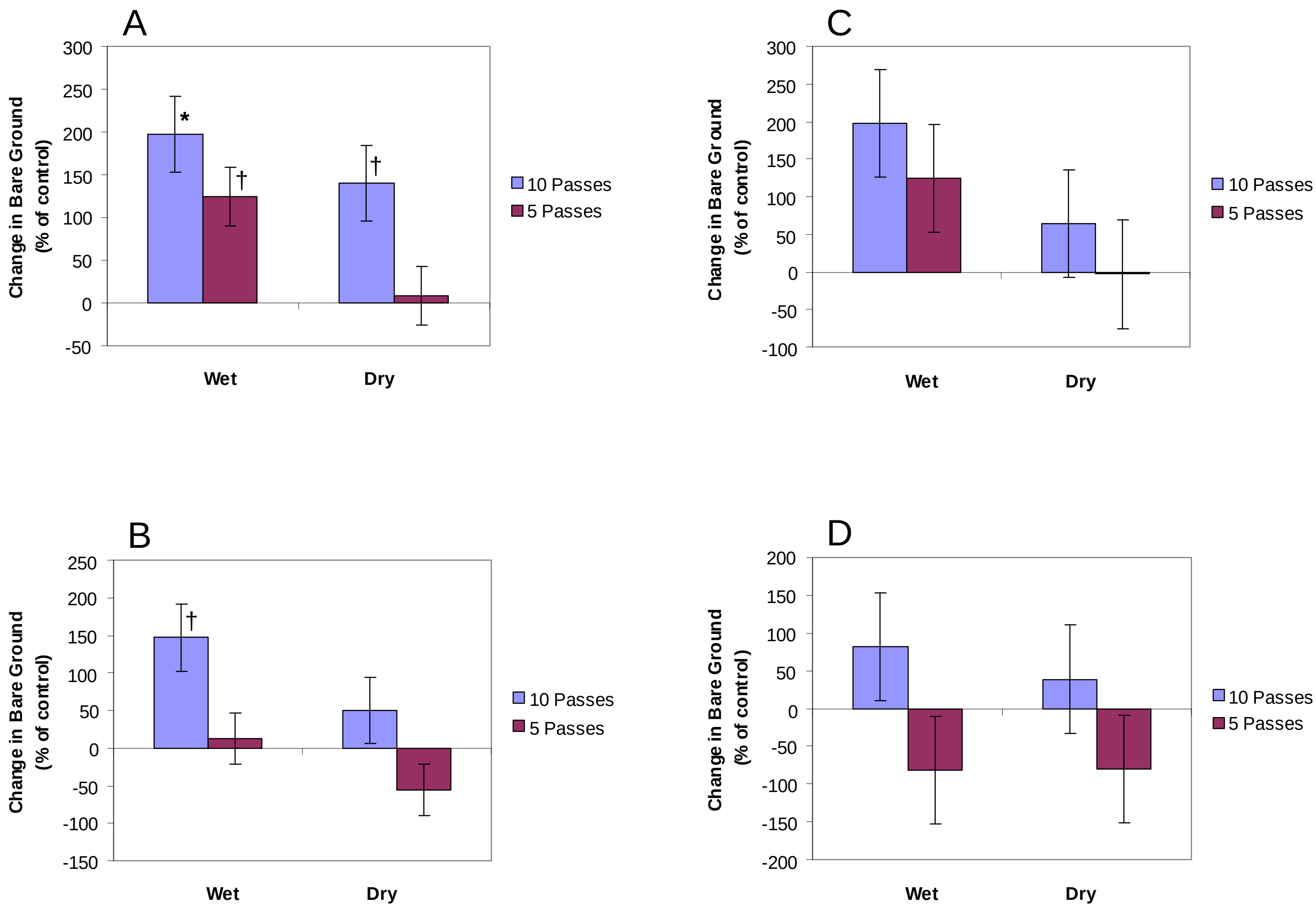


Figure 1.16. Disturbance response for bare ground in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2007. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, * indicate $p \leq 0.10$, 0.05, respectively. Bare ground averaged 38 and 16 % for burned and unburned controls, respectively, in silty clay loam soil and 24 and 8 % for burned and unburned controls, respectively, in silt loam soil.

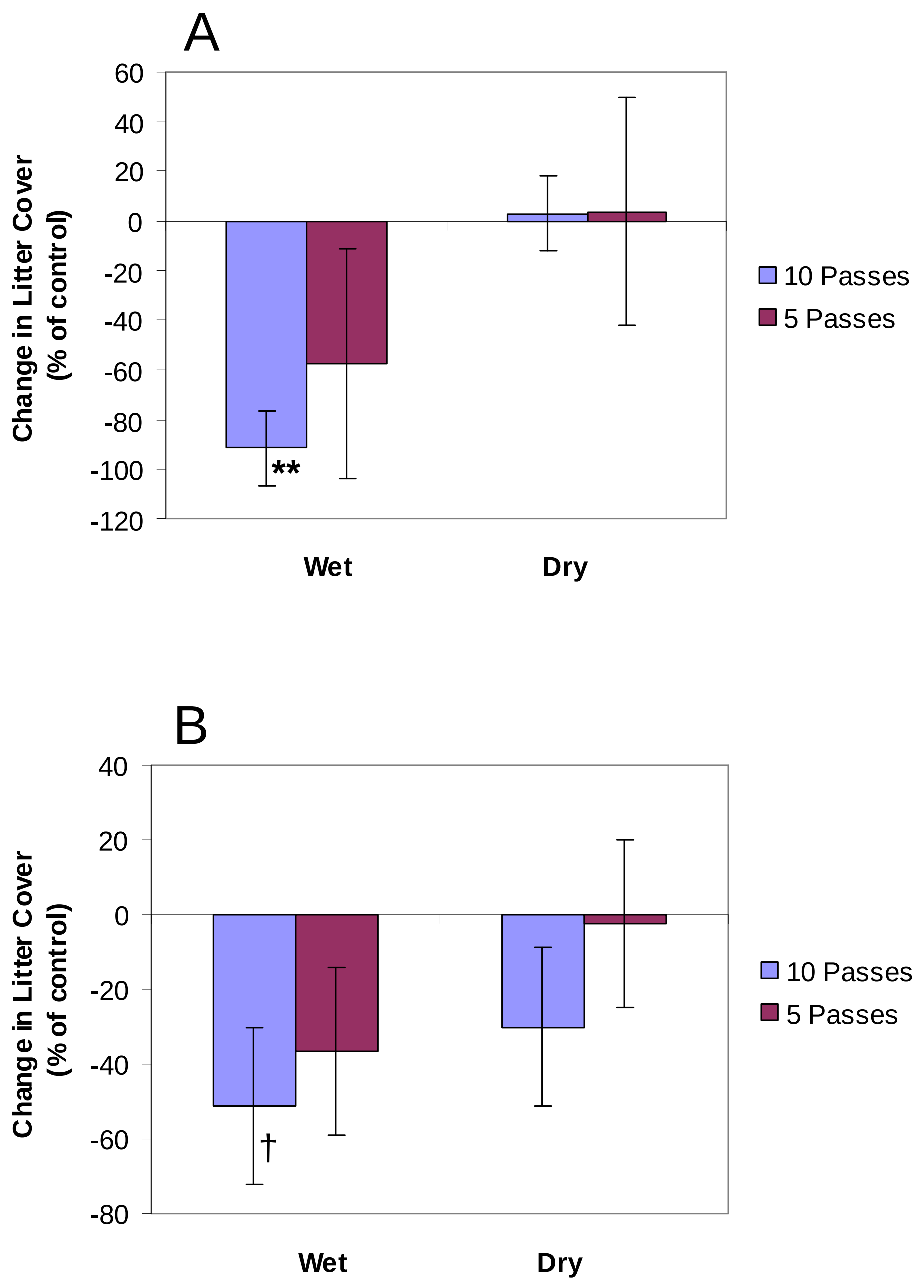


Figure 1.17. Disturbance response for litter cover in (A) silty clay loam soil and (B) silt loam soil, 2005. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, ** indicate $p \leq 0.10$, 0.01, respectively. Litter cover averaged 40 and 89 % for controls in silty clay loam soil and silt loam soil, respectively.

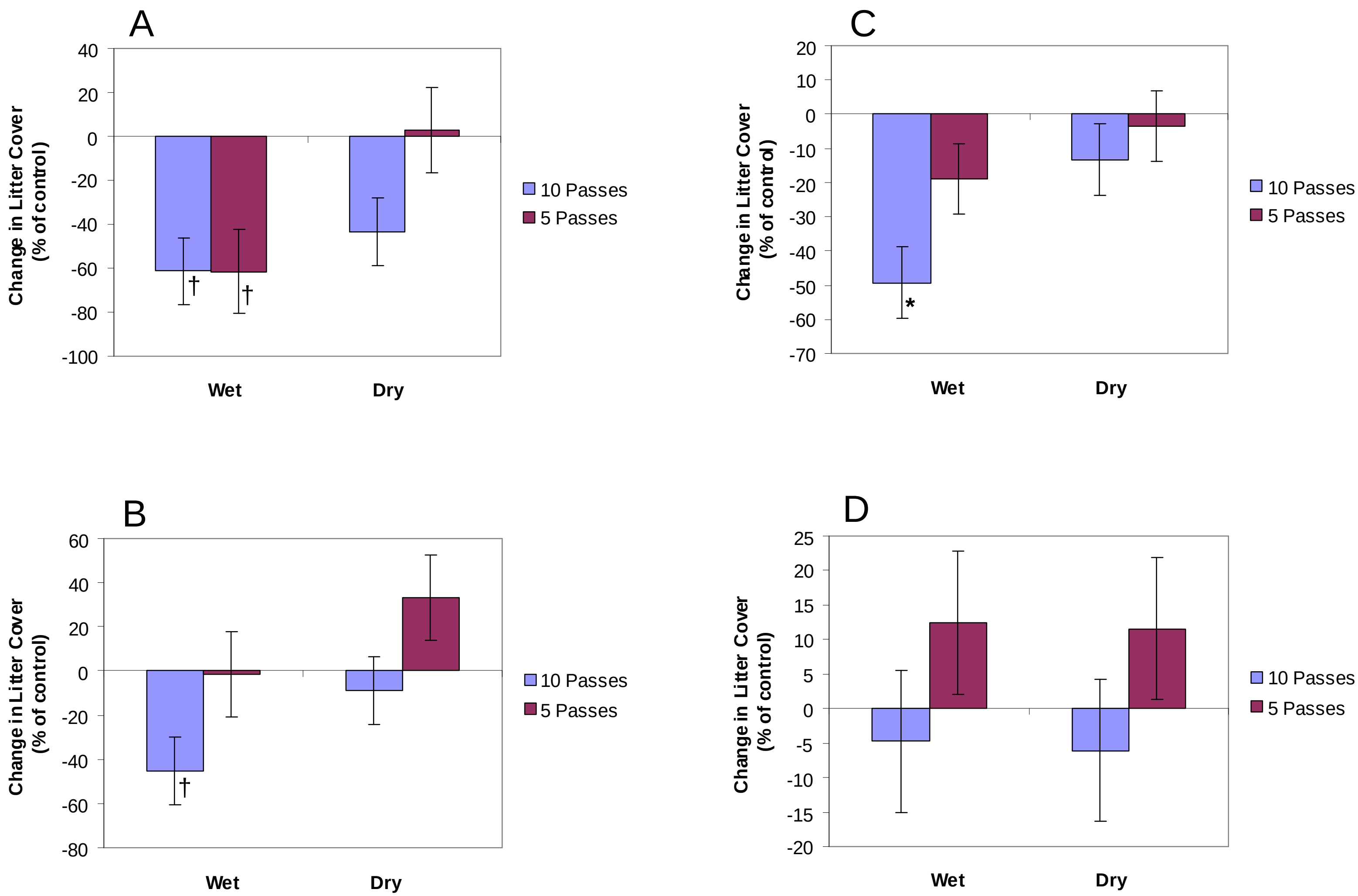


Figure 1.18. Disturbance response for litter cover in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2007. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, * indicate $p \leq 0.10$, 0.05, respectively. Litter cover averaged 46 and 77 % for burned and unburned controls, respectively, in silty clay loam soil and 76 and 91 % for burned and unburned controls, respectively, in silt loam soil.

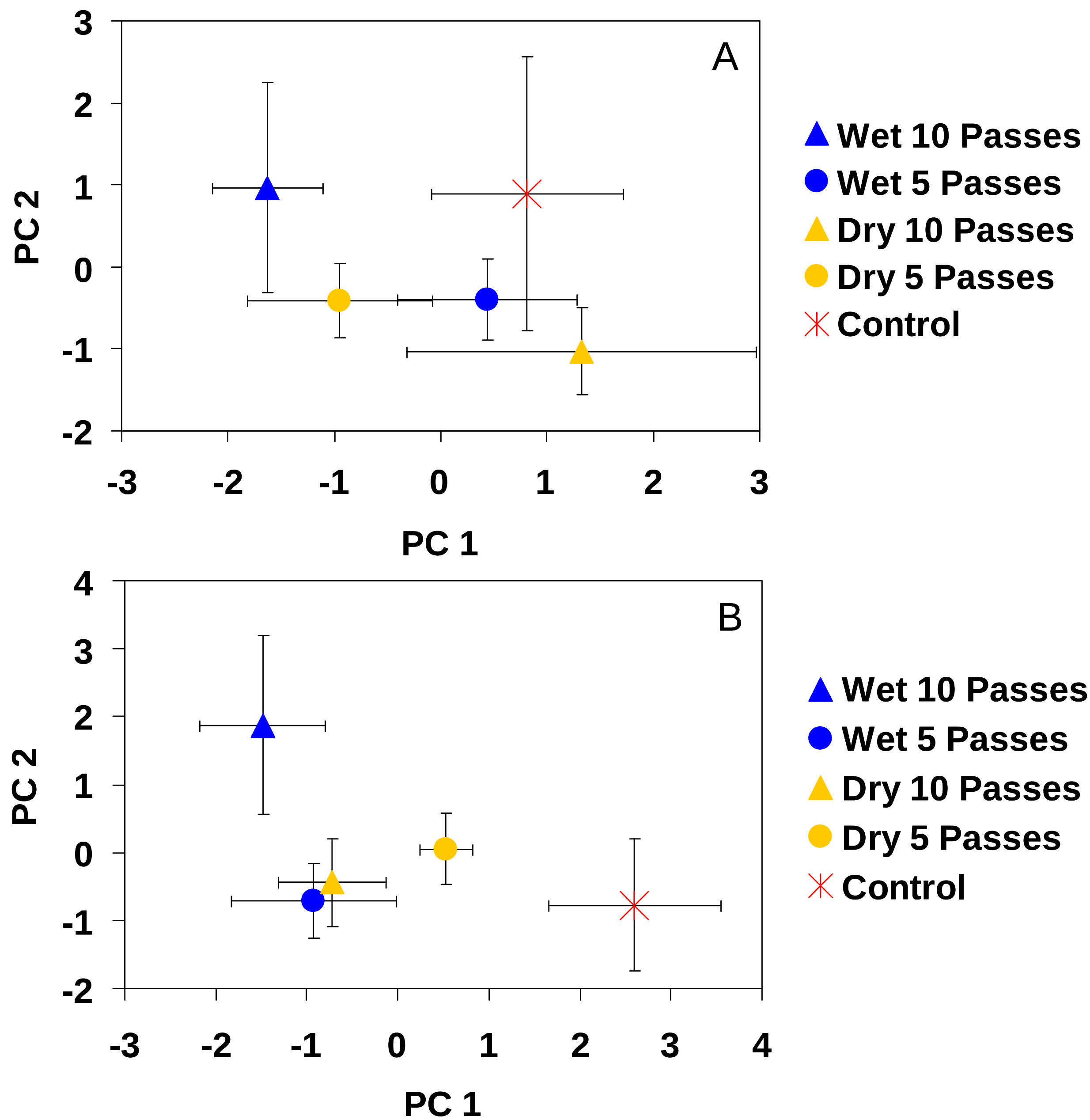


Figure 1.19. Scatterplot of first and second principal components for major vegetation taxa (see Table 1.6) in (A) silty clay loam soil and (B) silt loam soil, 2005. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard errors.

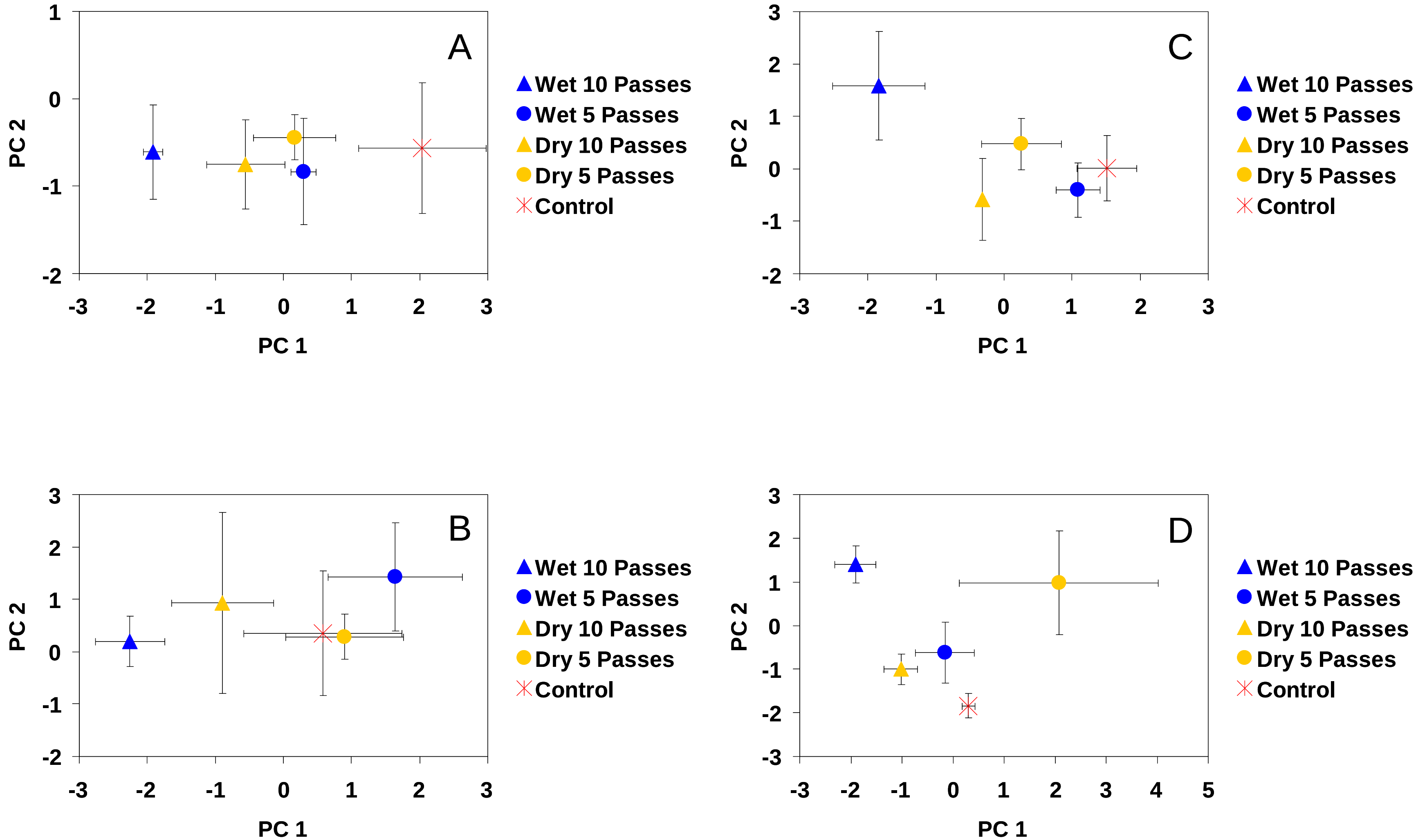


Figure 1.20. Scatterplot of first and second principal components for major vegetation taxa (see Table 1.6) in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2007. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard errors.

Table 1.1. Analysis of variance (F-values) for disturbance response[A] of vegetation in the silty clay loam and silt loam soils, 2005.

	F-values									
	Biomass						Cover			
Effect[B]	Grass ($g\ 0.1\ m^{-2}$)		Forb ($g\ 0.1\ m^{-2}$)		Total ($g\ 0.1\ m^{-2}$)		Litter (%)		Bare Ground (%)	
					Silty Clay Loam					
Treatment (T)	2.29		0.82		8.85	†	11.77	†	11.39	†
Split (S)	7.89	*	5.93	†	17.92	**	0.17		0.05	
T × S	0.03		2.63		6.08	†	0.15		0.56	
Area (A)	3.27		0.00		2.40		N/A		N/A	
T × A	0.56		2.88		0.15		N/A		N/A	
S × A	0.00		0.72		0.64		N/A		N/A	
T × S × A	0.94		1.16		0.60		N/A		N/A	
					Silt Loam					
Treatment (T)	0.41		0.46		0.17		155.22	**	2.63	
Split (S)	21.71	**	1.34		10.34	*	0.53		0.65	
T × S	0.94		0.66		0.23		0.05		0.00	
Area (A)	1.30		0.63		1.36		N/A		N/A	
T × A	1.36		0.25		0.77		N/A		N/A	
S × A	0.08		0.05		0.15		N/A		N/A	
T × S × A	0.53		3.37	†	8.39	*	N/A		N/A	

[A] Disturbance response = (disturbed measurement-undisturbed measurement)/(undisturbed measurement).
[B] Represents treatment = (T) tank traffic during wet or dry soil conditions, (S) Split = half of the plot treated (i.e., 5 passes 2003, plus 5 additional passes, repeated traffic, 2004), or left untreated for 2004 (i.e., 5 passes single traffic, 2003), (A) Area = subplot from which sample was collected (i.e., curve, straight-a-way).
†, *, ** Denotes significance at the $p \leq 0.10$, 0.05, 0.01 probability levels, respectively.
N/A = not applicable (data not collected separately for areas).

Table 1.2. Analysis of variance (F-values) for disturbance response[A] of vegetation in the silty clay loam soil, 2006.

	F-values		
	Biomass		
Effect[B]	Grass (g 0.1 m^{-2})	Forb (g 0.1 m^{-2})	Total (g 0.1 m^{-2})
Treatment (T)	0.47	0.38	0.00
Split (S)	1.52	0.19	3.67
T × S	1.76	0.52	0.27
Area (A)	4.07 †	2.99	0.04
T × A	0.28	0.06	0.24
S × A	0.22	1.71	0.27
T × S × A	0.01	0.00	0.15
Burn (B)	6.94 †	0.00	7.59 *
T × B	0.38	2.98	3.49
S × B	0.34	2.16	2.95
T × S × B	0.31	0.79	2.47
A × B	3.00	0.79	0.17
T × A × B	1.02	1.45	0.51
S × A × B	0.01	0.23	1.80
T × S × A × B	0.30	4.33 †	1.29

[A] Disturbance response = (disturbed measurement-undisturbed measurement)/(undisturbed measurement).
[B] Represents treatment = (T) tank traffic during wet or dry soil conditions, (S) Split = half of the plot treated (i.e., 5 passes 2003, plus 5 additional passes, repeated traffic, 2004), or left untreated for 2004 (i.e., 5 passes single traffic, 2003), (A) Area = subplot from which sample was collected (i.e., curve, straight-a-way).
[†], * Denotes significance at the $p \leq 0.10$, 0.05 probability levels, respectively.

Table 1.3. Analysis of variance (F-values) for disturbance response[A] of vegetation in the silt loam soil, 2006.

	F-values		
	Biomass		
Effect[B]	Grass ($g\ 0.1\ m^{-2}$)	Forb ($g\ 0.1\ m^{-2}$)	Total ($g\ 0.1\ m^{-2}$)
Treatment (T)	0.38	0.30	0.06
Split (S)	2.17	0.47	0.02
T × S	0.09	0.07	0.02
Area (A)	0.14	1.77	0.11
T × A	0.96	0.54	1.08
S × A	0.01	0.36	0.03
T × S × A	0.19	0.35	0.01
Burn (B)	0.18	0.08	0.15
T × B	0.03	2.06	1.10
S × B	0.80	1.35	0.54
T × S × B	0.00	0.19	1.50
A × B	2.80	0.03	3.16
T × A × B	1.17	4.22 †	1.55
S × A × B	1.29	0.42	0.01
T × S × A × B	0.00	0.00	0.68

[A] Disturbance response = (disturbed measurement-undisturbed measurement)/(undisturbed measurement).
[B] Represents treatment = (T) tank traffic during wet or dry soil conditions, (S) Split = half of the plot treated (i.e., 5 passes 2003, plus 5 additional passes, repeated traffic, 2004), or left untreated for 2004 (i.e., 5 passes single traffic, 2003), (A) Area = subplot from which sample was collected (i.e., curve, straight-a-way).
† Denotes significance at the $p \leq 0.10$ probability levels.

Table 1.4. Analysis of variance (F-values) for disturbance response[A] of vegetation in the silty clay loam soil, 2007.

Effect[B]	Grass ($g\ 0.1\ m^{-2}$)	Forb ($g\ 0.1\ m^{-2}$)	Total ($g\ 0.1\ m^{-2}$)	Litter (%)	Bare Ground (%)
	F-values				
	Biomass			Cover	
Treatment (T)	0.02	0.92	3.09	9.97 †	7.74
Split (S)	6.92 †	0.29	2.62	4.77	11.58 †
T × S	0.26	0.15	0.12	1.86	0.07
Area (A)	3.26	0.13	6.98 *	N/A	N/A
T × A	0.00	0.35	0.23	N/A	N/A
S × A	0.58	0.46	0.13	N/A	N/A
T × S × A	5.98 *	0.04	3.67 †	N/A	N/A
Burn (B)	6.16 †	0.38	4.40 †	5.72	7.62
T × B	0.00	0.10	4.73 †	0.14	0.01
S × B	2.90	0.56	1.42	0.56	0.13
T × S × B	0.02	0.10	0.04	9.58 †	1.33
A × B	0.61	1.44	11.15 *	N/A	N/A
T × A × B	1.54	0.74	0.14	N/A	N/A
S × A × B	2.58	0.47	2.04	N/A	N/A
T × S × A × B	0.04	0.25	0.00	N/A	N/A

[A] Disturbance response = (disturbed measurement-undisturbed measurement)/(undisturbed measurement).
[B] Represents treatment = (T) tank traffic during wet or dry soil conditions, (S) Split = half of the plot treated (i.e., 5 passes 2003, plus 5 additional passes, repeated traffic, 2004), or left untreated for 2004 (i.e., 5 passes single traffic, 2003), (A) Area = subplot from which sample was collected (i.e., curve, straight-a-way). †, * Denotes significance at the $p \leq 0.10$, 0.05 probability levels, respectively.
N/A = not applicable (data not collected separately for areas).

Table 1.5. Analysis of variance (F-values) for disturbance response [A] of vegetation in the silt loam soil, 2007.

Effect[B]	F-values							
	Biomass					Cover		
	Grass ($g\ 0.1\ m^{-2}$)	Forb ($g\ 0.1\ m^{-2}$)		Total ($g\ 0.1\ m^{-2}$)		Litter (%)		Bare Ground (%)
Treatment (T)	0.00	0.49		0.75		1.78		3.53
Split (S)	0.42	0.99		28.82	**	11.47	†	3.99
T × S	0.38	0.77		1.86		0.82		0.10
Area (A)	1.78	1.23		0.43		N/A		N/A
T × A	0.44	0.66		3.62	†	N/A		N/A
S × A	0.05	0.07		0.12		N/A		N/A
T × S × A	1.56	0.00		1.51		N/A		N/A
Burn (B)	3.86	0.28		7.25	*	9.09	†	4.01
T × B	0.10	0.71		0.00		2.72		1.84
S × B	0.17	0.63		4.83	†	0.06		0.44
T × S × B	0.22	3.69	†	0.04		0.91		0.06
A × B	0.15	0.07		3.20		N/A		N/A
T × A × B	0.10	0.00		1.87		N/A		N/A
S × A × B	0.03	0.68		0.47		N/A		N/A
T × S × A × B	0.50	0.04		0.01		N/A		N/A

[A] Disturbance response = (disturbed measurement-undisturbed measurement)/(undisturbed measurement).
[B] Represents treatment = (T) tank traffic during wet or dry soil conditions, (S) Split = half of the plot treated (i.e., 5 passes 2003, plus 5 additional passes, repeated traffic, 2004), or left untreated for 2004 (i.e., 5 passes single traffic, 2003), (A) Area = subplot from which sample was collected (i.e., curve, straight-a-way).
†, *, ** Denotes significance at the $p \leq 0.10$, 0.05, 0.01 probability levels, respectively.
N/A = not applicable (data not collected separately for areas).

Table 1.6. Principal components analysis of vegetation taxa for the silty clay loam and silt loam soils, 2005 and 2007.

	Eigenvectors							
	Silty Clay Loam				Silt Loam			
	2005		2007		2005		2007	
Plant Taxa	PC[A] 1	PC 2	PC 1	PC 2	PC 1	PC 2	PC 1	PC 2
Andropogon gerardii (big bluestem)	-0.30	0.27	-0.08	-0.30	0.12	0.00	0.25	-0.33
Schizachyrium scoparium (little bluestem)	0.14	0.36	0.10	0.03	0.16	0.50	0.40	0.21
Panicum virgatum (switchgrass)	-0.02	-0.02	0.33	-0.22	0.35	0.02	-0.01	-0.04
Sorghastrum nutans (indiangrass)	0.42	-0.13	0.29	0.46	0.49	0.05	-0.20	-0.13
Sporobolus asper (dropseed)	0.09	-0.43	-0.16	-0.27	0.23	-0.24	-0.16	0.25
Bromus spp. (brome)	-0.15	-0.32	-0.20	-0.10	-0.13	0.33	-0.29	0.44
Koeleria macrantha (prairie junegrass)	0.40	0.08	0.06	0.52	-0.08	0.25	0.43	0.28
Carex spp. (sedge)	0.12	0.24	0.15	-0.12	0.25	-0.27	0.36	-0.20
Other Grasses	-0.29	0.19	-0.31	-0.04	-0.13	-0.28	-0.21	-0.50
Aster ericoides (heath aster)	0.23	-0.11	0.38	0.00	0.27	0.30	0.11	0.04
Desmanthus illinoensis (Illinois bundleflower)	-0.38	-0.14	0.12	-0.28	0.36	0.12	0.00	0.00
Ambrosia spp. (ragweed)	-0.13	-0.20	-0.27	-0.01	-0.22	0.25	-0.08	0.09
Solidago spp. (goldenrod)	0.31	-0.05	0.36	0.03	-0.01	0.45	0.40	0.25
Erigeron strigosus (daisy fleabane)	-0.09	0.51	-0.23	0.43	-0.27	0.04	-0.29	0.36
Other Forbs	-0.32	-0.24	-0.42	0.13	-0.34	0.04	-0.11	0.10
Eigenvalue	3.57	2.88	3.00	2.09	3.40	2.60	2.81	2.13
Cumulative variance (%)	23.81	42.99	19.98	33.89	22.69	39.99	20.06	35.30

[A] PC = principal component.

CHAPTER 2 - Evaluation of Soil Physical and Chemical Characteristics Following Disturbance by an Abrams M1A1 Main Battle Tank

Peggy S. Althoff, S.J. Thien, M.B. Kirkham, T.C. Todd, and P.S. Gipson.

Peggy S. Althoff, M.B. Kirkham, and S.J. Thien, Dept. Of Agronomy; T.C. Todd, Dept. Of Plant Pathology; P.S. Gipson, U.S.G.S. Kansas Cooperative Fish and Wildlife Research Unit, Kansas State University; Manhattan, KS, 66506.

For submission to Agronomy Journal.

ABSTRACT

Mechanized maneuver training can impact soil quality in many ways, most notably through soil displacement and compaction. Numerous studies have identified ecological processes susceptible to military training activities but additional research is needed to identify indicator variables for inclusion in monitoring programs on military lands. A replicated small-plot study of tracked vehicle disturbance effects on tallgrass prairie soils and communities was initiated on Fort Riley, Kansas in 2003. The objectives were to evaluate rates of recovery in a suite of plant and soil-quality indicators over a range of disturbances encompassing soil type, environmental conditions, and traffic intensity. A randomized complete block design composed of three treatments (a non-trafficked control, M1A1 tank traffic during wet soil conditions, and tank traffic during dry soil conditions) and three replications was established in each of two soil types, a silty clay loam and a silt loam. Soil physical (rutting and compaction) and chemical (soil organic matter and nutrients) properties were monitored during 2005 through 2007. Rut depth remained significant ($p \leq 0.10$) for inside and outside tracks of the repeated traffic-wet soil condition treatment and for the inside track of the repeated traffic-dry soil condition treatment in both soil types. Curve areas exhibited increased penetrometer resistances and greater bulk densities than straight-a-ways across all treatments in silty clay loam and silt loam soil, respectively. Total soil C and N were reduced ($p \leq 0.10$) to a greater extent for disturbance during wet compared to dry soil conditions and for curve compared to straight-a-way areas in both soil types. Disturbance impacts on soil fertility levels varied with year and treatment. Soil displacement and compaction can have profound effects on soil function by limiting water and oxygen infiltration, reducing root and microbial functions, and increasing erosion potential, and placing the resiliency of the ecosystem at risk, but, overall, tallgrass prairie soils appear

relatively resilient to mission training activities on Fort Riley and can meet the requirement for sustainability provided suitable management of impacts.

INTRODUCTION

The ecological integrity of a landscape largely is dependent on the quality of its soils, which in turn is a function of the physical, chemical, and biological components (Andrews et al., 2004). Mechanized maneuver training can impact soil quality in many ways, most notably through displacement and compaction. The environmental impacts of military vehicle use have been reviewed recently by Anderson et al. (2005). Numerous studies have identified ecological processes susceptible to military training activities but additional research is needed to identify indicator variables for inclusion in monitoring programs on military lands. In a study of mechanized training impacts on Fort Riley, bulk density, porosity, and water content all were negatively impacted in disturbed areas (Althoff et al., 2007). In a controlled Fort Riley study, the severity of compaction was dependent on soil type, moisture condition, and traffic intensity (Althoff, 2005). Maximum bulk densities occurred after repeated tank traffic during wet soil conditions for both silty clay loam and silt loam soils, although moisture condition had a greater effect in the silty clay loam soil. Penetrometer resistance indicated that compaction was more severe in the silt loam soil. Vehicle rutting, another prominent disturbance on military lands, is expected to be greater for wet soil conditions than for dry soil conditions (Jones et al., 2005), but similar levels of rutting were observed for both wet and dry soil conditions in the Fort Riley study (Althoff, 2005; Althoff and Thien, 2005).

Soil disturbance also can result in significant changes in chemical properties (Brye et al., 2004; Mikha and Rice, 2004; Potthoff et al., 2005). Soil organic matter is particularly sensitive, and its loss can lead to lower productivity. Reductions in total soil C and N have been observed for heavy-use sites at Fort Riley and other military installations (Garten et al., 2003; Althoff et al., 2007). Other soil chemical properties were not consistently correlated with military vehicle disturbance.

Fire is a natural occurrence in the tallgrass prairie ecosystem and represents an effective tool for land managers (Wright, 1974; Collins and Gibson, 1990). Prescribed burning stimulates vegetation biomass which provides greater cover for long-term sustainability. Approximately one-third of the Fort is burned annually, including prescribed burns, and both naturally-occurring and training-related wildfires, resulting in a mosaic of vegetation patterns at the landscape level. The effects of fire on soil organic matter remain unclear for the tallgrass prairie (Rice et al., 1998). Fire increases belowground productivity but decreases N availability, potentially resulting in greater N limitation (Turner et al., 1997). Increased belowground production also may be offset by more rapid organic matter turnover due to increased soil temperatures after burning (Rice et al., 1998).

Land maintenance on military training lands is currently guided by regulations set forth by the Integrated Training Area Management (ITAM) Program, which outlines procedures for achieving sustainable use of training lands (Army Regulation 350-4, 1988). A key component of this program, Range and Training Land Assessment (RTLA), provides information and recommendations regarding the condition of training lands to range managers to assist scheduling of training areas and monitoring of the effectiveness of rehabilitation projects (US Army Environmental Center. 2006).

Fort Riley Military Installation, located in the Flint Hills of northeastern Kansas, is a major training reservation, with seventy percent of its 40,434 ha used for mechanized maneuvers. Fort Riley started implementing portions of the assessment protocol under the Land Condition Trend Analysis (LCTA) Program, monitoring trends in plant communities related to military vehicle traffic patterns during 1994-2001 (Althoff et al., 2006). Assessment of soil quality indices, including physical, chemical, and biological properties began in 2002 (Althoff, 2005; Althoff and Thien, 2005; Althoff et al., 2007).

A replicated small-plot study of tracked vehicle disturbance effects on tallgrass prairie soils and communities was initiated on Fort Riley in 2003. The objectives were to evaluate rates of recovery in a suite of plant and soil-quality indicators over a range of disturbances encompassing soil type, environmental conditions, and traffic intensity. Results from the first two years are reported in Althoff (2005) and Althoff and Thien (2005). This manuscript reports longer-term trends in recovery of soil physical and chemical properties subsequent to tank disturbance.

MATERIALS AND METHODS

Site Description

Research was conducted at Fort Riley Military Installation, an Army base in operation since 1853, located in Clay, Geary, and Riley counties in the Flint Hills of northeastern Kansas (39°15’N, 96°50’W) (Pride, 1997; McCale and Young, 2000). The installation, located in a mesic, tallgrass-prairie ecosystem, uses 29,542 ha (70,926 ac) of its 40,434 ha (100,656 ac) for maneuver training. The Flint Hills grasslands encompass more than 1.6 million ha, covering much of eastern Kansas from near the Kansas-Nebraska border south into northeastern Oklahoma, and contain the largest remaining areas of untilled tallgrass prairie in North America (Knapp and Seastedt, 1998). Hot summers and cold, dry winters characterize the climate. Mean monthly temperatures range from -2.7°C in January to 26.6°C in July. Annual precipitation averages 83.5 cm, with 75% of precipitation occurring during the growing season (Hayden, 1998). Fort Riley lands host three major vegetation communities: grasslands (ca. 32,200 ha), shrublands (ca. 6, 000 ha), and woodlands (ca. 1,600 ha). The soil at the study plots was classified as a Wymore series consisting of very deep, moderately drained, slowly or very slowly permeable soils that formed in loess (USDA, 1975). This soil series is found on most of the fort's training area. Wymore soils are classified as Fine, smectitic, mesic Aquertic Argiudolls.

Experimental Treatments

A randomized complete block design composed of three treatments (a non-trafficked control, tank traffic during wet soil conditions, and tank traffic during dry soil conditions) and three replications (blocks) was established in each of two soil types, a silty clay loam and a silt loam, in 2003 (Althoff and Thien, 2005). An Abrams M1A1 main battle tank created disturbances by driving 5 circuits around a figure eight pattern in designated plots either during wet or dry soil conditions. The M1A1 weighs 57.2 t with a ground pressure of 0.00626 t/cm (13.8 pounds/sq inch). The tracks are approximately 63.5 cm (25 inches) wide 4.57 m (15 feet) long. It has a maximum cross country speed of 48 km/h (30 mph). Tank speed was maintained at approximately 8 km/h (5 mph).

In 2004, one-half of each of the previously disturbed plots received 5 additional tank passes during wet or dry conditions similar to 2003. On a randomly selected half of the original figure eight, 5 additional passes were made with an M1A1 tank, producing a S-shaped pattern (Althoff, 2005). The second year of treatments allowed comparison of different levels of traffic intensity (one-time-traffic with 5 passes versus repeated traffic with a total of 10 passes). Two areas, a curve and straight-a-way, within each traffic intensity subplot were designated for sampling in 2003-2005. Data from the first and second years of disturbance are reported in Althoff (2005) and Althoff and Thien (2005).

In April 2006, each whole plot was again split and a randomly selected half received a burn treatment. Curve and straight-a-way areas within each burn-intensity subplot were designated for sampling in 2006 and 2007.

Field Sampling and Laboratory Methods

Physical Properties

Ridge height and rut depth of tank tracks were measured from each curve area using a transit and surveying rod (Spectra Precision Laserplane 500c transit, Dayton, Ohio; Surveying Rod, Crain Enterprises I, Rod City, USA) immediately following disturbance in 2003 and 2004, and on 31 August 2007 (3-4 years post disturbance). Ridge height and rut depth are defined as the difference between the undisturbed surface height and the ridge top and track pad, respectively.

A Remik CP 40 American Society of Agricultural Engineers (ASAE) standard cone penetrometer (RFM Australia Pty Ltd Agridry, Toowoombia, Queensland, Australia) was used to measure penetration resistance and compaction. ASAE-recommended standards for intervals (25 mm) with an insertion speed of 2 m min^{-1} were used. The maximum load and default value was 75 kg. Measurements were collected within seven days of the tank application during both wet and dry soil conditions in 2003 and 2004 (Althoff, 2005; Althoff and Thien, 2005), and on 13 April 2006 (pre-burn), 24 September 2006, and 18 June 2007.

Bulk density, porosity, and gravimetric water content were determined for each sampling area (curve and straight-a-way) on 19 November 2005, 24 September 2006, and 20 June 2007, from three 7.6-cm diameter soil cores extracted using stainless steel sleeves (volume of 347.5 cm^3) hammered into the soil to a depth of 7.6 cm. The sleeves were excavated using a shovel and the soil was immediately transferred to covered tins for transport to the lab. Soil wet weights were recorded and samples were dried at 105^{o}C for 96 hours. Bulk density was calculated as the oven-dried soil mass divided by the sample volume. Porosity was estimated using the formula: 100-(bulk density/particle density)*100. A particle density value of 2.65 mg m^{-3} was used in all porosity calculations (Brady and Weil, 2002). Water content was calculated as wet soil mass minus the dry soil mass, divided by the dry soil mass.

Chemical Components

Bulk soil samples for determination of soil chemical properties were collected on the same dates as bulk density samples. A 20 × 50-cm Daubenmire frame (Daubenmire, 1959) was positioned at each sampling area (curve and straight-a-way) and the soil was removed to a depth of 7.6 cm, placed in a 22-liter plastic bucket and covered with a lid. Samples were stored at 5^{o}C (41^{o}F) until further processing. All samples from disturbed areas were collected from the track pad (see Fig. 2.1), while control samples were collected from the undisturbed soil surface. Sampled depth, therefore, did not represent the same portion of the disturbed and undisturbed soil profiles.

Soil pH, extractable potassium (K), available phosphorus (P), calcium (Ca), total nitrogen (N), and total carbon (C) were determined from a subsample of the bulk soil samples. Tests were conducted by the Kansas State University Department of Agronomy Soil Chemistry Lab according to its standard soil-testing procedures (U.S.D.A., Soil Survey Laboratory Methods Manual, 1996).

Statistical Analyses

A disturbance effect index was calculated for all variables using the following formula:

(*disturbed measurement-undisturbed measurement)/ (undisturbed measurement*).

This disturbance effect index was expressed as a percentage of the control and subjected to mixed-model analysis of variance using SAS (SAS Institute, Cary, NC, 2000). The data were analyzed as a strip-split-split plot with soil moisture condition as the whole plot treatment, stripped burn and traffic intensity subplots, correlated intensity subplots (5 passes vs. 10 passes) and correlated sub-subplots (curved vs. straight areas) with each subplot. The significance of the disturbance index was tested for individual treatment combinations using Least Squares Means (H_0: mean = 0).

RESULTS

Physical Properties

Curve ridge height decreased from an initial maximum of 21 and 23 cm at the time of disturbance (Fig. 2.2) to a 2007 maximum of 5 and 9 cm in silty clay loam and silt loam soil, respectively (Fig. 2.3). Maximum ridge height initially occurred for the outside track of plots with repeated traffic under wet soil conditions in both soil types. By 2007, elevations of the ridges of most disturbance treatments were not different ($p > 0.10$) from that of undisturbed soil. In contrast, there was little change in rut depth from initial disturbance in 2003-2004 (Fig. 2.4) to 2007 (Fig. 2.5). A maximum rut depth of 9 and 12 cm was measured at the time of disturbance for silty clay loam and silt loam soil, respectively. Again, the outside track of the repeated traffic treatment exhibited the greatest disturbance, with the exception of the repeated traffic treatment during dry soil conditions in silt loam soil, where the rut depth was greater for the inside track than for the outside track. In contrast to the pattern of recovery observed for ridge height, 2007 rut depth remained significant ($p \leq 0.10$) for inside and outside tracks of the repeated traffic-wet soil condition treatment and for the inside track of the repeated traffic-dry soil condition treatment in both soil types.

Penetrometer resistance indicated significant compaction primarily in the upper 10-15 cm depths of both soil types through 2007 (Figs. 2.6-2.15). In 2005, resistance was greater ($p \leq 0.10$) for the curve area compared to the straight-a-way across treatments in silt loam, but not silty clay loam soil (Table 2.1, Figs. 2.6, 2.7). In 2006, penetrometer resistance varied among tank treatments and burn conditions (Tables 2.2, 2.3), with significant compaction most often indicated for disturbance during wet soil conditions (Figs. 2.8-2.11). Curve areas remained significantly more compacted ($p \leq 0.10$) than straight-a-ways across disturbance treatments in the silty clay loam soil in 2007 (Table 2.4, Figs. 2.12, 2.13). Significant compaction also remained for all disturbance treatments in silt loam soil in 2007, but no distinct patterns among treatments could be detected (Table 2.5, Figs. 2.14, 2.15).

Bulk densities in control plots in this study averaged 1.12 g cm^{-3} for the silty clay loam soil and 0.99 g cm^{-3} for the silt loam soil. Bulk density did not indicate significant compaction for any disturbance treatment in silty clay loam soil in 2005, but did suggest greater compaction in the curve areas compared to the straight-a-ways across disturbance treatments (Table 2.1, Fig 2.16). As trends in treatment responses by porosity were the inverse of those for bulk density (Tables 2.1-2.5, Figs. 2.19-2.21), only the results of the latter are discussed here. In 2006, bulk density values were greater in silty clay loam soil plots with repeated compared to single traffic (Table 2.2, Fig. 2.17). In silt loam soil, 2006 bulk densities were greater on curve compared to straight-a-way areas, particularly in burned-wet soil condition treatments and unburned-dry soil condition treatments (Table 2.3, Fig. 2.17). No significant compaction was indicated for silty clay loam soil in 2007, but, similar to 2005 and 2006, curve areas exhibited greater bulk densities than straight-a-ways across all treatments in silt loam soil (Table 2.5, Fig. 2.18).

The disturbance index for gravimetric water content in 2005 was greater (more negative) across curve compared to straight-a-way areas in both soil types, and for 10 passes compared to 5 passes in silt loam soil (Table 2.1, Fig. 2.22). Burning effects and interactions dominated gravimetric water responses in 2006, with increased water content compared to control plots observed for repeated traffic during dry soil moisture conditions in the presence of burning and decreased water content compared to control plots observed for repeated and single traffic during wet and dry moisture conditions, respectively, in the absence of burning (Tables 2.2-2.3, Fig. 2.23). As for 2005, disturbance effects were greatest for curve areas. Interactions among all the experimental factors were observed for gravimetric water content in both soil types in 2007, with none of the individual treatments exhibiting a significant ($p \leq 0.10$) disturbance index (Tables 2.4-2.5, Fig. 2.24).

Chemical Components

Total C was reduced ($p \leq 0.10$) to a greater extent for disturbance during wet compared to dry soil conditions and for curve compared to straight-a-way areas in both soil types in 2005 (Table 2.1, Fig. 2.25). This trend continued through 2006 and 2007, with burning interactions also becoming prominent for those years (Tables 2.6-2.9, Figs. 2.26-2.27). In general, more significant ($p \leq 0.10$) disturbance indices, both positive and negative, were observed for unburned compared to burned plots. Trends for total N were nearly identical to those for total C, but with fewer significant disturbance effects observed for 2007 (Tables 2.6-2.9, Figs. 2.28-2.30).

No consistent trends were observed for soil P across treatments in either soil type (Tables 2.6-2.9, Figs. 2.31-2.32). Significant changes in soil P levels in disturbed relative to control plots were observed only for 2007 and were all positive (increased P) for silty clay loam soil and all negative (decreased P) for silt loam soil (Fig. 2.32). Disturbance indices for soil K were more negative for curve compared to straight-a-way areas across treatments in both soil types, with significant negative indices observed only for curve areas (Tables 2.6-2.9, Figs. 2.33-2.34). No significant disturbance effects were observed for soil Ca in silty clay loam soil, but disturbance indices were greater (more negative) for curve compared to straight-a-way areas across treatments in silt loam soil in both 2006 and 2007 (Tables 2.6-2.9, Figs. 2.35-2.36). Similarly, there was no change in pH for any of the disturbance treatments in silty clay loam soil, but pH was reduced in plots with repeated traffic during dry moisture conditions in silt loam soil (Fig. 2.37).

DISCUSSION

Rutting and soil compaction are immediate impacts of military training maneuvers with tracked vehicles. Grasslands are relatively resilient to military training activities (Schaeffer et al., 1990; Yorks et al., 1997), but soil displacement and compaction can have profound effects on soil function by limiting water and oxygen infiltration, reducing root and microbial function, and increasing erosion potential (Unger and Kaspar, 1994; Raper, 2005), therefore placing the resiliency of the ecosystem at risk.

The width and depth of tracked-vehicle ruts and the height of the ridges are a function of the operating characteristic of the vehicle, with sharper turns resulting in greater disturbance (Ayers, 1994). Maximum rut depths of 9-12 cm were measured on curve areas in this study compared to a maximum of 4.5 cm observed by Ayers (1994). The M1A1 tank which weighs 63 t with a ground pressure of 0.00626 t cm^{-1} and has the capability to turn each track independently; the two tracks can move in opposite directions and at different rates of speed. During wet conditions, the outer track speed is increased while the inner track remains at a slower speed, resulting in more soil displacement with the outer track. Compared to the M113 Personnel carrier in Ayers' study which weighs 13.5 t and has a ground pressure of 0.003915 t cm^{-1}, there is a substantial increase in earth-moving ability. The M113 does not have the capability of controlling each track independently and therefore both tracks create approximately the same amount of disturbance.

Armored military maneuvers can result in long-term (decades) soil compaction in sensitive ecosystems such as the southwestern deserts of the United States (Webb and Wilshire, 1983; Prose, 1985). Soil compaction also results from tracked vehicle use in grassland systems (Prosser et al., 2000; Althoff and Thien, 2005; Althoff et al., 2007), but appears to be a relatively short-tem response. Although penetrometer and bulk density measurements detected compaction at the Fort Riley site through 2007, these effects were relatively small, primarily limited to curve areas, and more frequently observed for the silt loam than for the silty clay loam soil. Compaction by tracked vehicles varies with soil type. Although higher bulk densities may be attained for coarser textured soils than for finer textured soils under similar vehicle pressure (Braunack, 1986), it is the finer textured soils that generally are considered more susceptible to compaction (Unger and Kaspar, 1994). Fine-textured soils such as the soils represented in this study generally have relatively low bulk densities and are not considered to be severely compacted until bulk densities exceed 1.5 g cm^{-3} (USDA, 1996). Seastedt and Ramundo (1990) reported bulk density values of 0.91 - 1.05 g cm^{-3} for native tallgrass prairie sites in the Flint Hills, which closely matches the values observed for the undisturbed controls at my Fort Riley site. Maximum bulk densities (0 - 7.6 cm depth) in disturbance treatments averaged 1.29 g cm^{-3} in silty clay loam soil and 1.21 g cm^{-3} in silt loam soil, an increase of 15% and 22%, respectively, from average bulk densities in undisturbed areas; however, bulk densities approaching the 1.5 g cm^{-3} threshold have been observed for disturbed sites on Fort Riley (Althoff et al., 2007). Similar increases in bulk density were observed following tracked vehicle disturbance of a Colorado grassland in silt loam soil (Prosser et al., 2000), Although these levels of compaction are relatively small, it should be noted that the threshold for inhibition of root penetration is lower for fine-textured than for coarse-textured soils (Brady and Weil, 1999). Compaction restricts root growth and penetration through mechanical impedance and decreased oxygen availability (Unger and Kaspar, 1994). Soils strengths of 2500 KPa to 3000 KPa have been found to eliminate root penetration (Taylor and Gardner, 1963; Taylor et al., 1966). These strengths frequently were exceeded in disturbed areas throughout this study (see Figs. 2.6 – 2.15).

The compaction effects of traffic generally are more pronounced and occur deeper in the soil profile during wet soil conditions (Gifford et al., 1977; Unger and Kaspar, 1994; Brady and Weil, 1999). While this pattern was observed following initial tank traffic disturbance (Althoff, 2005), there was little evidence of residual soil moisture effects on bulk density or penetrometer resistance during the subsequent three recovery years. In contrast, significant effects of soil moisture conditions at the time of treatment were frequently observed for soil water content, with reduced water content associated with disturbance during wet soil conditions. The effects of compaction on soil strength and, therefore, on root penetration are increased when soils are drier (Brady and Weil, 1999). Additionally, compaction restricts the range of soil water contents available for plant uptake.

Chemical properties determine characteristics such as soil fertility, biological activity, degree of pollution, salinity, corrosiveness, or shrink-swell potential which are quantifiable and related to soil quality (Pierzynski et al., 1994). Carbon, phosphorus, and nitrogen levels are concentrated in the top 2-3 cm of soil and disturbance can dramatically reduce these nutrients due to soil displacement or through wind and water erosion of the nutrient-rich upper zone once exposed. Soil C, was particularly sensitive to tank traffic in my study, with limited recovery observed in plots with the greatest levels of disturbance (e.g. curves). Increases in soil C were observed in some cases for straight-a-way areas. Because vegetation on the straight-a-ways was crushed and not removed as on the curves, an increase in decomposition following traffic disturbance would be expected to produce increases in soil organic matter. Much of the substrate in soils is unavailable to microorganisms due to physical protection mechanisms (e.g., aggregation) and disturbance releases these substrates, resulting in a flush of nutrients through decomposition, (Watts et al., 2000). In addition to the implications for recovery of plant and soil microbial populations, soil organic matter contributes to soil structure, with organic C content the strongest predictor of bulk density (Heuscher et al., 2005).

Burning helps to stimulate belowground plant growth and microbial biomass (Rice et al., 1998; Johnson and Matchett, 2001), but increases the C:N ratio of the litter and reduces available N, thus increasing N limitation for the system (Groffman et al., 1993). Tallgrass prairie plants are able to sustain productivity by tightly conserving N. The rapid growth of grasses stimulated by burning also depletes soil moisture. The combination of greater root production, decreased root tissue quality, and drier soil conditions may act to reduce organic matter decomposition rates and offset N limitation (Rice et al., 1998). Since roots are the major source of organic matter in tallgrass prairie, burning would be expected to enhance recovery of soil organic matter levels following disturbance. Although burning effects were inconsistent in my study, recovery rates of total C and N generally appeared to be more rapid for burned than for unburned plots.

Tracked vehicle maneuvers resulted in changes in tallgrass prairie soil physical and chemical properties that persisted for at least four years after initial disturbance. Rutting in particular, remained severe on curve areas, representing increased erosion susceptibility and a potential safety hazard for future training activities. The impact of tank traffic on soil compaction (bulk density) was comparatively minor overall with the exception of the curve areas. Soil organic matter reflected similar trends for areas, but effects were more severe for traffic during wet soil conditions. Overall, tallgrass prairie soils appear relatively resilient to mission training activities on Fort Riley and can meet the requirement for sustainability provided suitable management of impacts. This includes restricting maneuvers during wet soil conditions and minimizing sharp turns. In addition, prairie management practices, such as prescribed burning, can be used to influence the quantity and quality of vegetation cover and thus soil organic matter.

ACKNOWLEDGEMENTS

Funding for this project was provided by the U.S. Army Military Installation, Integrated Training Area Management (ITAM) Program. I thank Philip B. Woodford (ITAM) Coordinator, Chris Otto, (ITAM), Lee Breidenstein (Range Control), Tony Davis, Troy Livingston, (GPS), Fred Siebe and staff (MPRC Gunnery Complex), and M1A1 tank crews, from Fort Riley Military Installation, for their effort and support. The author also expresses her appreciation to Monte Cales (NRCS, Fort Riley) for conducting and collecting the rut depth measurements. I am indebted to Keith Arnold, Bradley Feldhausen, Lance Noll, and Travis Halter for their assistance in collecting the soil samples and to the Soil Testing lab staff at Kansas State University for their chemical analyses.

REFERENCES

Althoff, P.S. 2005. Evaluation of soil quality indicators following disturbance by an Abrams M1A1 Main Battle Tank. M.S. Thesis. Kansas State University, Manhattan, KS, 136 pp.

Althoff, P.S., and S.J. Thien. 2005. Impact of M1A1 main battle tank disturbance on soil quality, invertebrates, and vegetation characteristics. Journal of Terramechanics 42:159-176.

Althoff, D.P., P.S. Althoff, N.D. Lambrecht, P.S. Gipson, J.S. Pontius, and P.B. Woodford. 2007. Soil Properties and perceived disturbance of grasslands subjected to mechanized military training: evaluation of an index. Land Degradation and Development 18:269-288.

Althoff, D.P., P.S. Gipson, J.S. Pontius, and P.B. Woodford. 2006. Plant community and bare ground trends on Fort Riley, Kansas: Implications for monitoring of a highly disturbed landscape. Transactions of the Kansas Academy of Science 109:101-106.

Amador, J.A., J.H. Gorres, and M.C. Savin. 2003. Carbon and nitrogen dynamics in *Lumbricus terrestris* (L) burrow soil: relationship to plant residues and macropores. Soil Sci. Soc. Am. J. 7:1755-1762.

Anderson, J.M. 1988. The role of soil fauna in agricultural systems. Pp 59-112 *In* J.R. Wilson (ed) Advances in nitrogen cycling in agricultural ecosystems. CAB International, Wallingford, England.

Anderson, A.B., G. Wang, S. Fang, G.Z. Gertner, B. Guneralp, and D. Jones. 2005. Assessing and predicting changes in vegetation cover associated with military land use activities using field monitoring data at Fort Hood, Texas. Journal of Terramechanics 42:207-229.

Andrews, S.S., D.L. Karlen, and C.A. Cambardella. 2004. The soil management assessment framework: a quantitative soil quality evaluation method. Soil Sci. Am. J. 68:1945-1962.

Army Regulation 350-4. 1988. Integrated Training Area Management (ITAM). Unclassified. Headquarters Department of the Army Washington, DC.

Brady, N.C., and R.R. Weil. 2002. The Nature and Properties of Soils. Thirteenth Edition. Prentice Hall, Upper Saddle Rive, New Jersey.

Braunack, M.V. 1986. The residual effects of tracked vehicles on soil surface properties. Journal of Terramechanics 23:37-50.

Brye, K.R., N.A. Slaton, M. Mozaffari, M.C. Savin, R.J. Norman, and D.M. Miller. 2004. Short-term effects of land leveling on soil chemical properties and their relationships to microbial biomass. Soil Sci. Soc. Am. J. 68:924-934.

Collins, S.L., and D.J. Gibson. 1990. Effects of fire on community structure in tallgrass and mixed-grass prairie. Pp 81-98 *In* S.L. Collins and L.L. Wallace (ed.). Fire in North American tallgrass prairies. University of Oklahoma Press, Norman, Publishing Division of the University.

Daubenmire, R. 1959. Measurement of species diversity using canopy coverage classes. Northwest Science 33:43-66.

Donkor, N.T., J.V. Gedir, R.J. Hudson, E.W. Bork, D.S. Chanasyk, and M.A. Naeth. 2002. Impacts of grazing systems on soil compaction and pasture production in Alberta. Canadian Journal of Soil Science 82:1-8.

Garten, Jr. C.T., T.L. Ashwood, and V.H. Dale. 2003. Effect of military training on indicators of soil quality at Fort Benning, Georgia. Ecological Indicators 3:171-179.

Gifford, G.F., R.H. Faust, and G.B. Coltharp. 1977. Measuring soil compaction on rangeland. Journal of Range Management 30:459-460.

Groffman, P.M., C.W. Rice, and J.M. Tiedje. 1993. Denitrification in a tallgrass prairie landscape. Ecology 74:855-862.

Hayden, B.P. 1998. Regional climate and the distribution of tallgrass prairies. Pp 19-34 *In* A.K. Knapp, J.M. Briggs, D.C. Hartnet, and S.L. Collins (eds.), Grassland dynamics: long-term ecological research in tallgrass prairie. Oxford University Press, NY, NY, USA.

Heuscher, S.A., C.C. Brandt, and P.M. Jardine. 2005. Using soil physical and chemical properties to estimate bulk density. Soil Sci. Soc. Am. J. 69:51-56.

Johnson, L.C. and J.R. Matchett. 2001. Fire and grazing regulate belowground processes in tallgrass prairie. Ecology 82:3377-3389.

Jones, R., D. Horner, P. Sullivan, and R. Ahlvin. 2005. A methodology for quantitatively assessing vehicular rutting on terrains. Journal of Terramechanics 42:245-257.

McKale, W., and W.D. Young. 2000. Fort Riley Citadel of the Frontier West, Kansas State Historical Society Topeka, Kansas.

McKale W., and W.D. Young. 2000. Fort Riley Citadel of the Frontier West, Kansas State Historical Society Topeka, Kansas.

Mikha, M.M., and C.W. Rice. 2004. Tillage and manure effects on soil and aggregate-associated carbon and nitrogen. Soil Sci. Soc. Am. J. 68:809-816.

Murphy, C.A., B.L. Foster, M.E. Ramspott, and K.P. Price. 2004. Grassland management effects on soil bulk density. Transactions of the Kansas Academy of Science 107:45-54.

Perkins, D.B., N.W. Haws, J.W. Jawitz, B.S. Das, and P.S.C. Rao. 2007. Soil hydraulic properties as ecological indicators in forested watersheds impacted by mechanized military training. Ecological Indicators 7:589-597.

Pierzynski, G.M., J. T. Sims, and G.F. Vance. 1994. Soil and Environment Quality. CRC Press Inc. Baca Raton, FL. 313pp.

Potthoff, M., L.E. Jackson, K.L. Steenwerth, I. Ramirez, M.R. Stromberg, and D.E. Rolston. 2008.Soil biological and chemical properties in restored perennial grassland in California. Restoration Ecology 13:61-73.

Pride, W.F. The History of Fort Riley. 1997. Manhattan, KS: U.S. Cavalry Museum and Fort Riley Historical and Archaeology Society.

Prose, D.V. 1985. Peresting effects of armored military maneuvers on some soil of the Mojave desert. Environ. Beol. Water Sci. 7:163-170.

Prosser, C.W., K.K. Sedivec, and W.T. Barker. 2000. Tracked vehicle effects on vegetation and soil characteristics. Journal of Range Management 53:666-670.

Raper, R.L. 2005. Agriculture traffic impacts on soil. Journal of Terramechanics. 42:259-280.

Rice, C.W., T.C. Todd, J.M. Blair, T.R. Seastedt, R.A. Ramundo, and G.W.T. Wilson. 1998. Belowground biology and processes. *In* A.K. Knapp et al. (eds), Grassland Dynamics, Oxford University Press, New York, Pp. 244-264.

SAS Institute Inc. 2000. SAS/STAT user's guide. Version 9.01. SAS Institute Inc., Cary NC, USA.

Seastedt, T.R. and R.A. Ramundo. 1990. The influence of fire on belowground processes of tallgrass prairie. Pp. 99-117 *in* S.L. Collins and L.L. Wallace, eds. Fire in North American tallgrass prairies. University of Oklahoma Press, Norman.

Taylor, H.M. and H.R. Gardner. 1963. Penetration of cotton seedling taproots as influence by bulk density, moisture content, and strength of soil. Soil Science 96:153-156.

Taylor, H.M., G.M. Robertson, and J.J. Parker, Jr. 1966. Soil strength—root penetration relations for medium-to coarse-textured soil materials. Soil Science 102:18-22.

Turner, C.L., J.M. Blair, R.J. Schartz, and J.C. Neel. 2007. Soil N and plant responses to fire, topography, and supplemental N in tallgrass prairie. Ecology 78:1832-1843.

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

US Army Environmental Center. 2006. Sustainable range program: Range and training land assessment program. https://srp.army.mil/itam/rtla.

USDA, Soil Conservation Service in cooperation with Kansas Agricultural Experiment Station. 1975. Soil Survey of Riley and Part of Geary County, Kansas.

USDA, Natural Resources Conservation Service. 1996. National Soil Survey Center. Soil Survey Laboratory Methods Manual. Soil Survey Investigations Report No. 42. Version 3.0. pp 693.

Yorks, T.P., N.E. West, R.J. Mueller, and S.D. Warren. 1997. Toleration of traffic by vegetation: Life form conclusions and summary extracts from a comprehensive data base. Environmental Management 21:121-131.

Watts, C.W., S. Eich, and A.R. Dexter. 2000. Effects of mechanical energy inputs on soil respiration at the aggregate and field scales. Soil and Tillage Research 53:231-243.

Webb, R.H. and H.G. Wilshire. 1983. Environmental effects of off-road vehicles: impacts and management in arid regions. Springer-Verlag, New York, NY.

Wright, H.A. 1974. Range burning. Journal of Range Management 27:5-11.

Figure 2.1 Example of M1A1 tank disturbance for the curve area. Ridge height is defined as the difference between ridge and undisturbed soil surface. Rut depth is defined as the difference between the undisturbed soil surface and the disturbed tack pad.

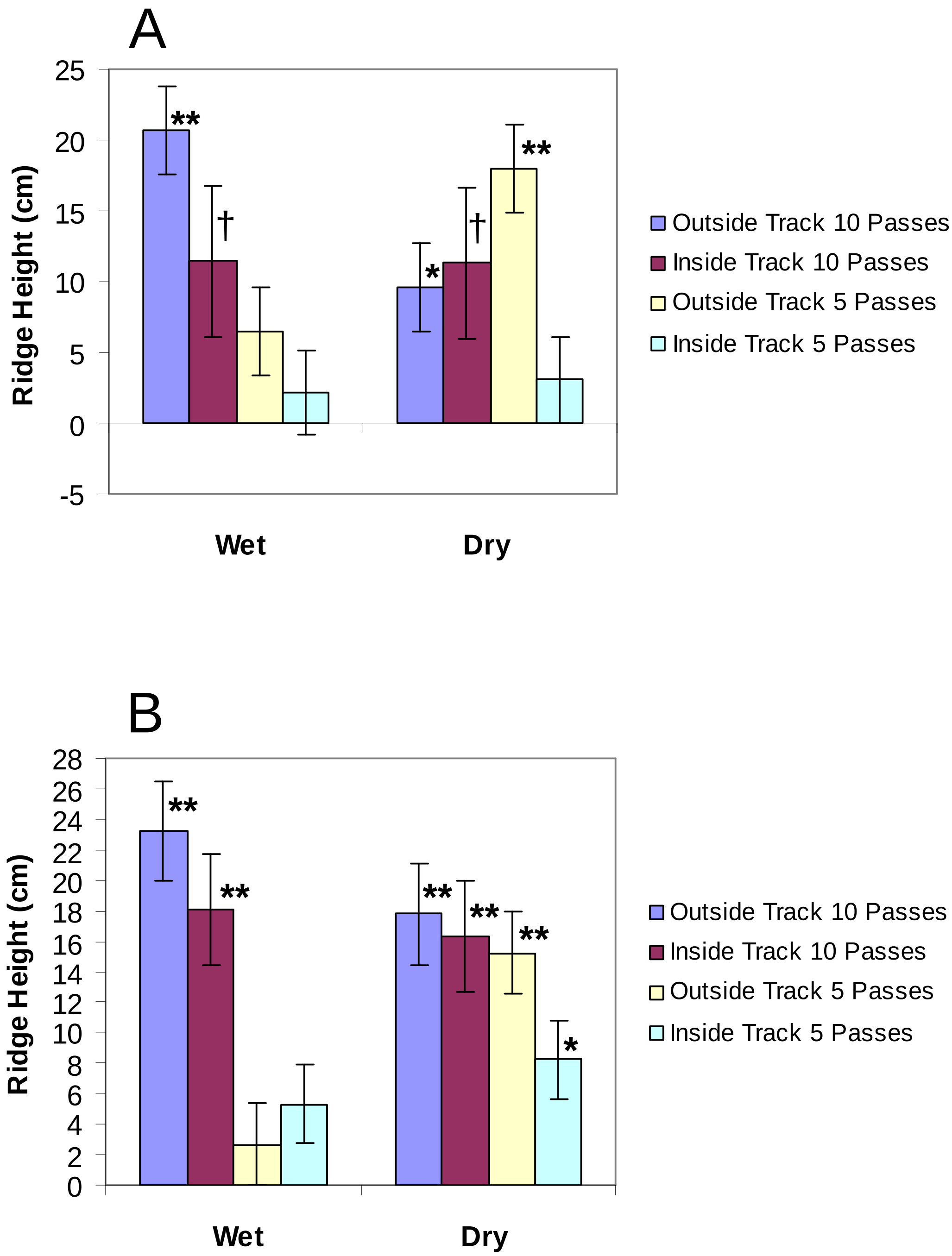


Figure 2.2. Effect of soil moisture (wet versus dry) on ridge height for the inside and outside tracks on (A) silty clay loam soil and (B) silt loam soil immediately following single (5 passes- 2003) and repeated (10 passes-2004) traffic by and Abrams M1A1 main battle tank. Data are means ± standard error. †, *, ** indicate $p \leq 0.10, 0.05, 0.01$, respectively.

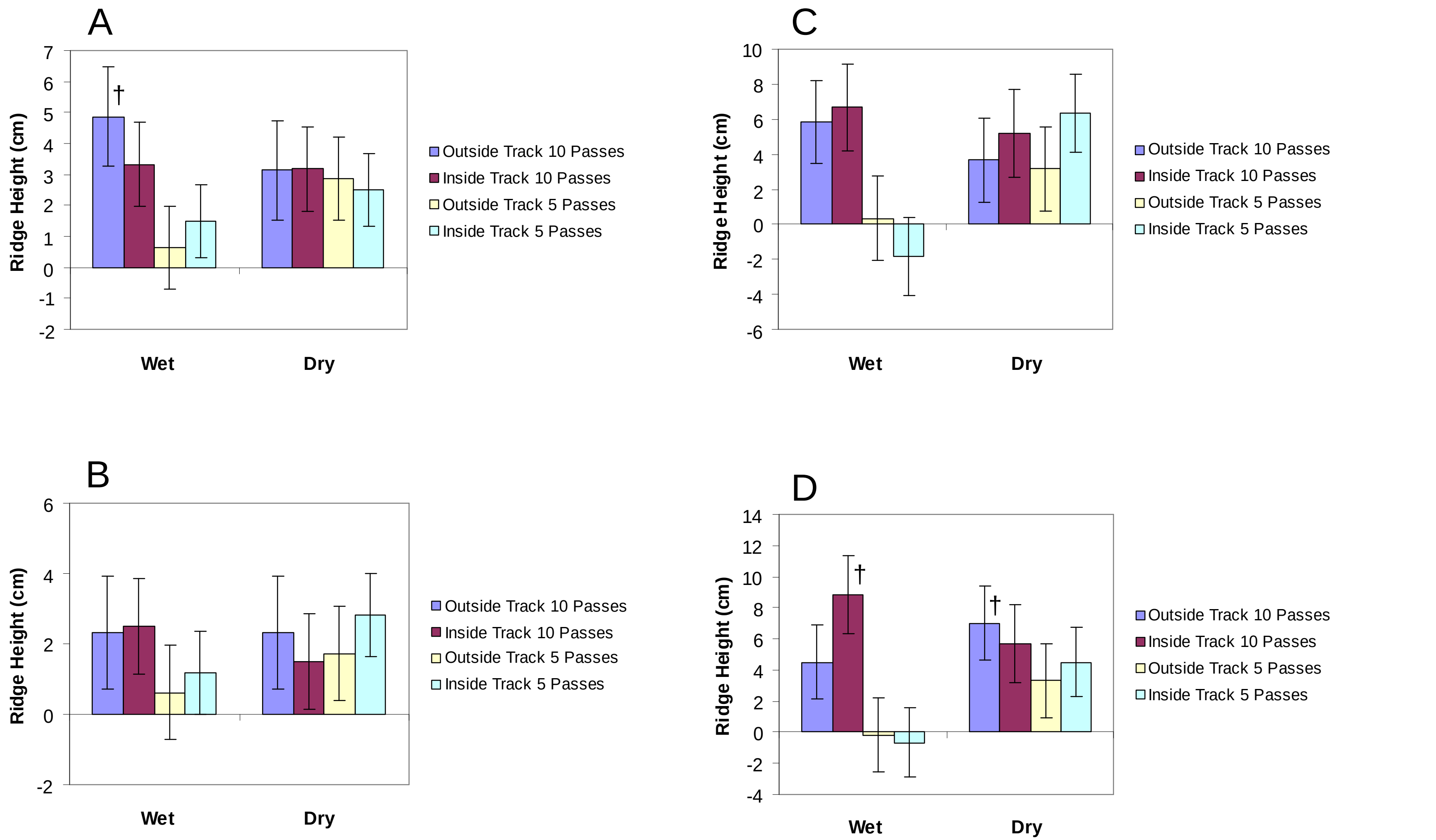


Figure 2.3. Ridge height for the inside and outside tracks on (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2007. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard errors. † indicates $p \leq 0.10$.

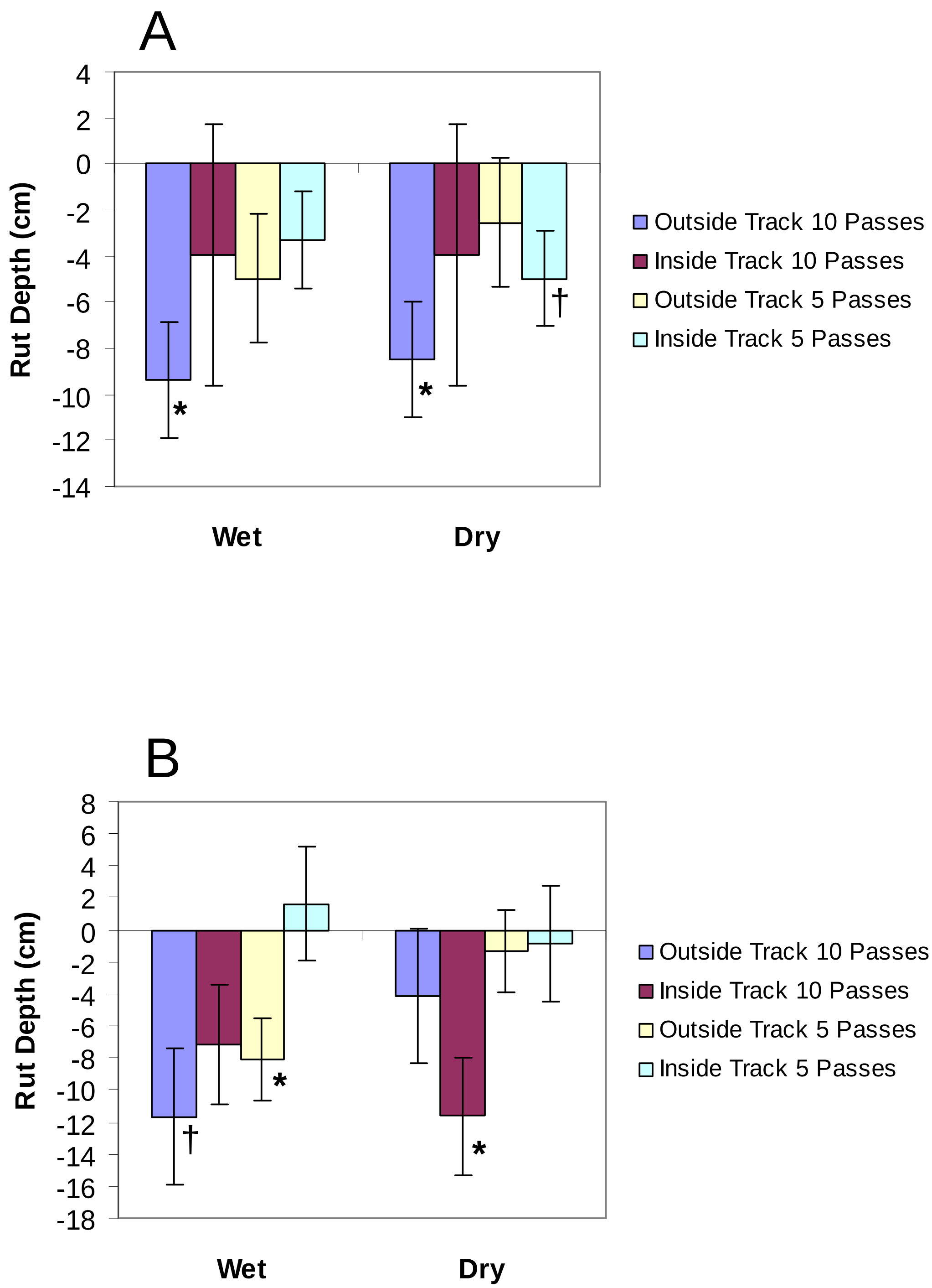


Figure 2.4. Effect of soil moisture (wet versus dry) on rut depth for the inside and outside tracks on (A) silty clay loam soil and (B) silt loam soil immediately following single (5 passes- 2003) and repeated (10 passes-2004) traffic by and Abrams M1A1 main battle tank. Data are means ± standard error. †, * indicate $p \leq 0.10$, 0.05, respectively.

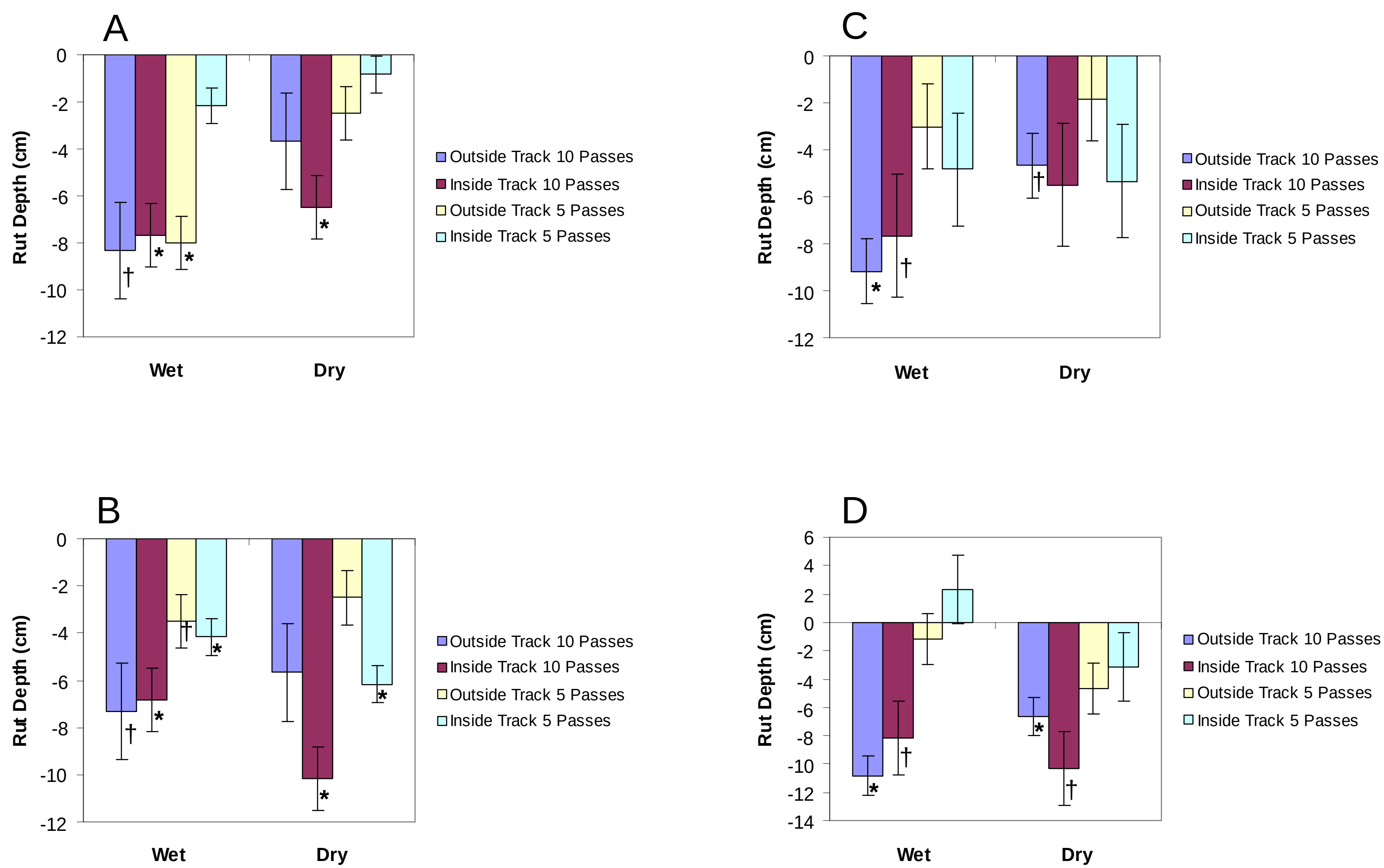


Figure 2.5. Rut depth for the inside and outside tracks on (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2007. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard errors. †, * indicate $p \leq 0.10, 0.05$, respectively.

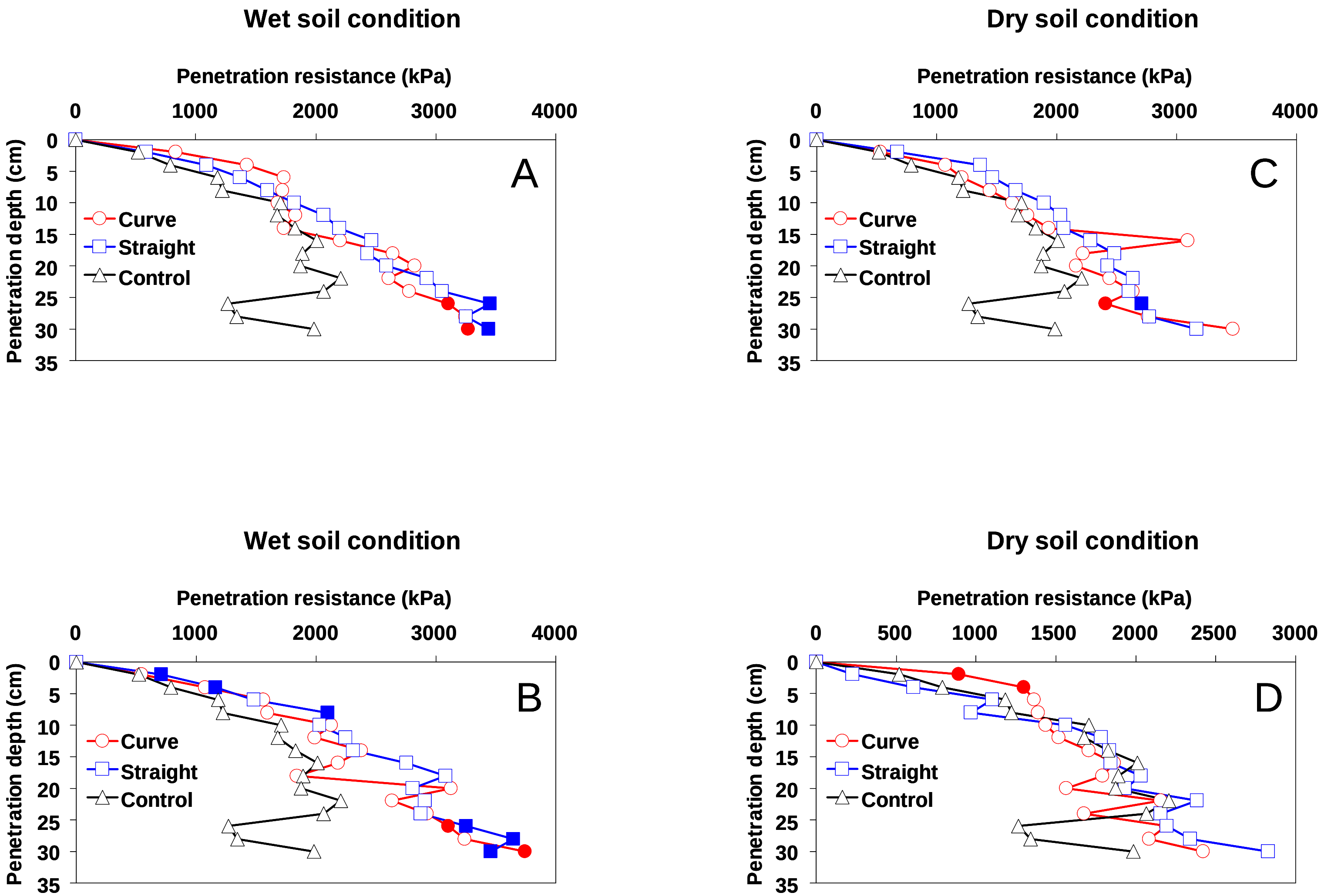


Figure 2.6. Penetrometer resistance for (A) 10 passes during wet soil conditions, (B) 5 passes during wet soil conditions, (C) 10 passes during dry soil conditions and (D) 5 passes during dry soil conditions with an Abrams M1A1 Main Battle Tank in silty clay loam soil, 2005. Filled symbols indicate significant compaction at that depth ($p \leq 0.05$).

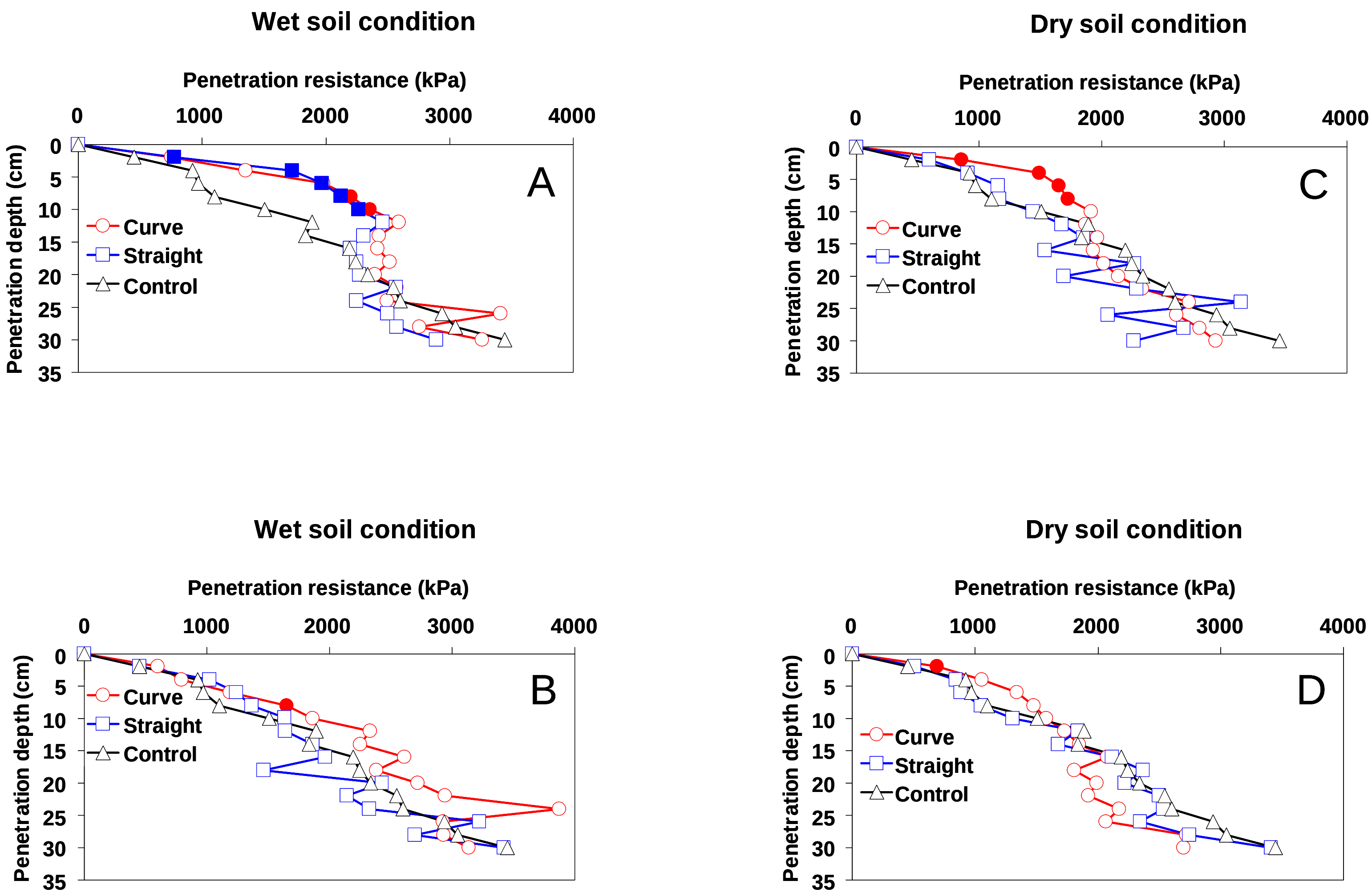


Figure 2.7. Penetrometer resistance for (A) 10 passes during wet soil conditions, (B) 5 passes during wet soil conditions, (C) 10 passes during dry soil conditions and (D) 5 passes during dry soil conditions with an Abrams M1A1 Main Battle Tank in silt loam soil, 2005. Filled symbols indicate significant compaction at that depth ($p \leq 0.05$).

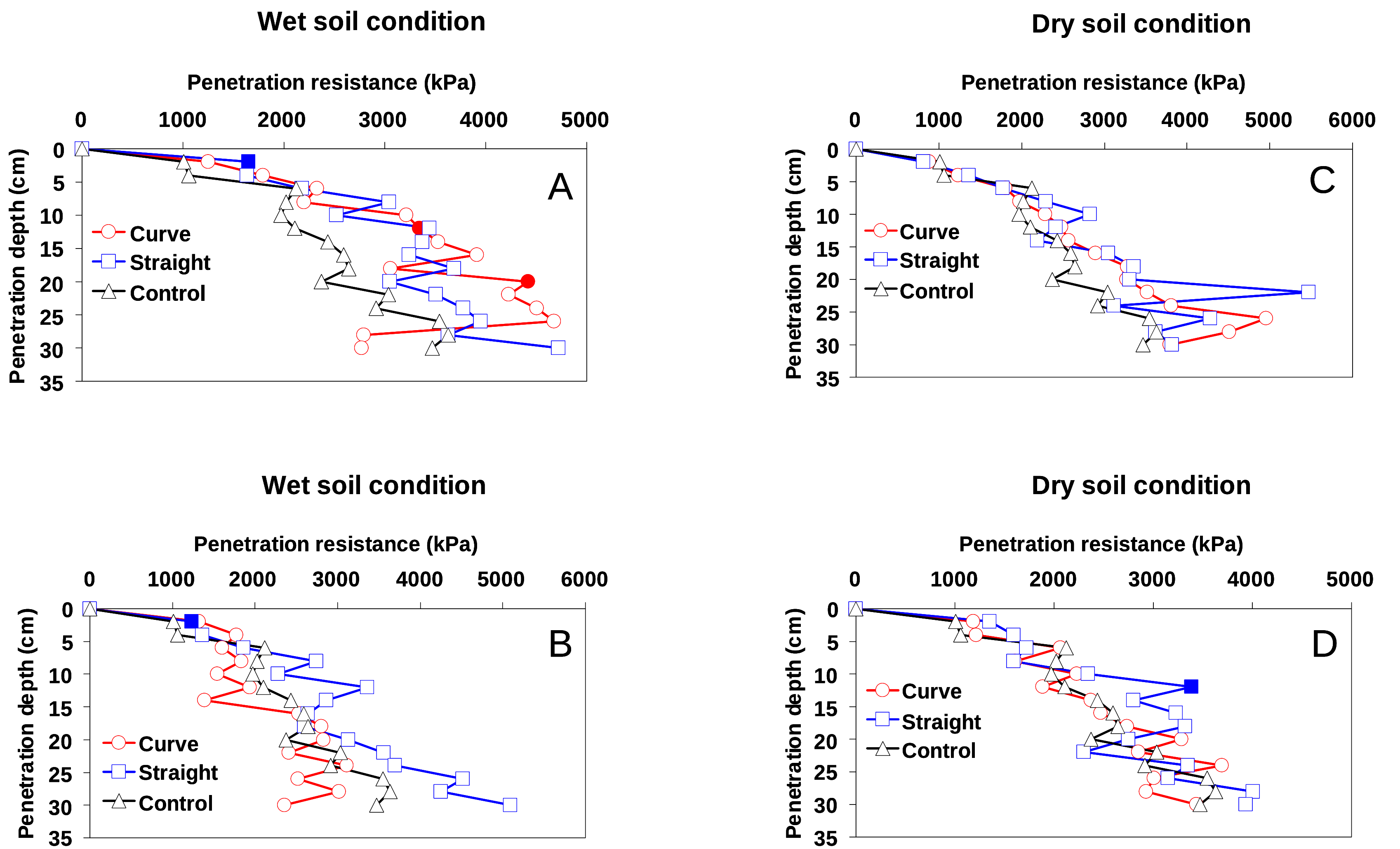


Figure 2.8. Penetrometer resistance for (A) 10 passes during wet soil conditions, (B) 5 passes during wet soil conditions, (C) 10 passes during dry soil conditions and (D) 5 passes during dry soil conditions with an Abrams M1A1 Main Battle Tank in burned silty clay loam soil, 2006. Filled symbols indicate significant compaction at that depth ($p \leq 0.05$).

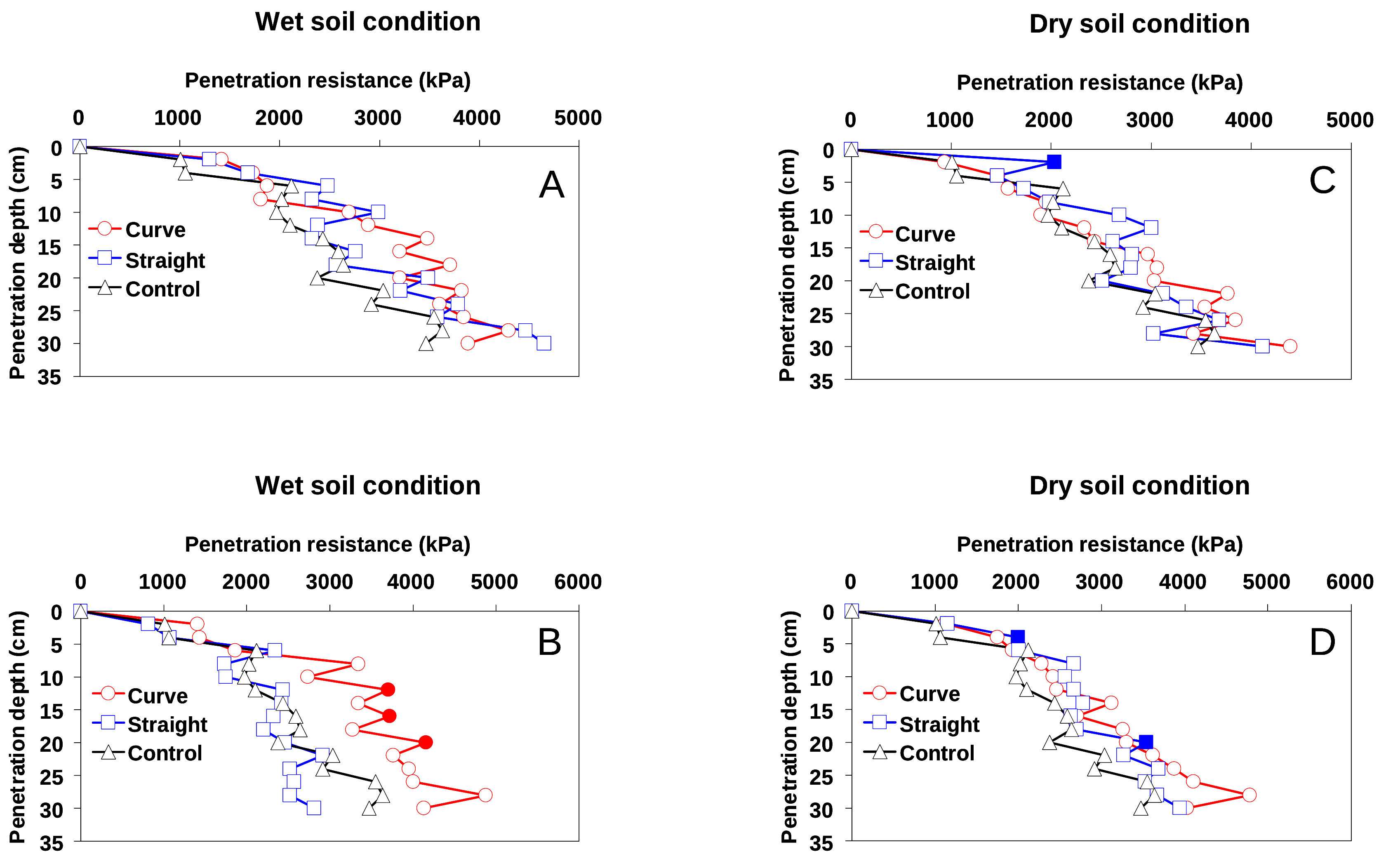


Figure 2.9. Penetrometer resistance for (A) 10 passes during wet soil conditions, (B) 5 passes during wet soil conditions, (C) 10 passes during dry soil conditions and (D) 5 passes during dry soil conditions with an Abrams M1A1 Main Battle Tank in unburned silty clay loam soil, 2006. Filled symbols indicate significant compaction at that depth ($p \leq 0.05$).

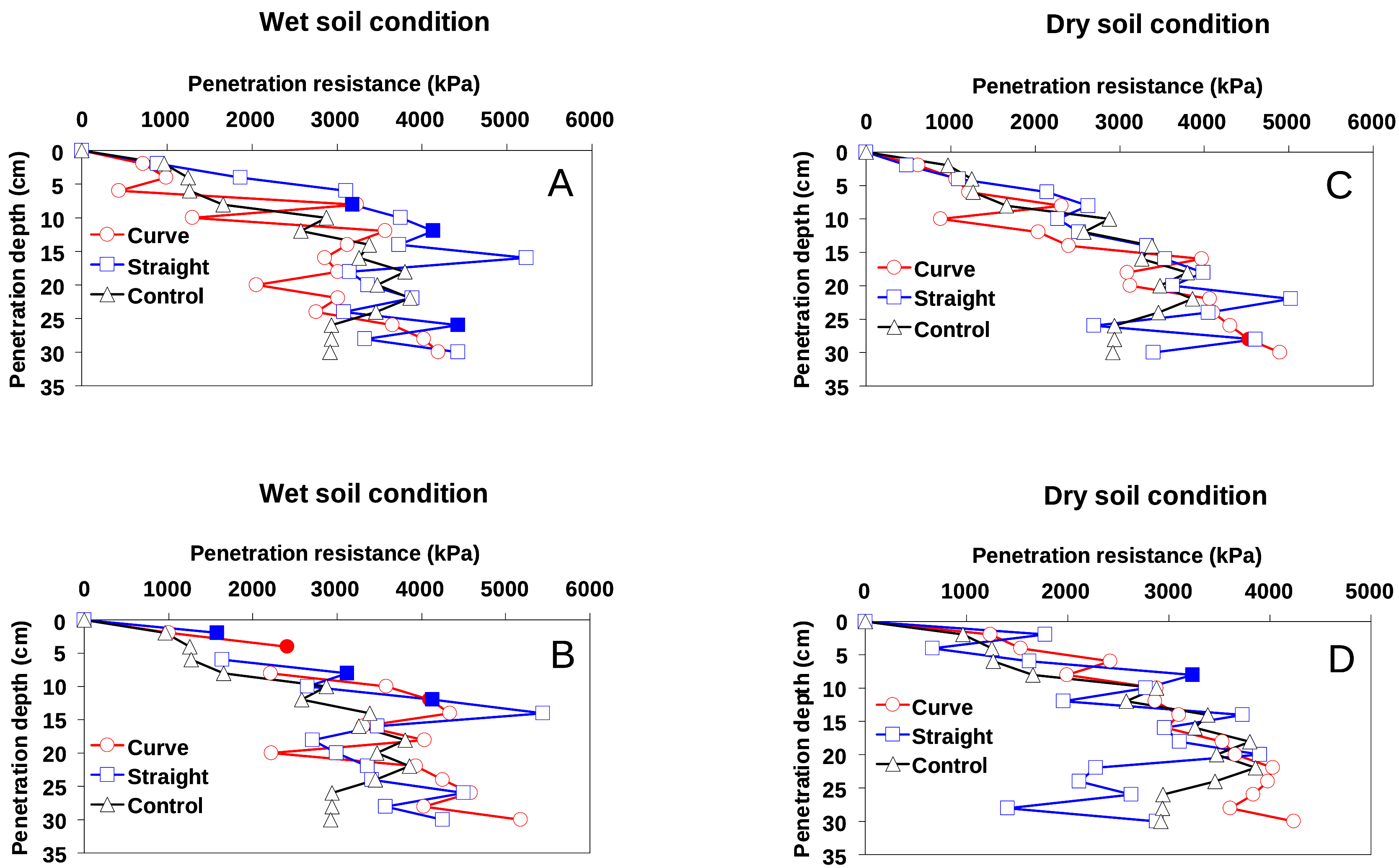


Figure 2.10. Penetrometer resistance for (A) 10 passes during wet soil conditions, (B) 5 passes during wet soil conditions, (C) 10 passes during dry soil conditions and (D) 5 passes during dry soil conditions with an Abrams M1A1 Main Battle Tank in burned silt loam soil, 2006. Filled symbols indicate significant compaction at that depth ($p \leq 0.05$).

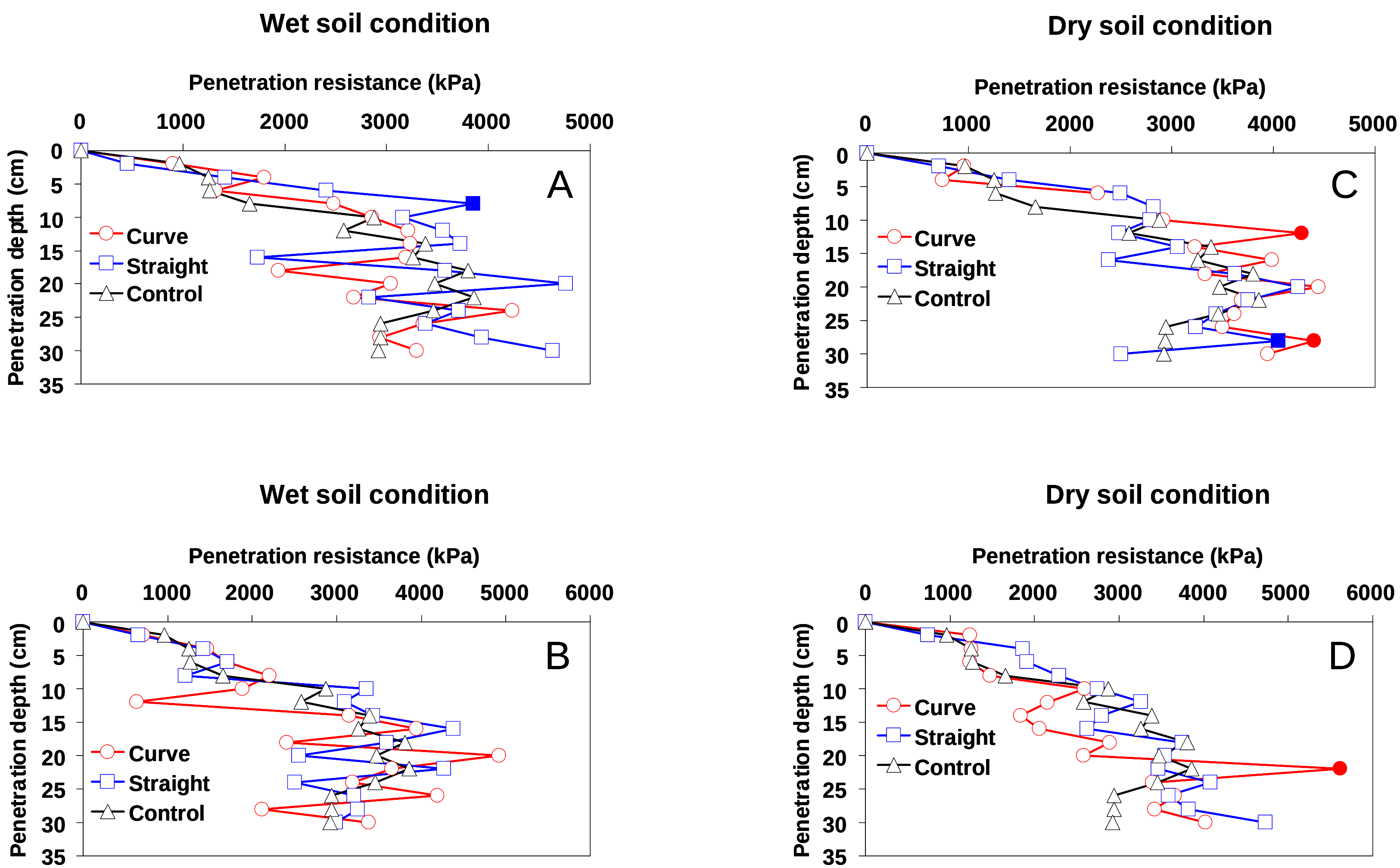


Figure 2.11. Penetrometer resistance for (A) 10 passes during wet soil conditions, (B) 5 passes during wet soil conditions, (C) 10 passes during dry soil conditions and (D) 5 passes during dry soil conditions with an Abrams M1A1 Main Battle Tank in unburned silt loam soil, 2006. Filled symbols indicate significant compaction at that depth ($p \leq 0.05$).

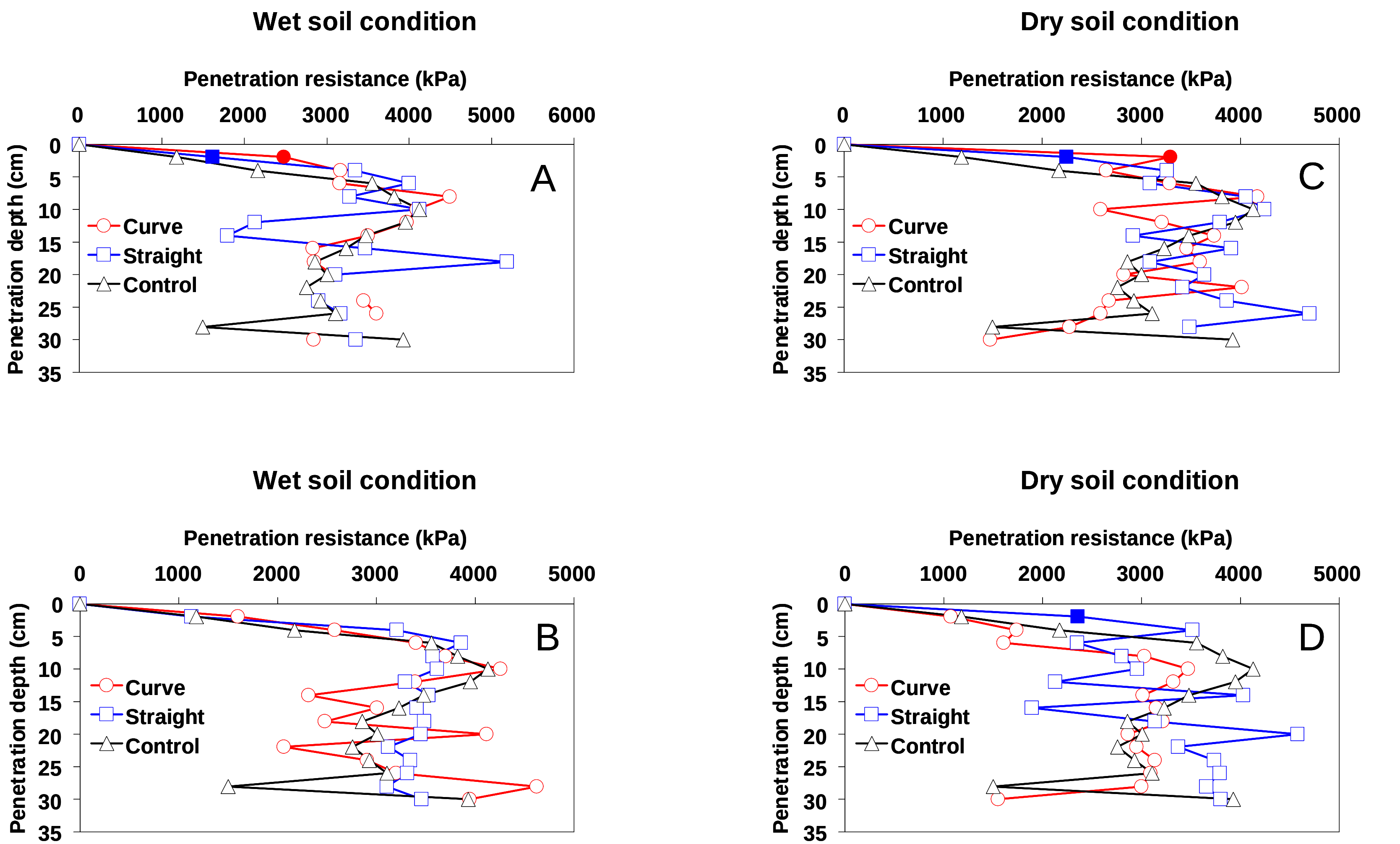


Figure 2.12. Penetrometer resistance for (A) 10 passes during wet soil conditions, (B) 5 passes during wet soil conditions, (C) 10 passes during dry soil conditions and (D) 5 passes during dry soil conditions with an Abrams M1A1 Main Battle Tank in burned silty clay loam soil, 2007. Filled symbols indicate significant compaction at that depth ($p \leq 0.05$).

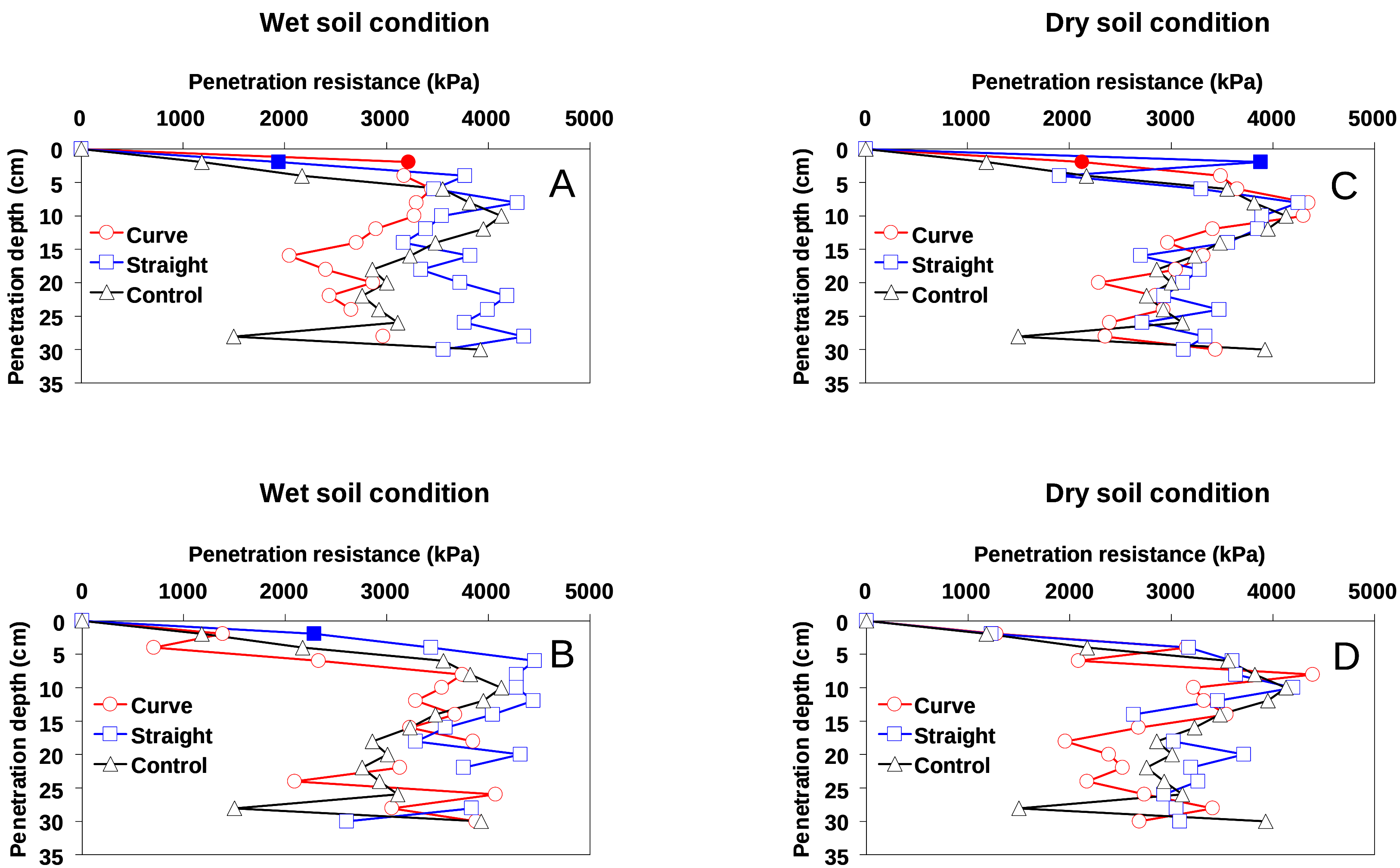


Figure 2.13. Penetrometer resistance for (A) 10 passes during wet soil conditions, (B) 5 passes during wet soil conditions, (C) 10 passes during dry soil conditions and (D) 5 passes during dry soil conditions with an Abrams M1A1 Main Battle Tank in unburned silty clay loam soil, 2007. Filled symbols indicate significant compaction at that depth ($p \leq 0.05$).

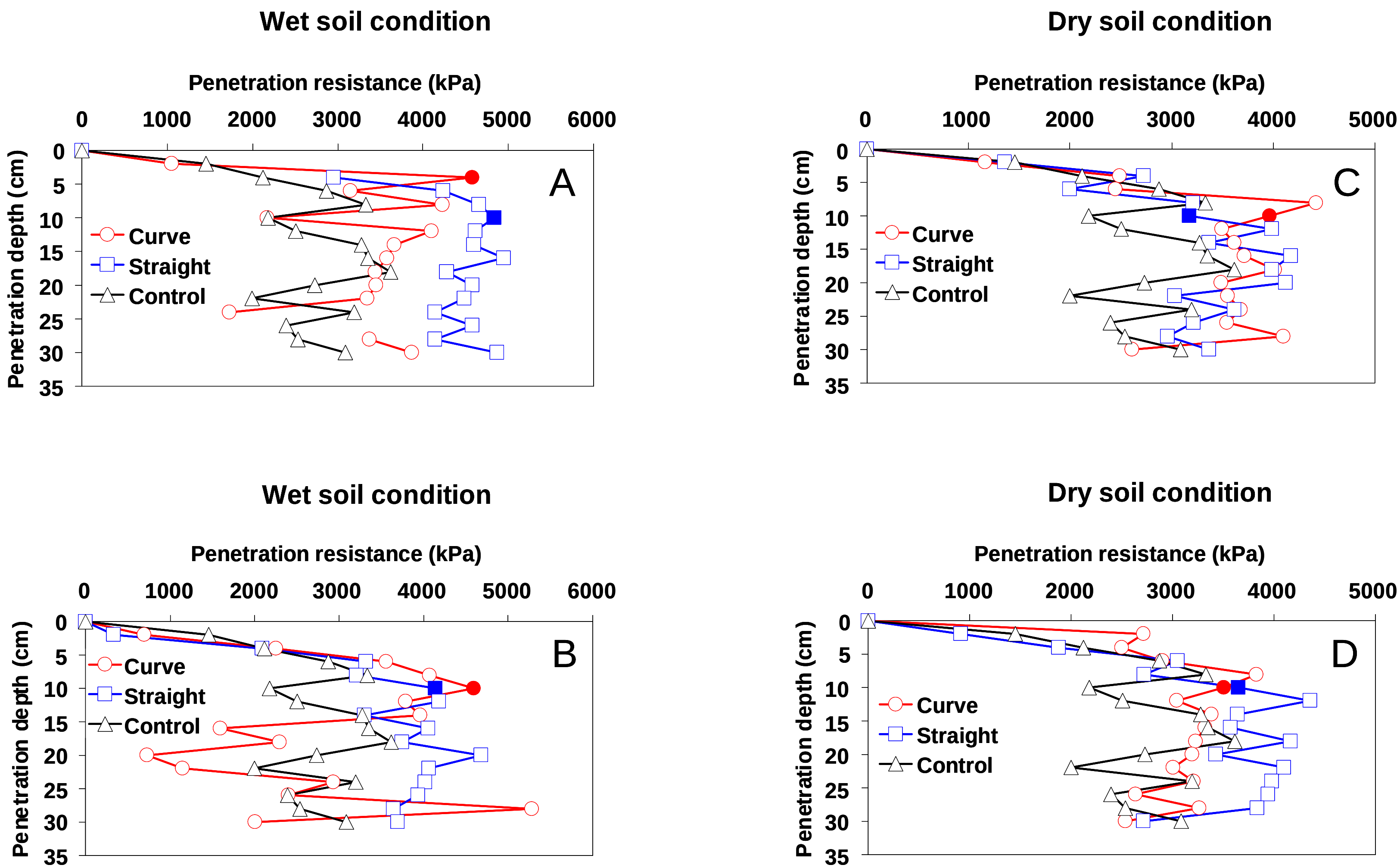


Figure 2.14. Penetrometer resistance for (A) 10 passes during wet soil conditions, (B) 5 passes during wet soil conditions, (C) 10 passes during dry soil conditions and (D) 5 passes during dry soil conditions with an Abrams M1A1 Main Battle Tank in burned silt loam soil, 2007. Filled symbols indicate significant compaction at that depth ($p \leq 0.05$).

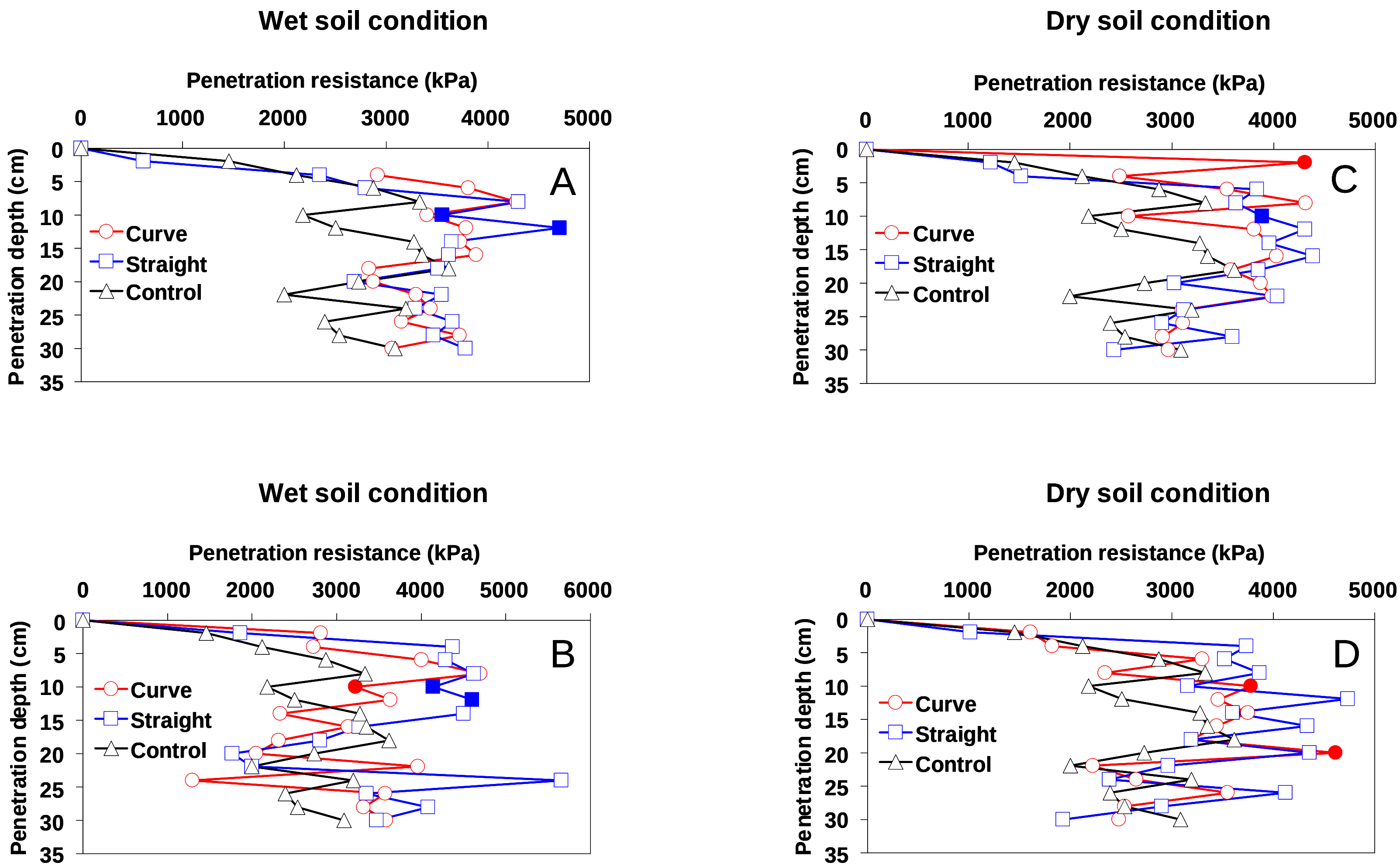


Figure 2.15. Penetrometer resistance for (A) 10 passes during wet soil conditions, (B) 5 passes during wet soil conditions, (C) 10 passes during dry soil conditions and (D) 5 passes during dry soil conditions with an Abrams M1A1 Main Battle Tank in unburned silt loam soil, 2007. Filled symbols indicate significant compaction at that depth ($p \leq 0.05$).

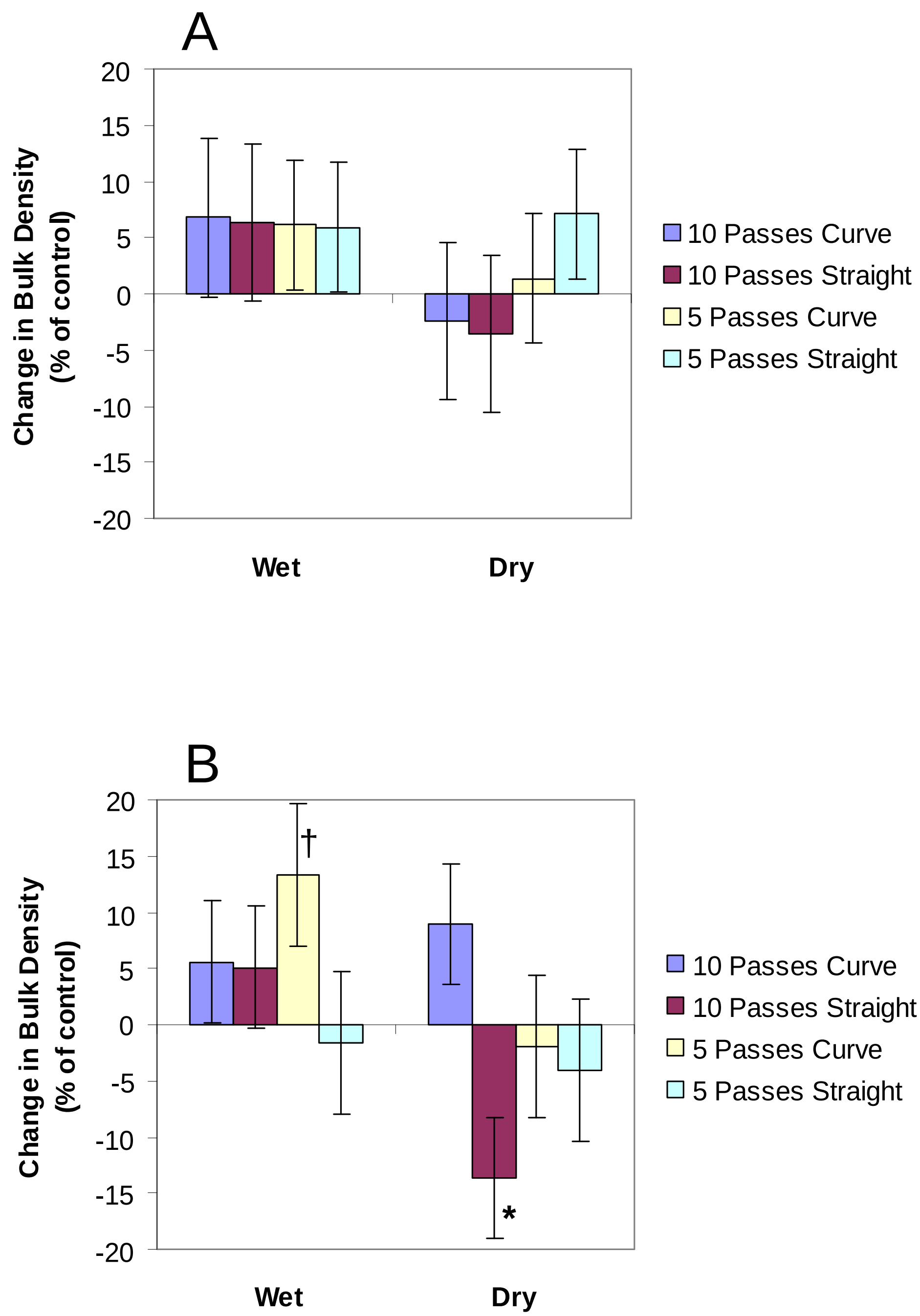


Figure 2.16. Disturbance response for bulk density in (A) silty clay loam soil and (B) silt loam soil, 2005. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, * indicate $p \leq 0.10, 0.05$ respectively. Bulk density averaged 1.06 and 0.97 g cm^{-3} for controls in silty clay loam soil and silt loam soil, respectively.

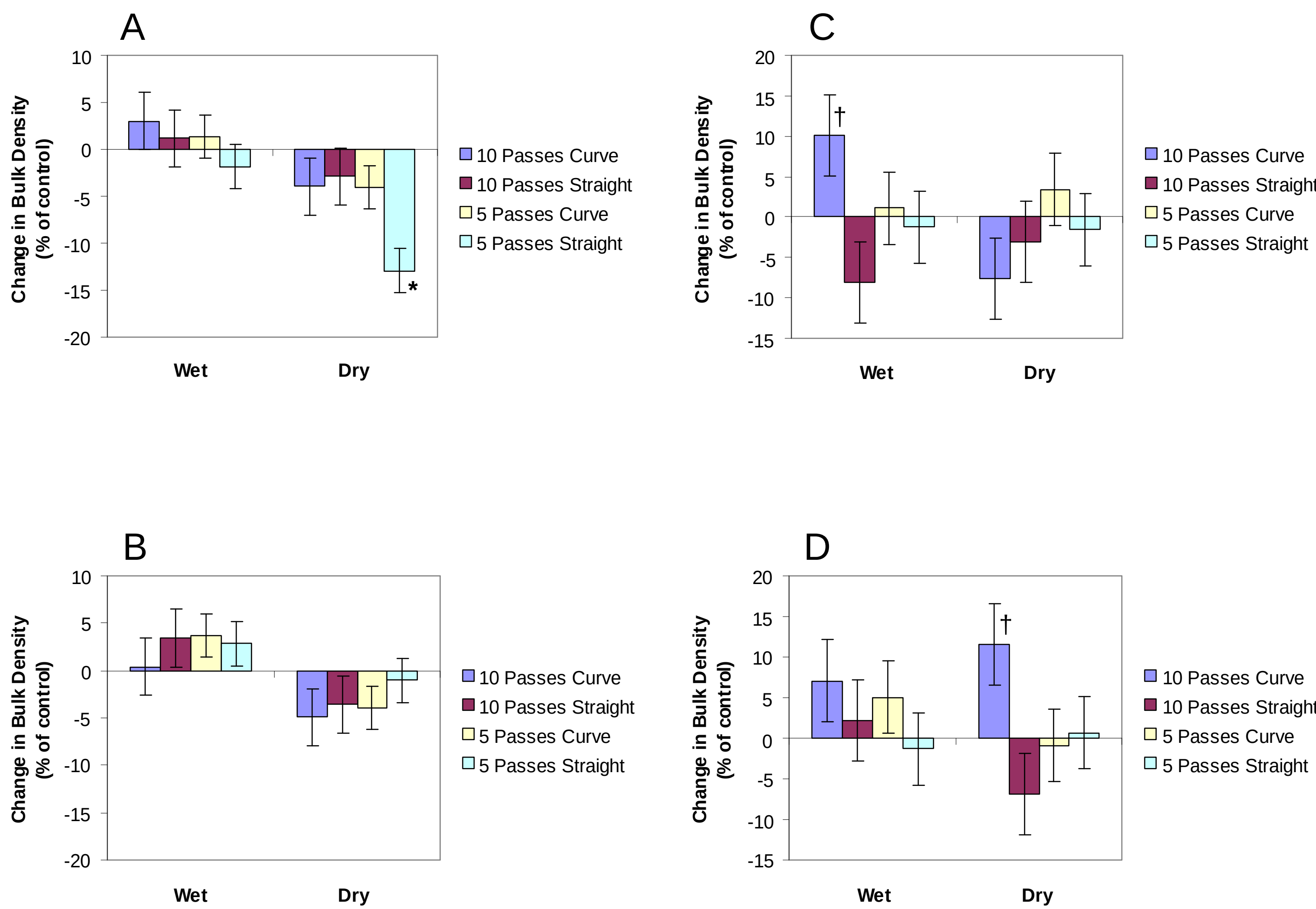


Figure 2.17. Disturbance response for bulk density in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2006. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. † indicates $p \leq 0.10$. Bulk density averaged 1.11 and 1.14 g cm^{-3} for burned and unburned controls, respectively, in silty clay loam soil and 1.00 and 0.96 g cm^{-3} for burned and unburned controls, respectively, in silt loam soil.

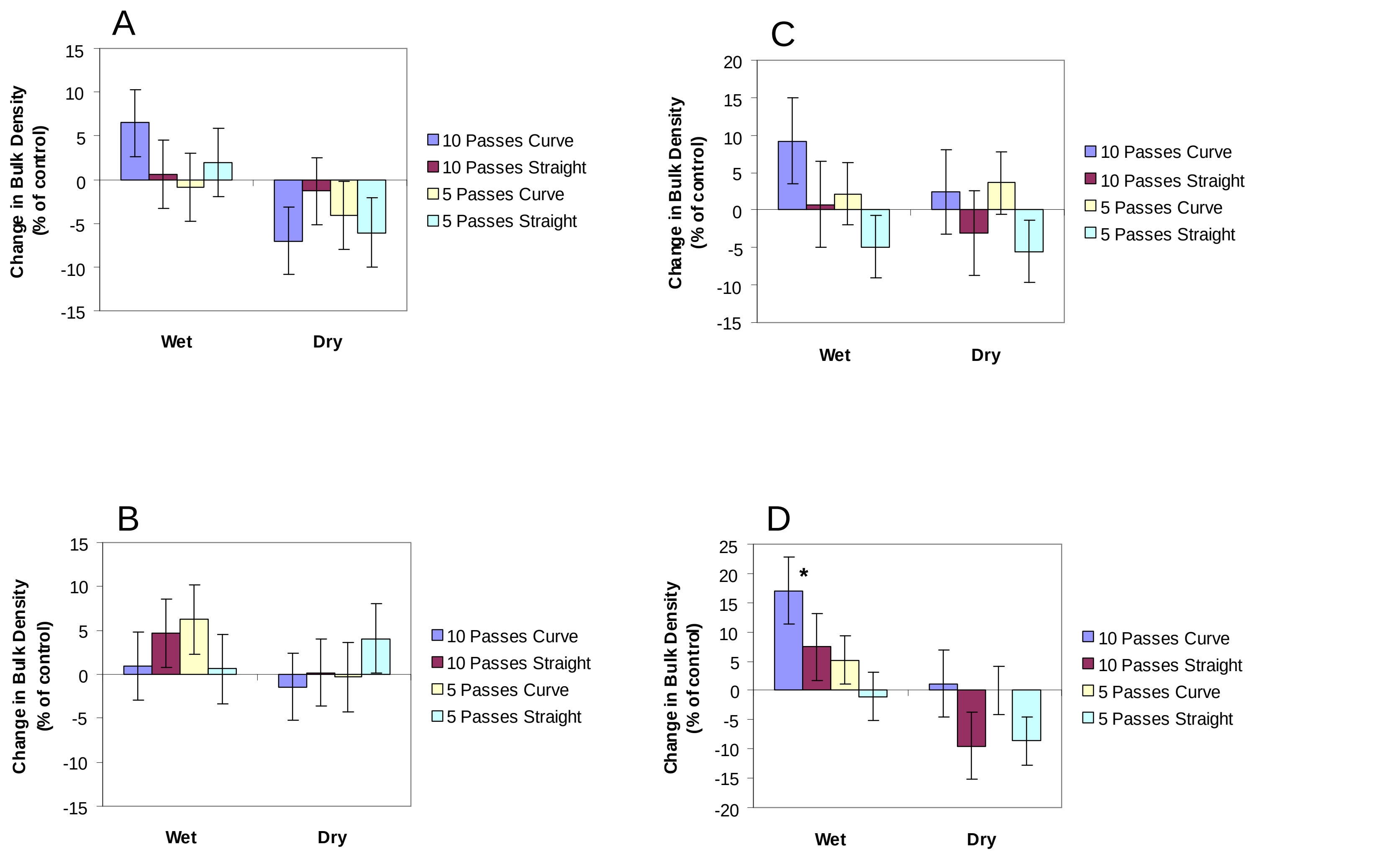


Figure 2.18. Disturbance response for bulk density in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2007. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. * indicates $p \leq 0.05$. Bulk density averaged 1.15 and 1.21 g cm^{-3} for burned and unburned controls, respectively, in silty clay loam soil and 1.03 and 1.04 g cm^{-3} for burned and unburned controls, respectively, in silt loam soil.

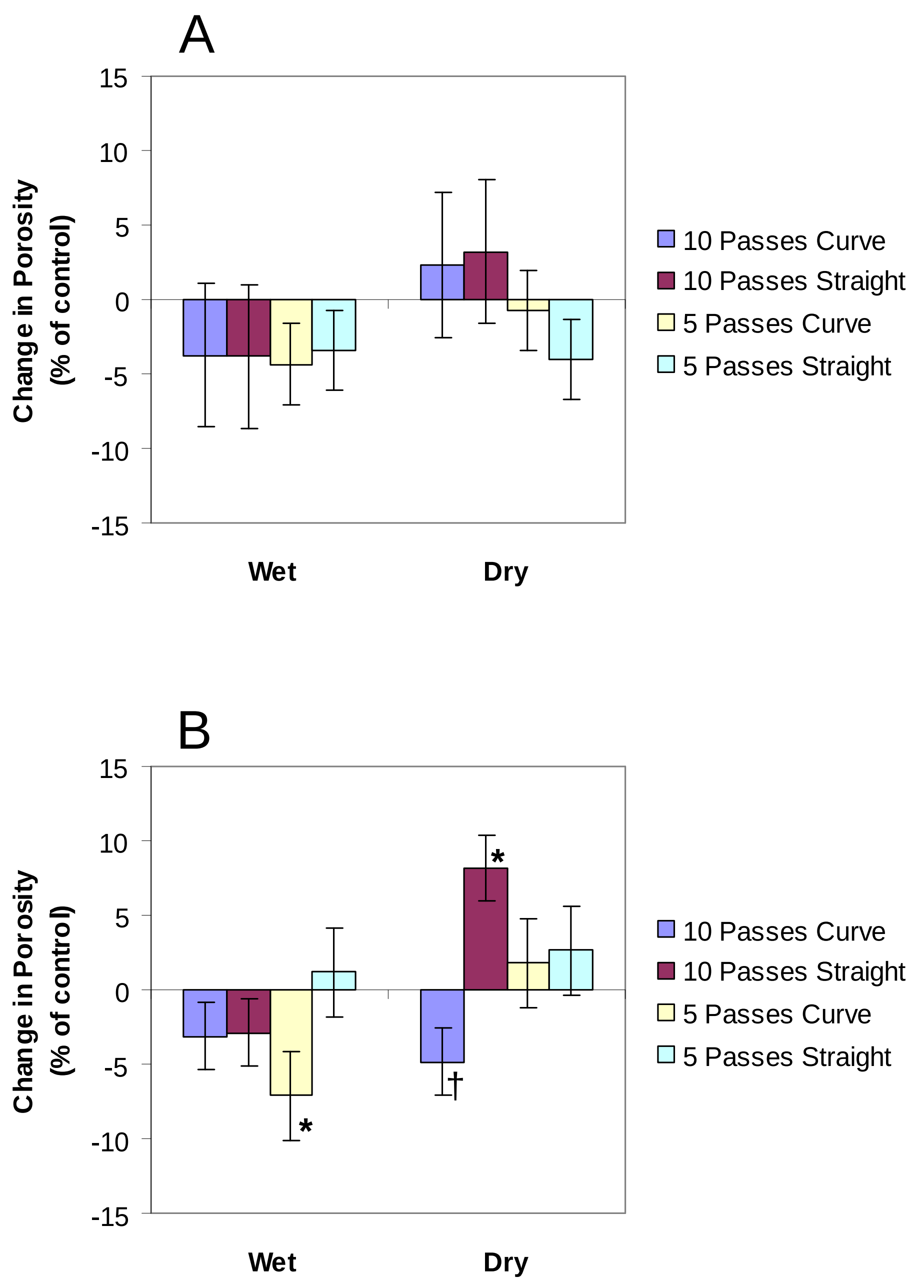


Figure 2.19. Disturbance response for porosity in (A) silty clay loam soil and (B) silt loam soil, 2005. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, * indicate $p \leq 0.10$, 0.05, respectively. Porosity averaged 60 and 63 % for controls in silty clay loam soil and silt loam soil, respectively.

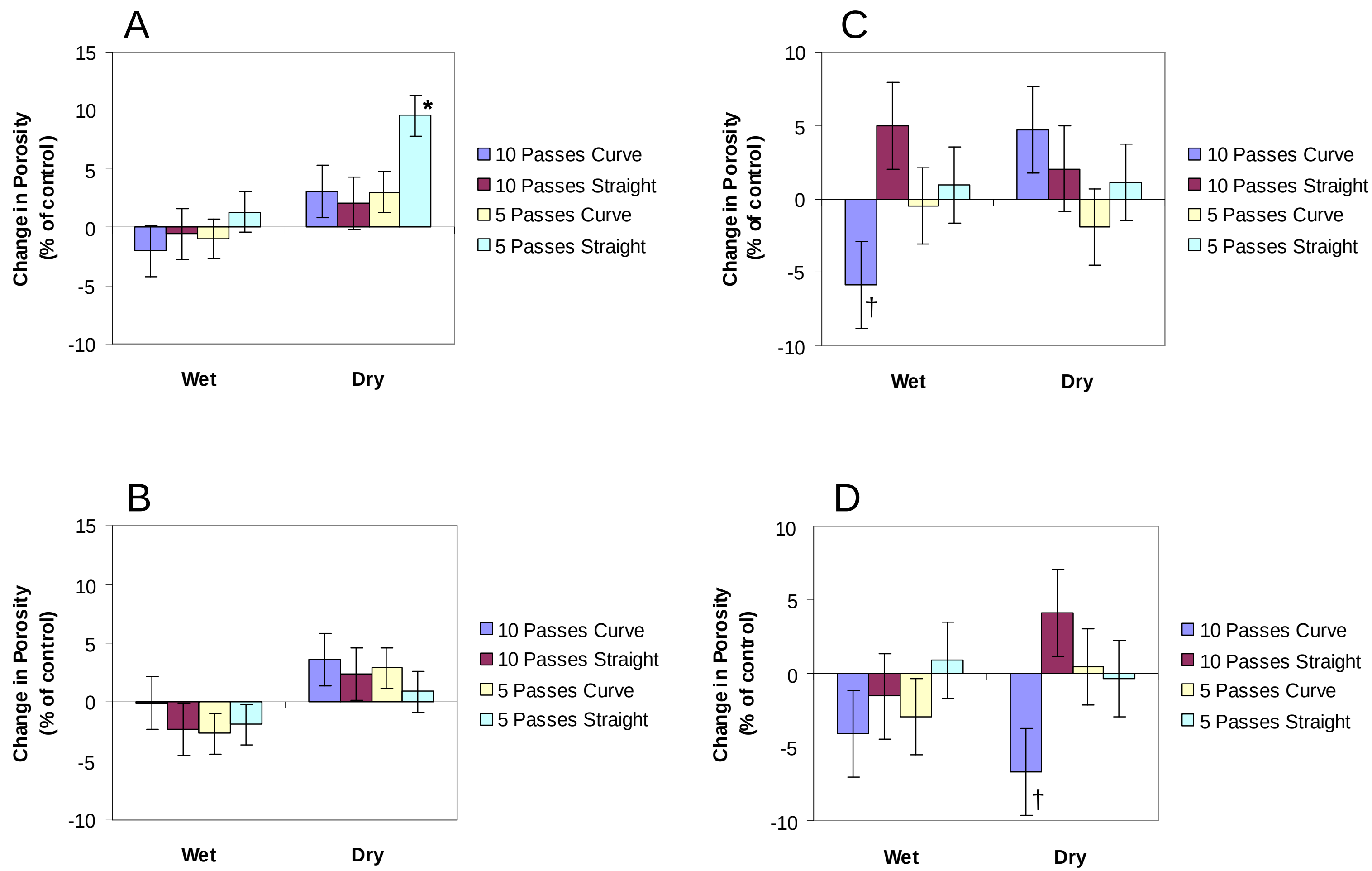


Figure 2.20. Disturbance response for porosity in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2006. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, * indicate $p \leq 0.10$, 0.05, respectively. Porosity averaged 58 and 57 % for burned and unburned controls, respectively, in silty clay loam soil and 62 and 64 % for burned and unburned controls, respectively, in silt loam soil.

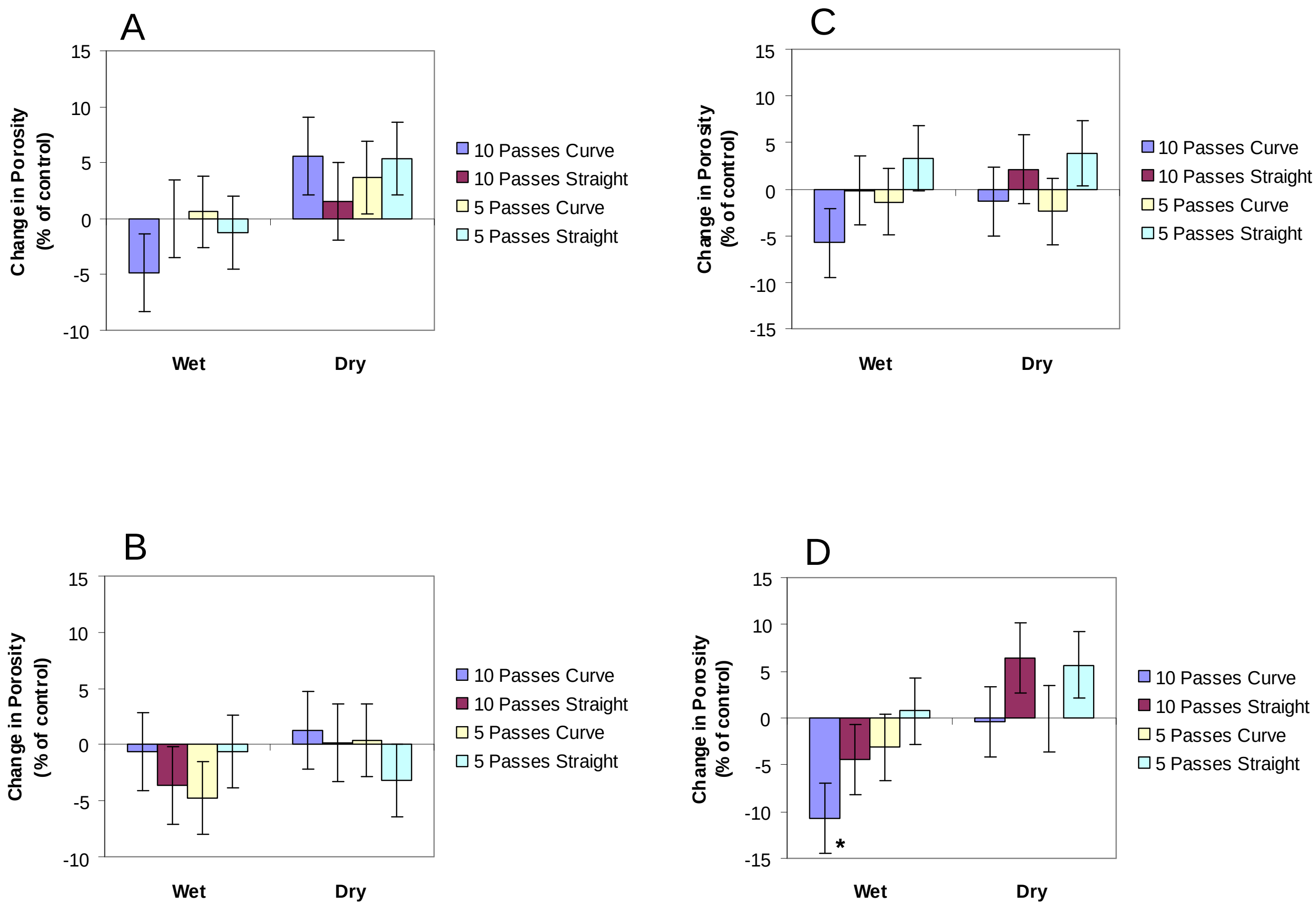


Figure 2.21. Disturbance response for porosity in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2007. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. * indicates $p \leq 0.05$. Porosity averaged 57 and 54 % for burned and unburned controls, respectively, in silty clay loam soil and 61 and 61 % for burned and unburned controls, respectively, in silt loam soil.

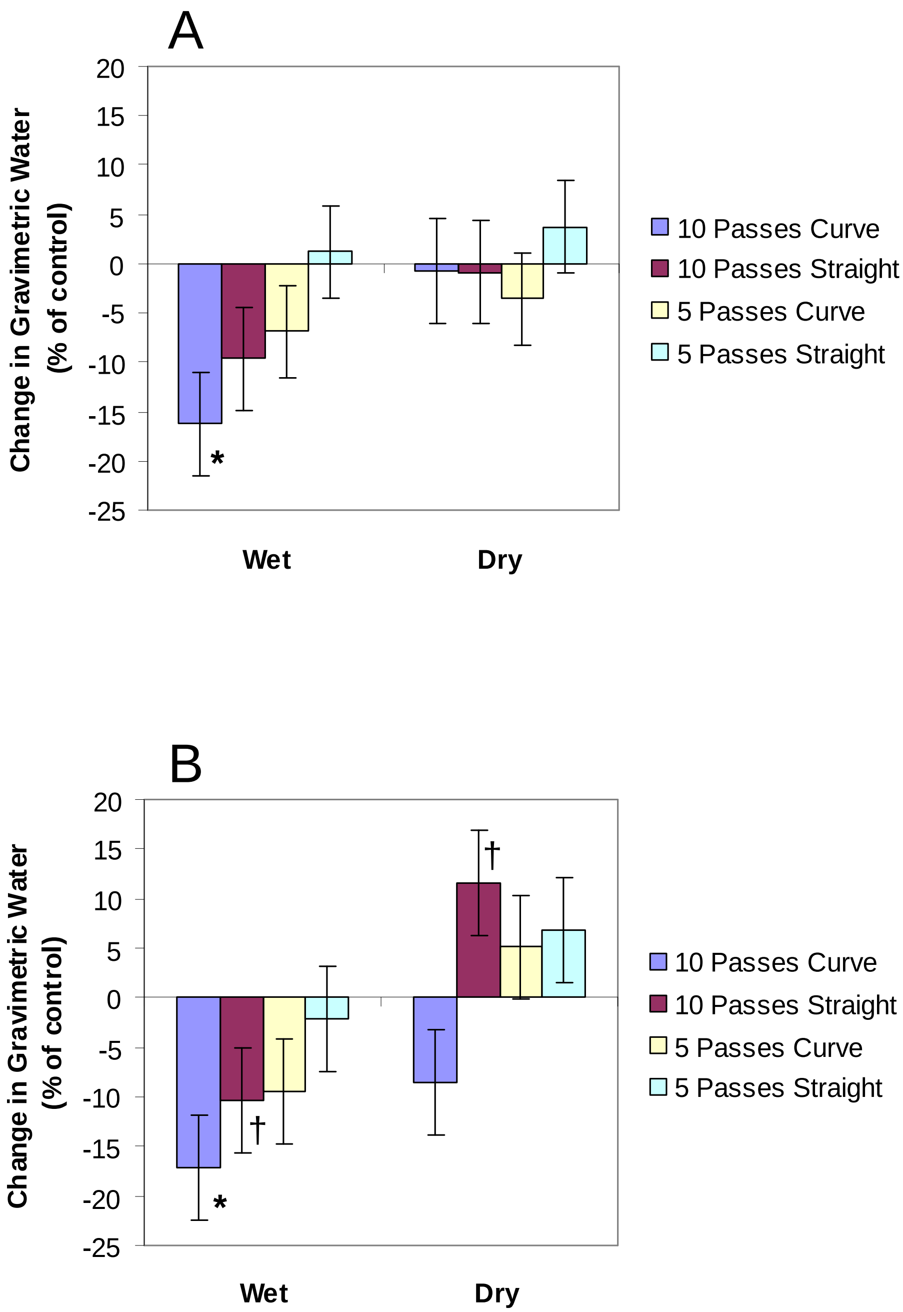


Figure 2.22. Disturbance response for gravimetric water in (A) silty clay loam soil and (B) silt loam soil, 2005. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, * indicate $p \leq 0.10$, 0.05, respectively. Water content averaged 31 and 34 g g^{-1} for controls in silty clay loam soil and silt loam soil, respectively.

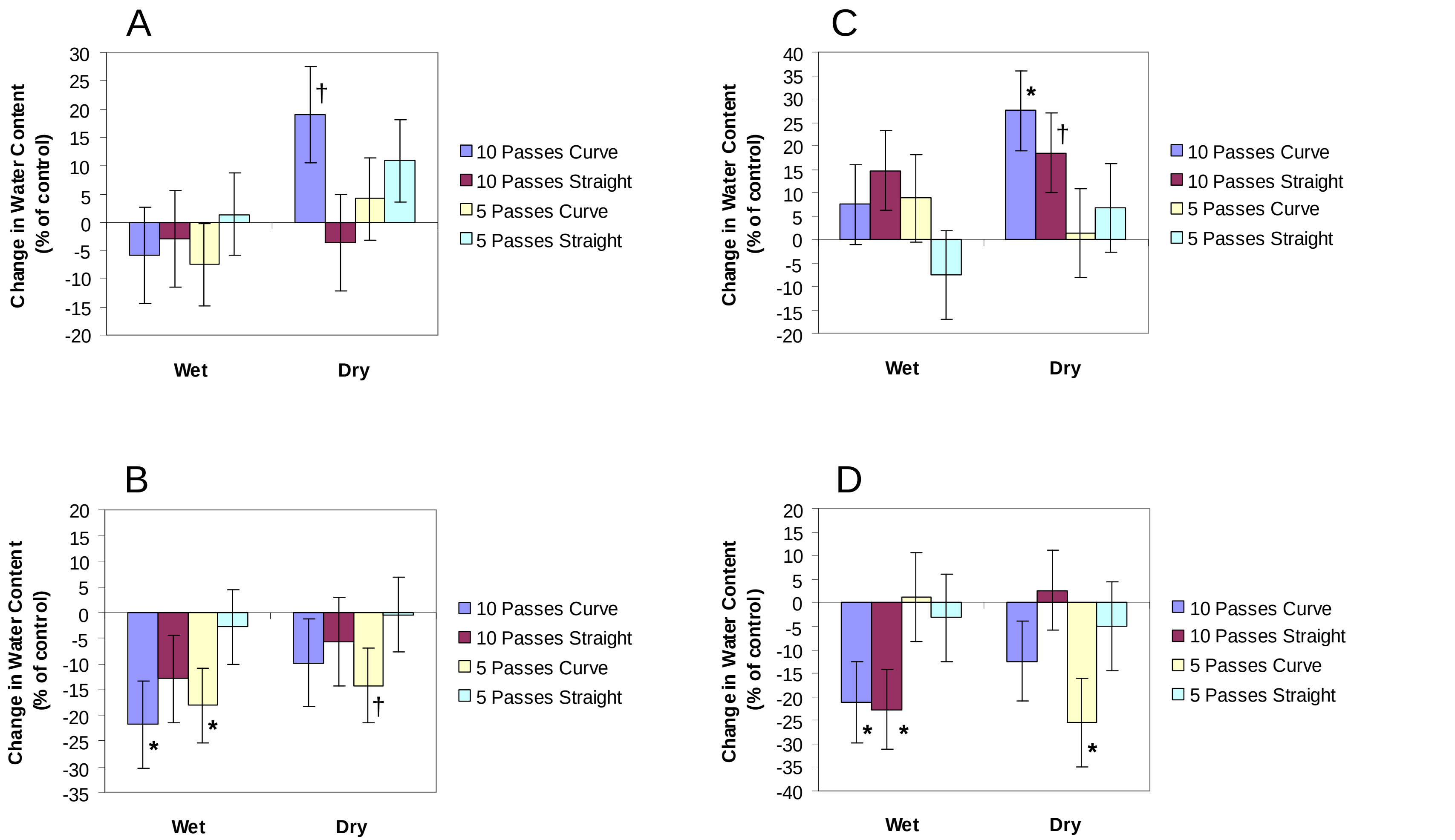


Figure 2.23. Disturbance response for gravimetric water in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2006. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, * indicate $p \leq 0.10, 0.05$, respectively. Water content averaged 25 and 31 g g^{-1} for burned and unburned controls, respectively, in silty clay loam soil and 21 and 33 g g^{-1} for burned and unburned controls, respectively, in silt loam soil.

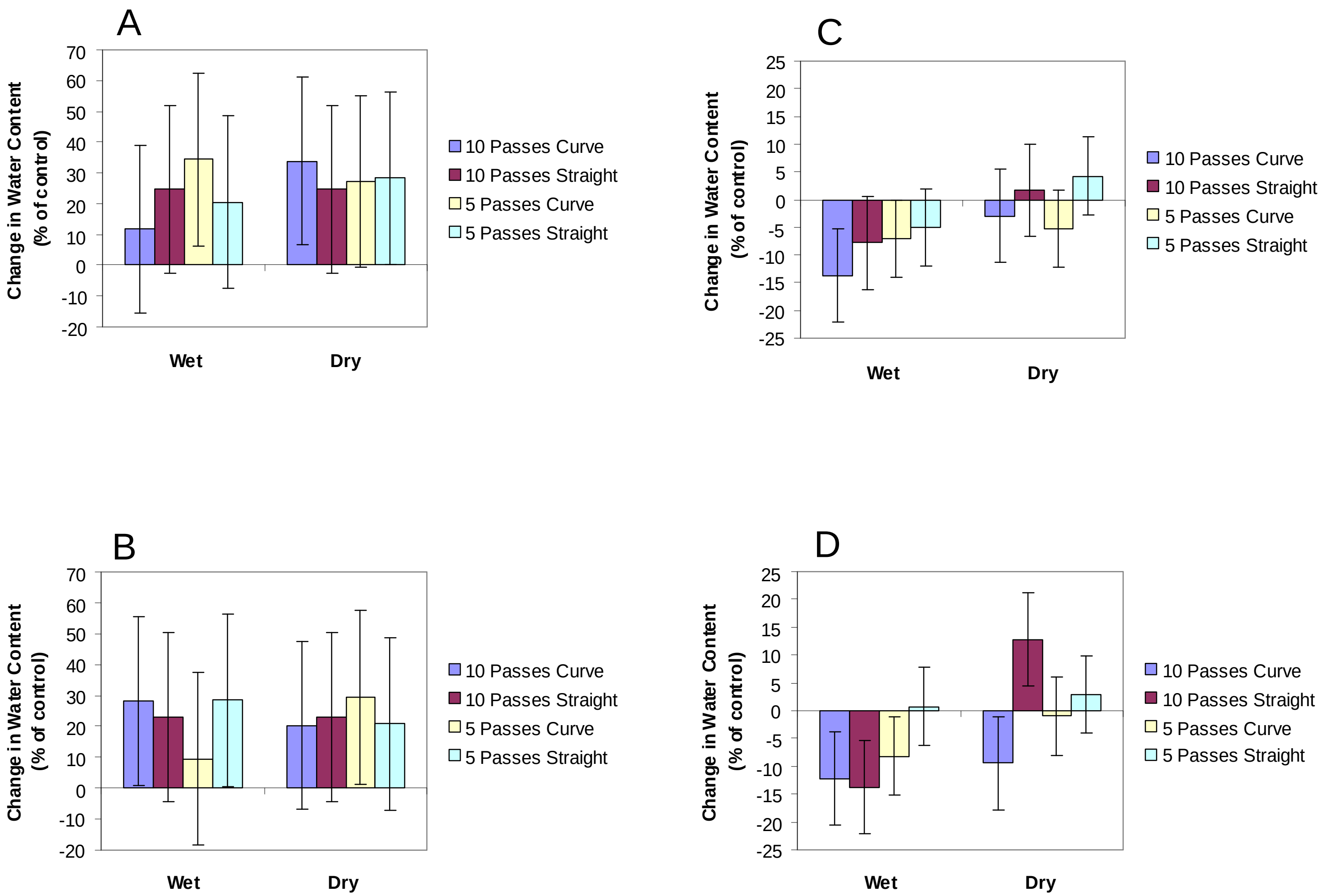


Figure 2.24. Disturbance response for gravimetric water in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2007. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. Water content averaged 30 and 22 g g^{-1} for burned and unburned controls, respectively, in silty clay loam soil and 30 and 36 g g^{-1} for burned and unburned controls, respectively, in silt loam soil.

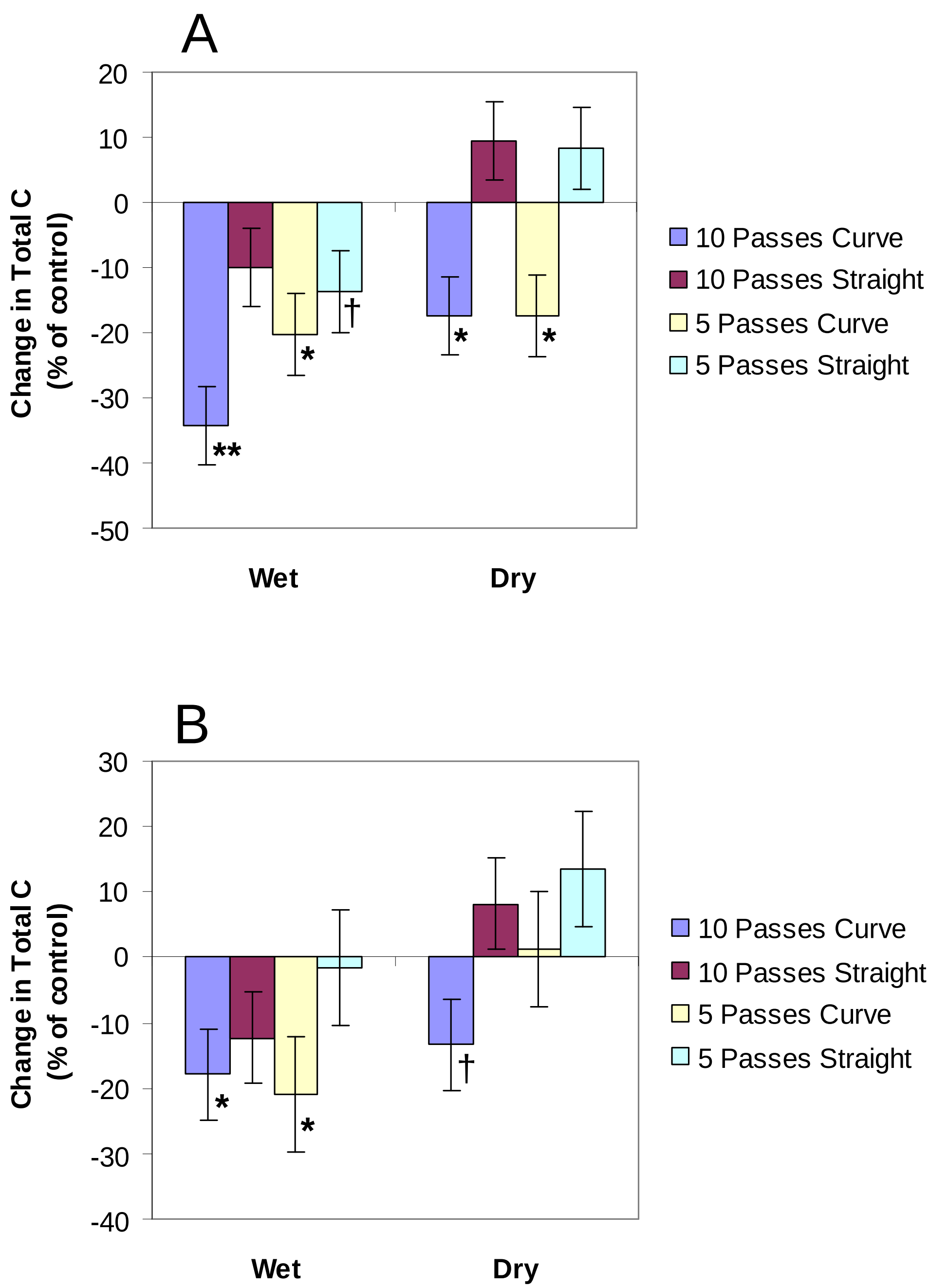


Figure 2.25. Disturbance response for total carbon in (A) silty clay loam soil and (B) silt loam soil, 2005. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, *, ** indicate $p \leq 0.10, 0.05, 0.01$, respectively. Total C averaged 2.25 and 3.42 g kg^{-1} for controls in silty clay loam soil and silt loam soil, respectively.

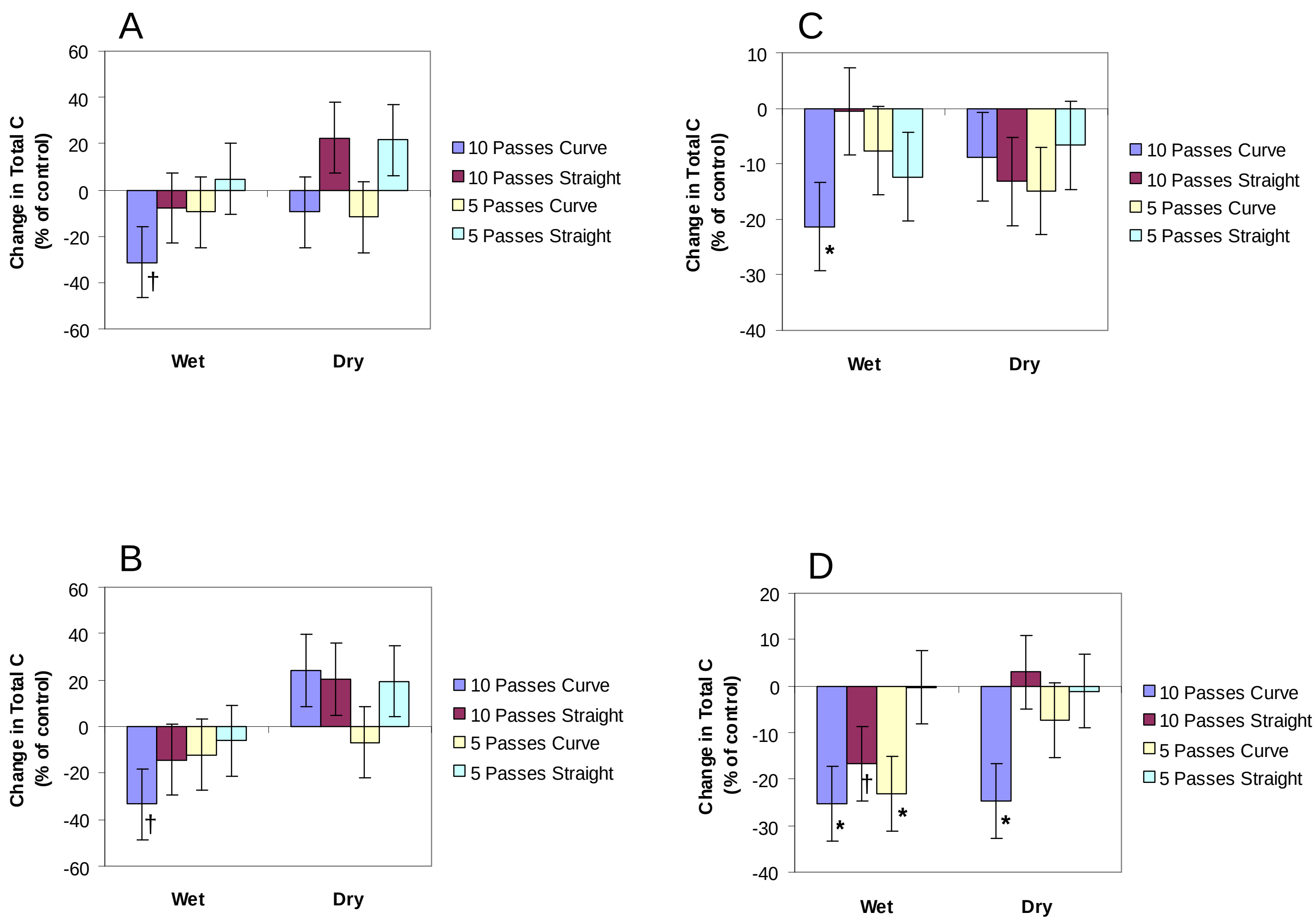


Figure 2.26. Disturbance response for total carbon in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2006. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, * indicate $p \leq 0.10, 0.05$, respectively. Total C averaged 1.93 and 2.06 g kg^{-1} for burned and unburned controls, respectively, in silty clay loam soil and 3.13 and 3.53 g kg^{-1} for burned and unburned controls, respectively, in silt loam soil.

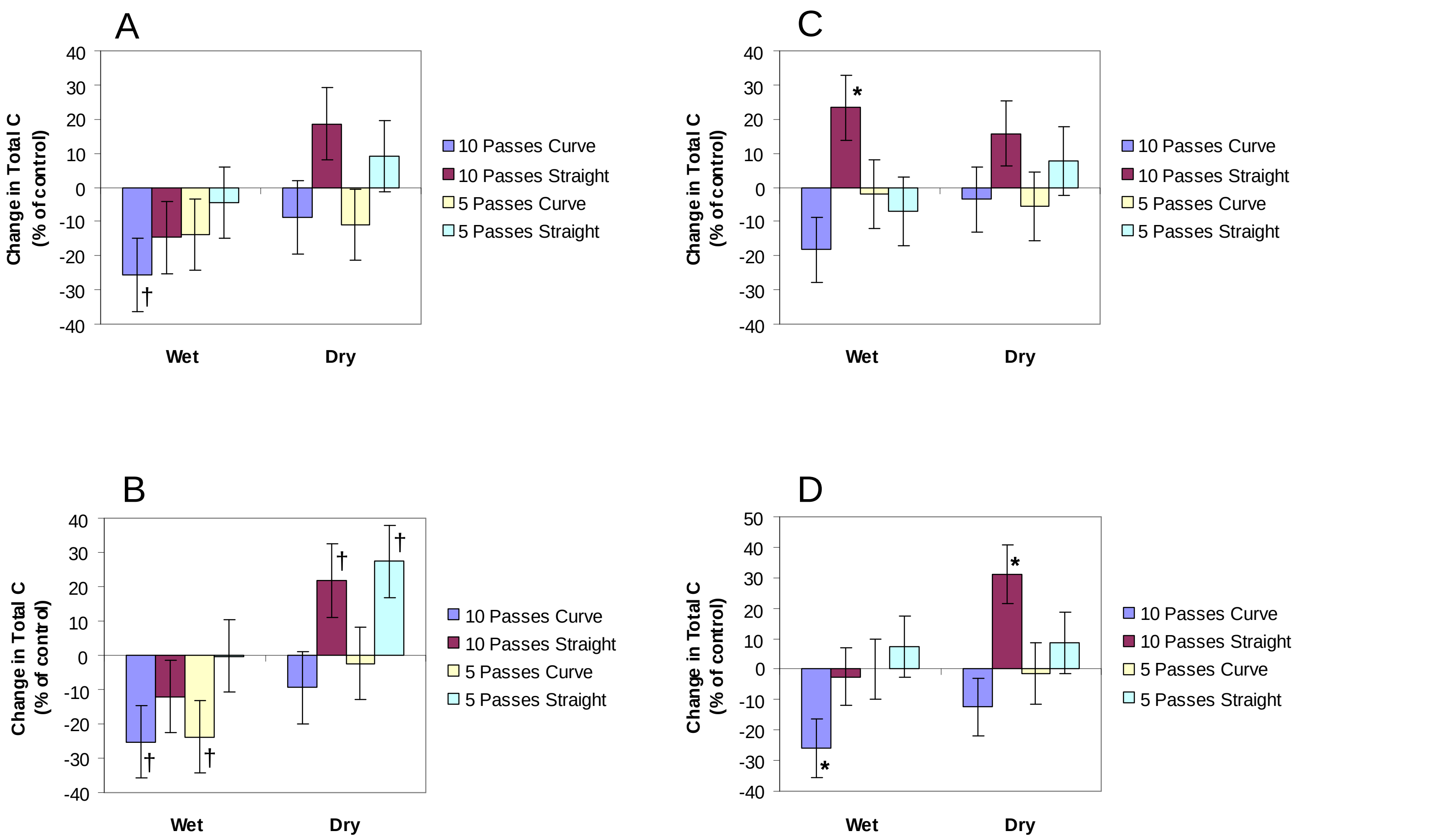


Figure 2.27. Disturbance response for total carbon in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2007. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, * indicate $p \leq 0.10, 0.05$, respectively. Total C averaged 1.90 and 1.82 g kg^{-1} for burned and unburned controls, respectively, in silty clay loam soil and 2.92 and 2.93 g kg^{-1} for burned and unburned controls, respectively, in silt loam soil.

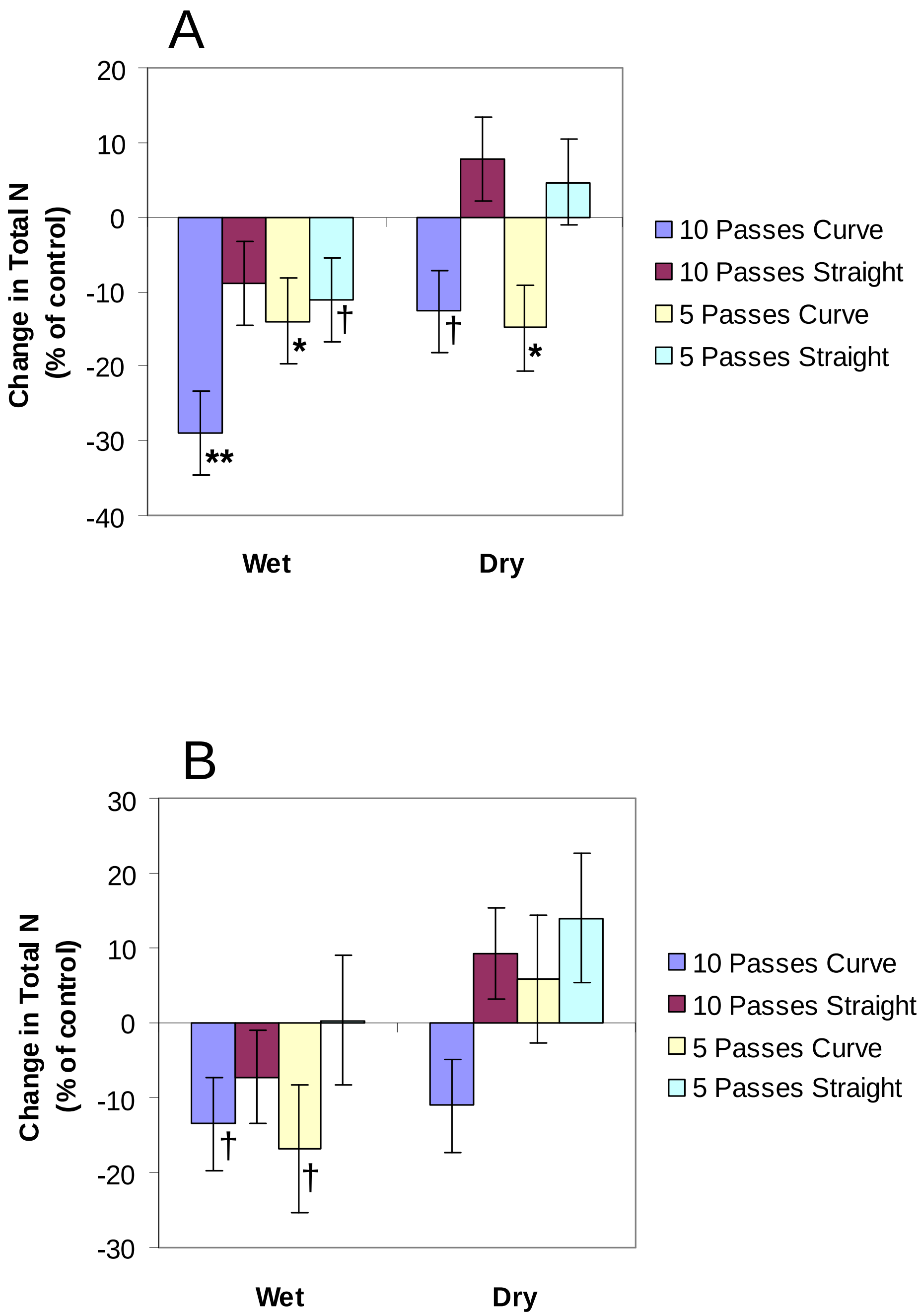


Figure 2.28. Disturbance response for total nitrogen in (A) silty clay loam soil and (B) silt loam soil, 2005. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, *, ** indicate $p \leq 0.10$, 0.05, 0.01, respectively. Total N averaged 0.19 and 0.28 g kg^{-1} for controls in silty clay loam soil and silt loam soil, respectively.

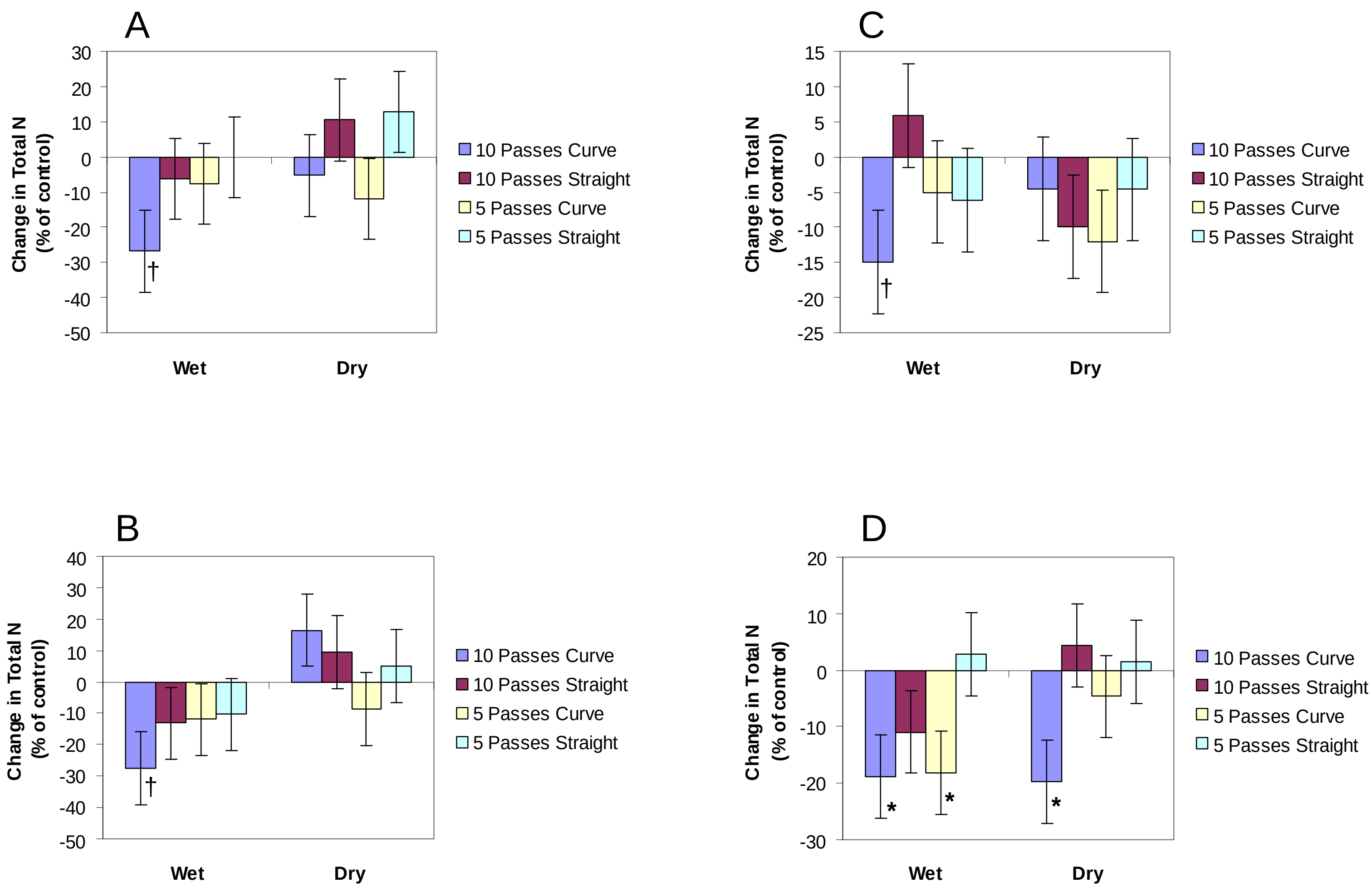


Figure 2.29. Disturbance response for total nitrogen in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2006. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, * indicate $p \leq 0.10$, 0.05, respectively. Total N averaged 0.18 and 0.18 g kg^{-1} for burned and unburned controls, respectively, in silty clay loam soil and 0.25 and 0.29 g kg^{-1} for burned and unburned controls, respectively, in silt loam soil.

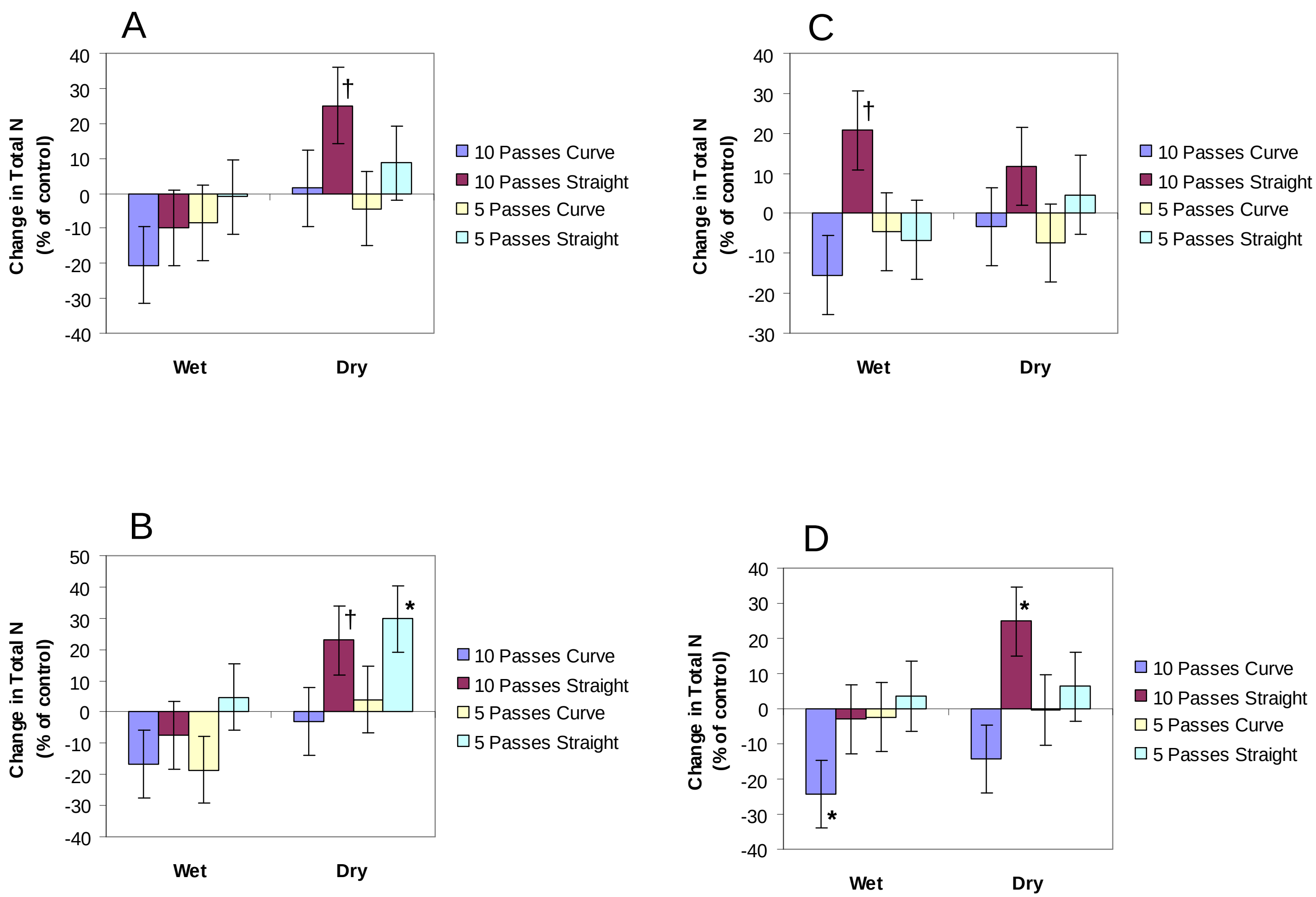


Figure 2.30. Disturbance response for total nitrogen in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2007. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, * indicate $p \leq 0.10$, 0.05, respectively. Total N averaged 0.15 and 0.14 g kg^{-1} for burned and unburned controls, respectively, in silty clay loam soil and 0.24 and 0.24 g kg^{-1} for burned and unburned controls, respectively, in silt loam soil.

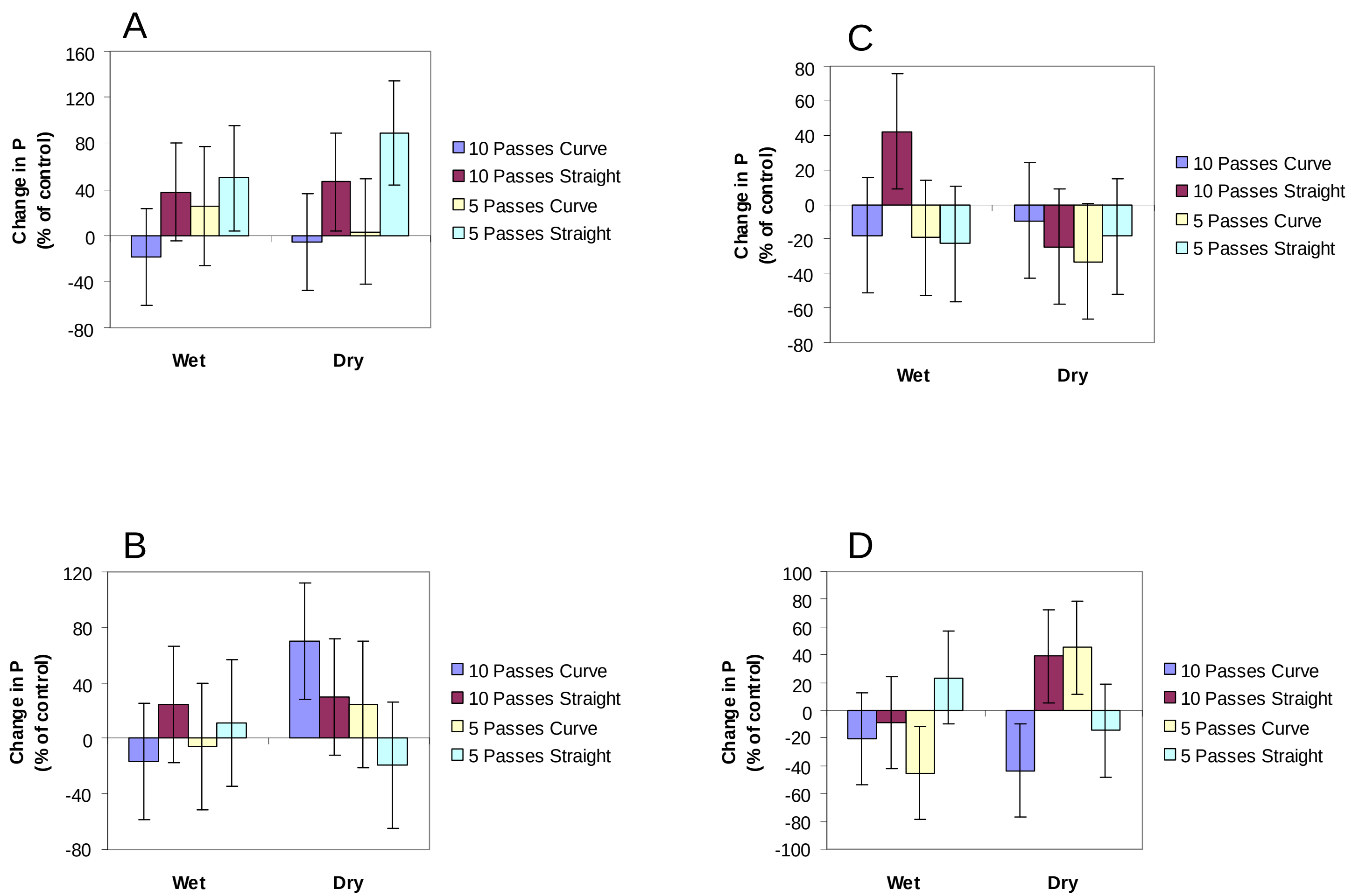


Figure 2.31. Disturbance response for soil phosphorus in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2006. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. Soil P averaged 4.67 and 4.67 mg kg^{-1} for burned and unburned controls, respectively, in silty clay loam soil and 14.00 and 11.67 mg kg^{-1} for burned and unburned controls, respectively, in silt loam soil.

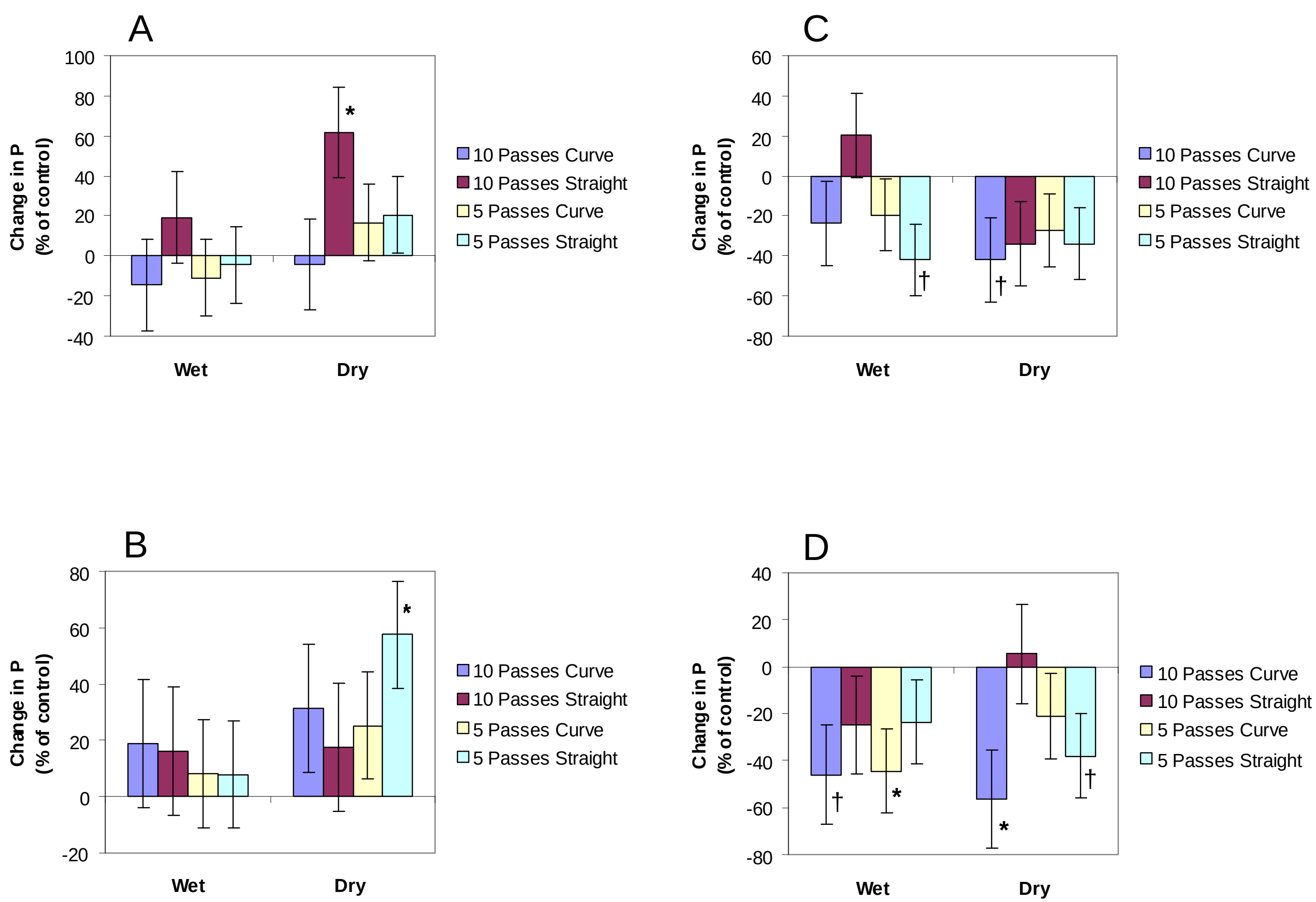


Figure 2.32. Disturbance response for soil phosphorus in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2007. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, * indicate $p \leq 0.10$, 0.05,respectively. Soil P averaged 5.67 and 3.67 mg kg^{-1} for burned and unburned controls, respectively, in silty clay loam soil and 10.33 and 20.67 mg kg^{-1} for burned and unburned controls, respectively, in silt loam soil.

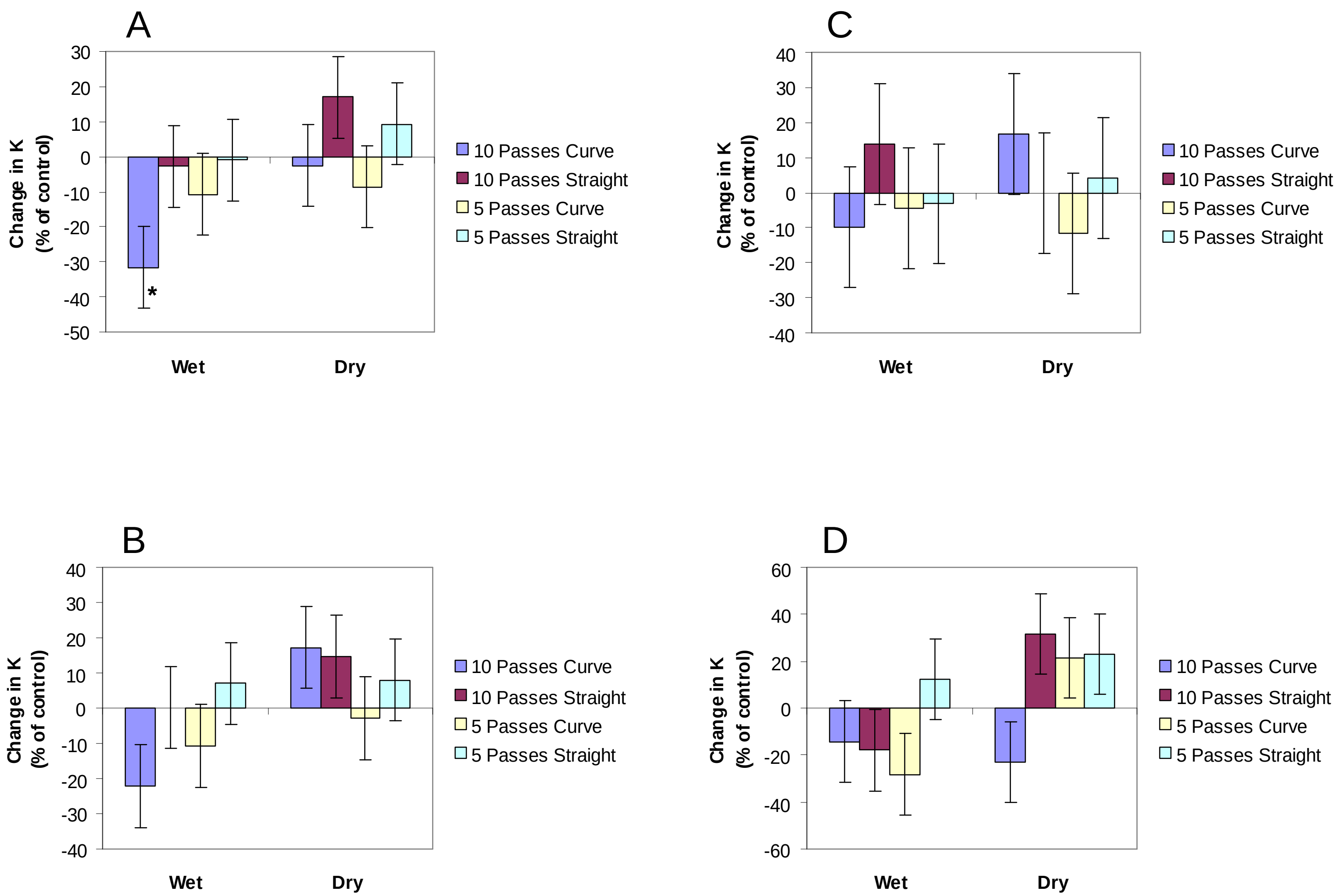


Figure 2.33. Disturbance response for soil potassium in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2006. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. * indicates $p \leq 0.05$. Soil K averaged 316 and 333 mg kg^{-1} for burned and unburned controls, respectively, in silty clay loam soil and 278 and 316 mg kg^{-1} for burned and unburned controls, respectively, in silt loam soil.

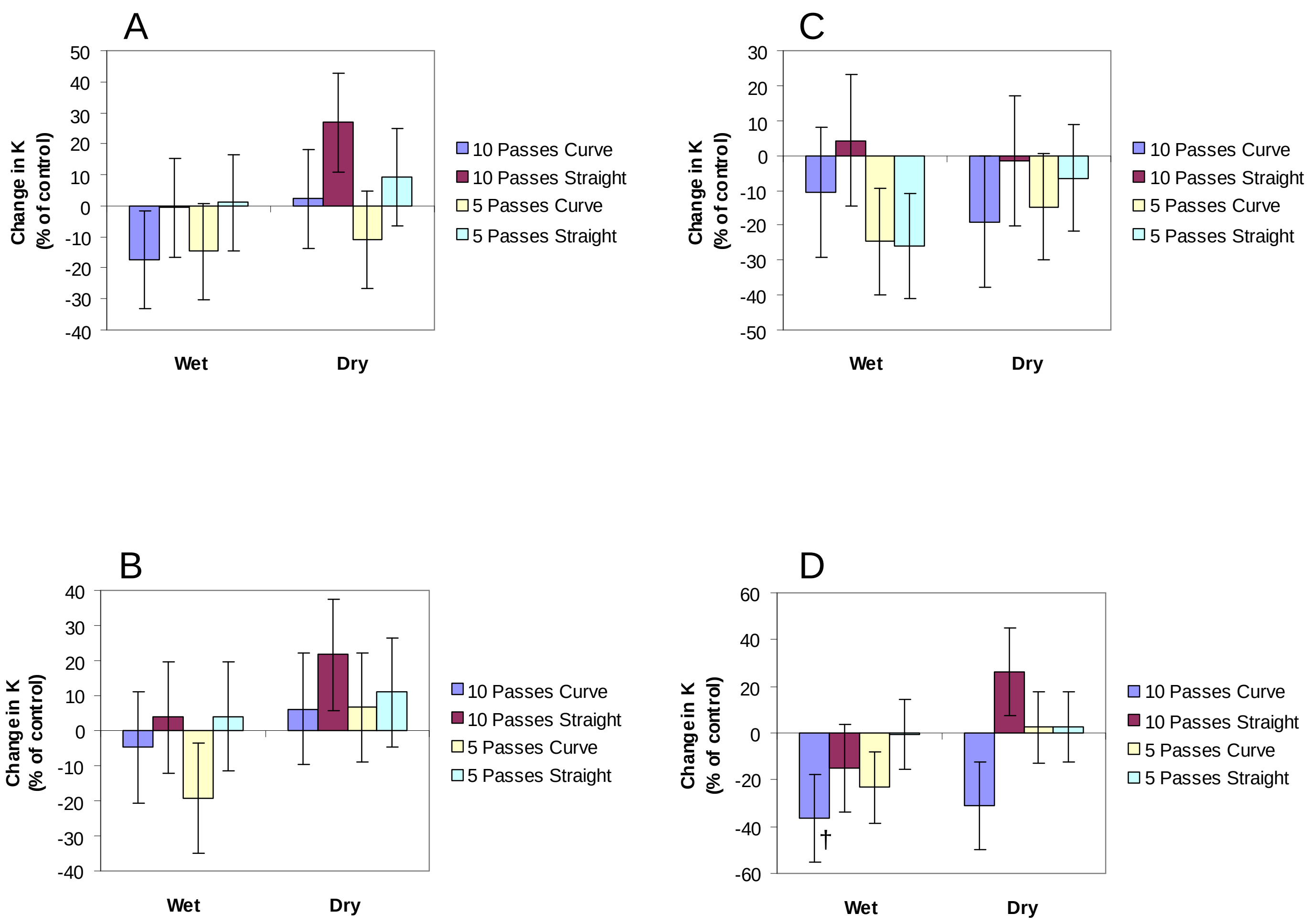


Figure 2.34. Disturbance response for soil potassium in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2007. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. † indicates $p \leq 0.10$. Soil K averaged 312 and 306 mg kg^{-1} for burned and unburned controls, respectively, in silty clay loam soil and 248 and 410 mg kg^{-1} for burned and unburned controls, respectively, in silt loam soil.

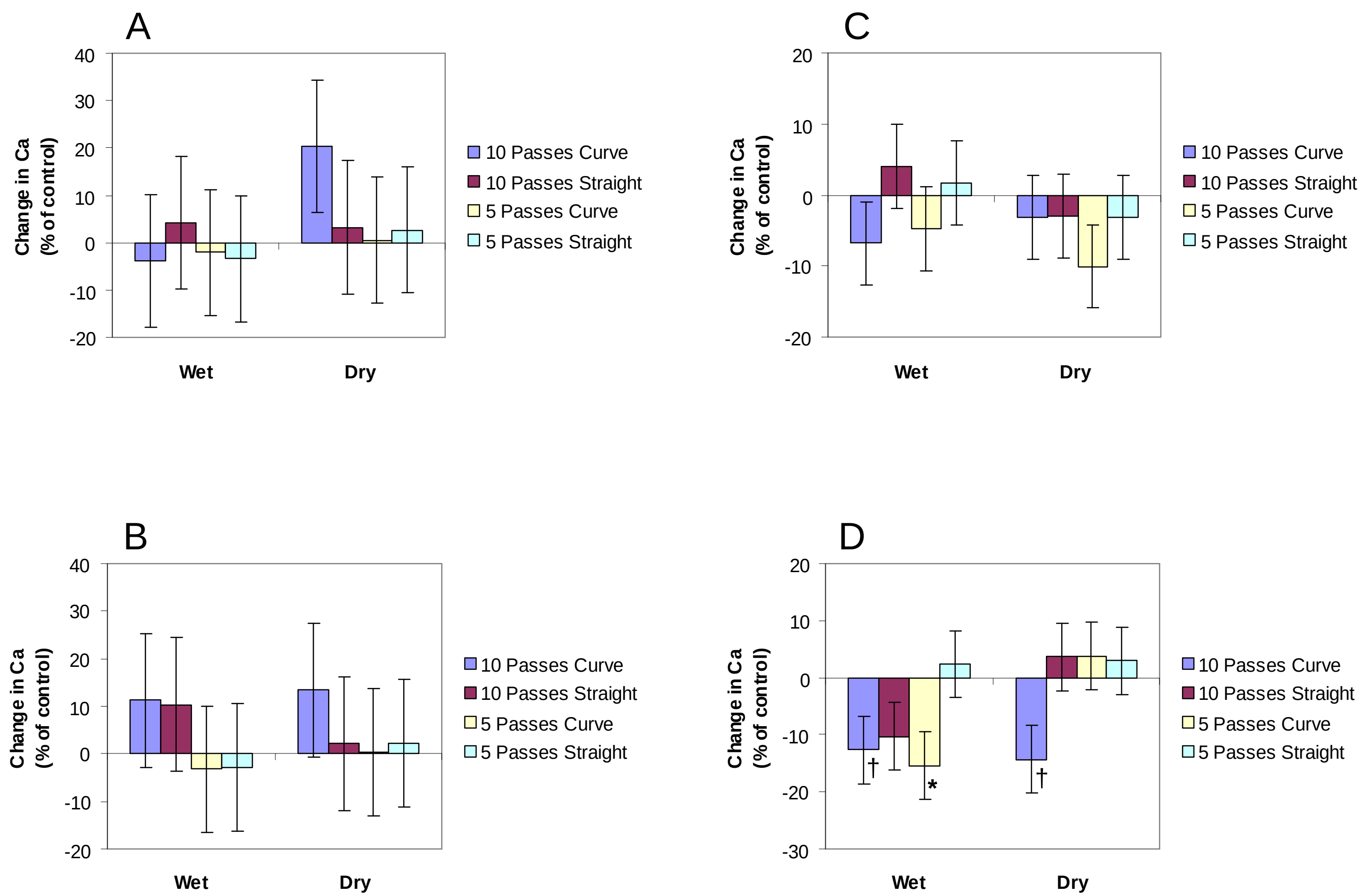


Figure 2.35. Disturbance response for soil calcium in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2006. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, * indicate $p \leq 0.10$, 0.05,respectively. Soil Ca averaged 2926 and 3062 mg kg^{-1} for burned and unburned controls, respectively, in silty clay loam soil and 2884 and 2723 mg kg^{-1} for burned and unburned controls, respectively, in silt loam soil.

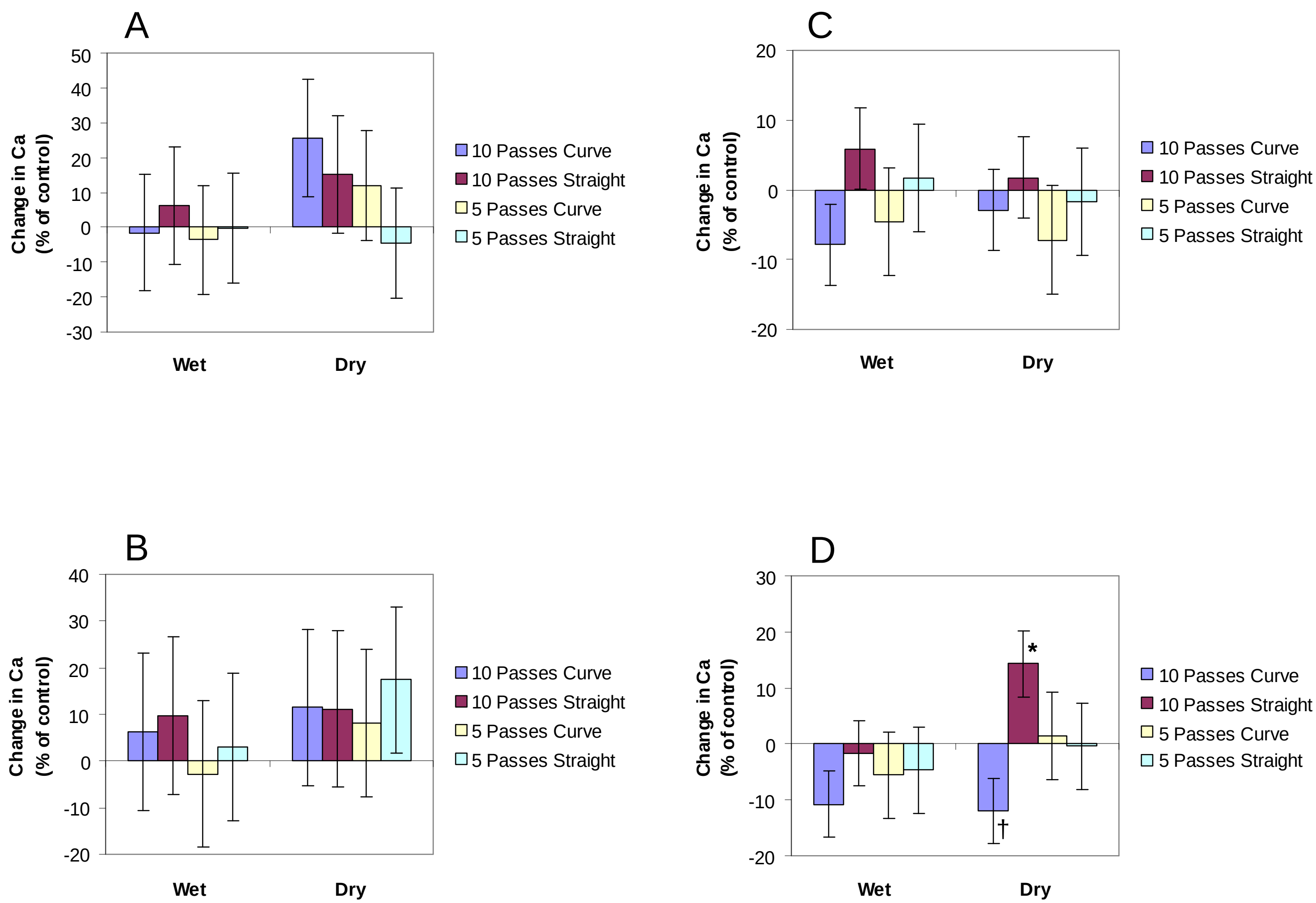


Figure 2.36. Disturbance response for soil calcium in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2007. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, * indicate $p \leq 0.10$, 0.05, respectively. Soil Ca averaged 2687 and 2808 mg kg^{-1} for burned and unburned controls, respectively, in silty clay loam soil and 2641and 2663 mg kg^{-1} for burned and unburned controls, respectively, in silt loam soil.

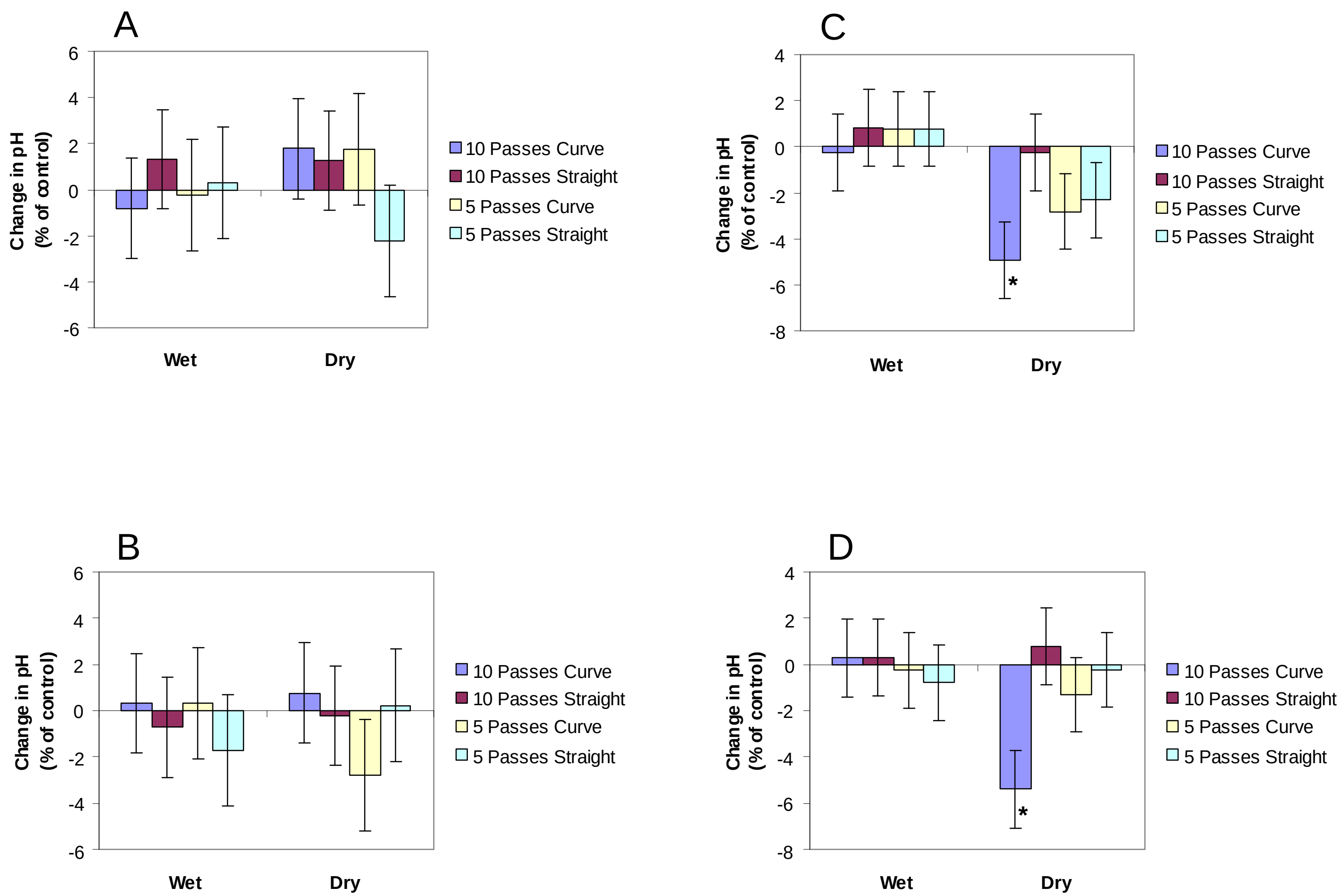


Figure 2.37. Disturbance response for soil pH in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2007. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. * indicates $p \leq 0.05$. Soil pH averaged 6.6 and 6.6 for burned and unburned controls, respectively, in silty clay loam soil and 6.4 and 6.5 for burned and unburned controls, respectively, in silt loam soil.

Table 2.1. Analysis of variance (F-values) for disturbance response [A] of soil physical properties in the silty clay loam and silt loam soils, 2005.

Effect [B]	F-values: Soil Physical Properties: Bulk Density ($kg\ cm^{-3}$)		Porosity (%)		Water Content ($g\ g^{-1}$)		Penetrometer Resistance (kPa)		Soil Chemical Properties: Total Carbon ($g\ kg^{-1}$)		Total Nitrogen ($g\ kg^{-1}$)	
	Silty Clay Loam											
Treatment (T)	2.24		0.78		4.22		2.52		46.27	*	23.33	*
Split (S)	0.77		1.91		2.78		0.52		2.36		1.83	
T × S	1.04		1.80		1.97		0.67		4.02		10.37	*
Area (A)	0.15		0.05		3.66	†	0.71		14.62	**	11.61	**
T × A	0.26		0.21		0.43		0.41		0.98		0.84	
S × A	0.50		0.20		0.60		0.13		0.74		0.97	
T × S × A	0.42		0.53		0.27		1.81		0.58		0.78	
	Silt Loam											
Treatment (T)	5.97		4.83		17.93	*	3.51		24.91	*	8.27	†
Split (S)	0.00		0.04		4.08		2.23		1.49		1.56	
T × S	0.03		0.03		0.32		0.64		0.30		0.71	
Area (A)	16.59	**	18.52	**	8.43	*	3.46	†	10.58	*	9.21	*
T × A	0.87		1.04		0.39		0.39		0.24		0.08	
S × A	0.39		0.63		2.05		0.09		0.06		0.00	
T × S × A	12.76	**	14.99	**	2.38		1.17		1.64		1.83	

[A] Disturbance response = (disturbed measurement-undisturbed measurement)/(undisturbed measurement).
[B] Represents treatment = (T) tank traffic during wet or dry soil conditions, (S) Split = half of the plot treated (i.e., 5 passes 2003, plus 5 additional passes, repeated traffic, 2004), or left untreated for 2004 (i.e., 5 passes single traffic, 2003), (A) Area = subplot from which sample was collected (i.e., curve, straight-a-way).
[†], *, ** Denotes significance at the $p \leq 0.10, 0.05, 0.01$ probability levels, respectively.

Table 2.2. Analysis of variance (F-values) for disturbance response [A] of soil physical properties in the silty clay loam soil, 2006.

	F-values							
	Soil Physical Properties							
Effect [B]	Bulk Density ($g\ cm^{-3}$)		Porosity (%)		Water Content ($g\ g^{-1}$)		Penetrometer Resistance (kPa)	
Treatment (T)	8.70	†	8.58	†	2.78		0.25	
Split (S)	0.80		0.69		0.53		0.21	
T × S	0.25		0.37		1.22		0.51	
Area (A)	0.35		0.36		1.64		0.02	
T × A	0.00		0.00		2.12		0.83	
S × A	1.65		1.86		3.05		0.18	
T × S × A	0.09		0.14		1.31		0.24	
Burn (B)	1.90		2.04		5.53	†	0.01	
T × B	0.08		0.13		0.27		0.94	
S × B	7.93	*	7.66	*	0.18		7.60	*
T × S × B	0.69		0.74		0.18		0.09	
A × B	6.57	*	6.96	*	2.47		13.16	**
T × A × B	0.41		0.44		0.84		11.38	**
S × A × B	1.44		1.38		0.43		21.96	**
T × S × A × B	3.49		3.93	†	0.73		6.23	**

[A] Disturbance response = (disturbed measurement-undisturbed measurement)/(undisturbed measurement).
[B] Represents treatment = (T) tank traffic during wet or dry soil conditions, (S) Split = half of the plot treated (i.e., 5 passes 2003, plus 5 additional passes, repeated traffic, 2004), or left untreated for 2004 (i.e., 5 passes single traffic, 2003), (A) Area = subplot from which sample was collected (i.e., curve, straight-a-way).
†, *, ** Denotes significance at the $p \leq 0.10, 0.05, 0.01$ probability levels, respectively.

Table 2.3. Analysis of variance (F-values) for disturbance response [A] of soil physical properties in the silt loam soil, 2006.

Effect[B]	F-values: Soil Physical Properties: Bulk Density ($g\ cm^{-3}$)		Porosity (%)		Water Content ($g\ g^{-1}$)		Penetrometer Resistance (kPa)	
Treatment (T)	5.48		5.33		1.11		0.58	
Split (S)	0.00		0.00		1.21		0.04	
T × S	0.52		0.65		5.33	†	0.00	
Area (A)	6.37	*	6.48	*	0.62		1.93	
T × A	3.11		2.73		4.97	†	1.23	
S × A	1.64		1.52		0.09		0.85	
T × S × A	0.22		0.21		4.83	†	0.32	
Burn (B)	1.57		1.90		8.96	*	1.93	
T × B	0.06		0.05		0.21		4.45	†
S × B	1.14		1.21		14.34	**	3.54	
T × S × B	2.92		2.48		4.63	†	2.27	
A × B	0.15		0.12		4.09	†	0.55	
T × A × B	9.79	*	9.50	*	2.90		3.67	†
S × A × B	0.41		0.33		0.31		4.85	†
T × S × A × B	32.37	**	31.09	**	2.01		0.01	

[A] Disturbance response = (disturbed measurement-undisturbed measurement)/(undisturbed measurement).
[B] Represents treatment = (T) tank traffic during wet or dry soil conditions, (S) Split = half of the plot treated (i.e., 5 passes 2003, plus 5 additional passes, repeated traffic, 2004), or left untreated for 2004 (i.e., 5 passes single traffic, 2003), (A) Area = subplot from which sample was collected (i.e., curve, straight-a-way).
[†], *, ** Denotes significance at the $p \leq 0.10$, 0.05, 0.01 probability levels, respectively.

Table 2.4. Analysis of variance (F-values) for disturbance response[A] of soil physical properties in the silty clay loam soil, 2007.

	F-values				
	Soil Physical Properties				
Effect[B]	Bulk Density ($g\ cm^{-3}$)	Porosity (%)	Water Content ($g\ g^{-1}$)	Penetrometer (kPa)	Rut Depth (cm)
Treatment (T)	6.94	3.18	0.35	0.43	7.07
Split (S)	0.02	0.00	0.05	0.88	1.45
T × S	0.54	0.22	0.00	0.03	0.00
Area (A)	0.16	0.07	0.00	4.22 †	N/A
T × A	1.68	1.37	1.53	0.03	N/A
S × A	0.22	0.15	0.03	1.36	N/A
T × S × A	0.14	0.08	0.00	0.69	N/A
Burn (B)	4.54 †	4.32	0.51	0.24	1.14
T × B	2.19	1.96	0.33	3.33	5.22 †
S × B	1.39	1.25	1.01	0.03	5.77
T × S × B	0.00	0.01	3.68 †	0.38	0.43
A × B	0.08	0.14	0.61	0.02	N/A
T × A × B	0.01	0.01	0.33	1.13	N/A
S × A × B	0.43	0.32	1.86	0.24	N/A
T × S × A × B	6.36 *	5.21 †	11.38 *	2.87	N/A

[A] Disturbance response = (disturbed measurement-undisturbed measurement)/(undisturbed measurement).
[B] Represents treatment = (T) tank traffic during wet or dry soil conditions, (S) Split = half of the plot treated (i.e., 5 passes 2003, plus 5 additional passes, repeated traffic, 2004), or left untreated for 2004 (i.e., 5 passes single traffic, 2003), (A) Area = subplot from which sample was collected (i.e., curve, straight-a-way).
†, * Denotes significance at the $p \leq 0.10$, 0.05 probability levels, respectively.
N/A = not applicable (data not collected separately for areas).

Table 2.5. Analysis of variance (F-values) for disturbance response [A] of soil physical properties in the silt loam soil, 2007.

Effect [B]	F-values: Soil Physical Properties: Bulk Density ($g\ cm^{-3}$)		Porosity (%)		Water Content ($g\ g^{-1}$)		Penetrometer (kPa)		Rut Depth (cm)	
Treatment (T)	1.90		4.51		4.73		0.33		2.74	
Split (S)	5.00	†	2.08		0.64		0.04		14.65	†
T × S	4.20		2.00		0.82		0.00		4.15	
Area (A)	11.88	**	10.85	*	6.78	*	0.61		N/A	
T × A	0.02		0.02		1.75		1.69		N/A	
S × A	0.02		0.02		0.11		0.02		N/A	
T × S × A	0.12		0.15		1.13		0.00		N/A	
Burn (B)	0.31		0.20		0.14		0.08		2.16	
T × B	8.05	*	6.00	†	0.14		0.46		2.48	
S × B	0.27		0.17		0.12		0.24		5.98	
T × S × B	0.46		0.41		0.32		1.87		15.80	†
A × B	0.15		0.08		0.29		0.41		N/A	
T × A × B	0.12		0.10		0.43		0.84		N/A	
S × A × B	0.35		0.32		0.17		0.05		N/A	
T × S × A × B	0.09		0.07		3.98	†	7.96	**	N/A	

[A] Disturbance response = (disturbed measurement-undisturbed measurement)/(undisturbed measurement).
[B] Represents treatment = (T) tank traffic during wet or dry soil conditions, (S) Split = half of the plot treated (i.e., 5 passes 2003, plus 5 additional passes, repeated traffic, 2004), or left untreated for 2004 (i.e., 5 passes single traffic, 2003), (A) Area = subplot from which sample was collected (i.e., curve, straight-a-way).
†, *, ** Denotes significance at the $p \leq 0.10$, 0.05, 0.01 probability levels, respectively.
N/A = not applicable (data not collected separately for areas).

Table 2.6. Analysis of variance (F-values) for disturbance response [A] of soil chemical properties in the silty clay loam soil, 2006.

Effect [B]	P ($mg\ kg^{-1}$)		K ($mg\ kg^{-1}$)		Ca ($mg\ kg^{-1}$)		Total C ($g\ kg^{-1}$)		Total N ($g\ kg^{-1}$)	
	F-values – Soil Chemical Properties									
Treatment (T)	0.40		5.56		0.20		8.38	†	6.56	
Split (S)	0.00		0.00		3.89		0.55		0.08	
T × S	0.38		13.38	*	0.00		6.22	†	5.86	†
Area (A)	2.00		18.05	**	0.69		14.64	**	8.44	*
T × A	0.45		2.18		3.47	†	0.40		0.01	
S × A	0.04		0.15		1.18		0.06		0.01	
T × S × A	0.47		2.55		6.09	*	1.82		3.13	
Burn (B)	0.63		0.57		0.10		0.14		0.05	
T × B	0.18		0.00		0.70		2.78		2.36	
S × B	2.23		0.35		0.47		1.71		1.57	
T × S × B	0.47		0.16		3.74	†	0.91		0.53	
A × B	3.20		0.89		0.01		4.72	†	3.30	
T × A × B	2.44		1.89		0.75		1.41		0.74	
S × A × B	0.05		1.04		0.05		0.95		0.23	
T × S × A × B	0.12		0.00		1.24		1.59		0.20	

[A] Disturbance response = (disturbed measurement-undisturbed measurement)/(undisturbed measurement).
[B] Represents treatment = (T) tank traffic during wet or dry soil conditions, (S) Split = half of the plot treated (i.e., 5 passes 2003, plus 5 additional passes, repeated traffic, 2004), or left untreated for 2004 (i.e., 5 passes single traffic, 2003), (A) Area = subplot from which sample was collected (i.e., curve, straight-a-way).
†, *, ** Denotes significance at the $p \leq 0.10$, 0.05, 0.01 probability levels, respectively.

Table 2.7. Analysis of variance (F-values) for disturbance response[A] of soil chemical properties in the silt loam soil, 2006.

	F-values				
	Soil Chemical Properties				
Effect[B]	P (mg kg^{-1})	K (mg kg^{-1})	Ca (mg kg^{-1})	Total C (g kg^{-1})	Total N (g kg^{-1})
Treatment (T)	0.00	1.77	0.46	0.77	0.20
Split (S)	0.12	0.06	0.87	1.58	0.69
T × S	0.41	0.01	0.00	0.06	0.01
Area (A)	1.78	3.12	8.31 *	9.95 *	9.70 *
T × A	0.92	0.01	0.39	0.13	0.39
S × A	0.99	0.00	0.00	0.54	0.30
T × S × A	0.79	0.39	1.21	0.01	0.02
Burn (B)	0.38	0.00	0.30	0.07	0.13
T × B	1.27	1.78	2.95	0.92	1.20
S × B	1.13	1.74	3.03	1.19	1.42
T × S × B	0.03	0.24	0.55	0.02	0.01
A × B	0.15	1.11	0.43	2.85	2.10
T × A × B	0.00	0.48	0.14	0.29	0.53
S × A × B	0.19	0.09	0.08	0.04	0.02
T × S × A × B	6.05 *	5.32 †	5.38 †	7.49 *	6.43 *

[A] Disturbance response = (disturbed measurement-undisturbed measurement)/(undisturbed measurement).
[B] Represents treatment = (T) tank traffic during wet or dry soil conditions, (S) Split = half of the plot treated (i.e., 5 passes 2003, plus 5 additional passes, repeated traffic, 2004), or left untreated for 2004 (i.e., 5 passes single traffic, 2003), (A) Area = subplot from which sample was collected (i.e., curve, straight-a-way).
[†], * Denotes significance at the $p \leq 0.10$, 0.05 probability levels, respectively.

Table 2.8. Analysis of variance (F-values) for disturbance response [A] of soil chemical properties in the silty clay loam soil, 2007.

Effect[B]	P ($mg\ kg^{-1}$)		K ($mg\ kg^{-1}$)		Ca ($mg\ kg^{-1}$)		pH		Total C ($g\ kg^{-1}$)		Total N ($g\ kg^{-1}$)	
Treatment (T)	3.91		7.95		0.62		0.03		79.39	**	22.31	*
Split (S)	0.04		1.68		1.37		2.41		0.73		0.20	
T × S	0.21		0.64		0.02		1.98		1.11		0.90	
Area (A)	2.39		13.09	**	0.01		0.25		16.40	**	10.78	*
T × A	0.63		0.00		1.41		0.22		2.88		1.37	
S × A	0.25		0.00		0.00		0.13		0.00		0.00	
T × S × A	0.02		0.70		0.03		0.54		0.34		0.45	
Burn (B)	1.38		0.76		0.08		0.96		0.45		0.42	
T × B	0.14		0.00		0.09		0.14		1.23		0.63	
S × B	0.49		0.00		0.82		0.00		0.15		0.44	
T × S × B	0.77		1.24		1.83		0.06		1.29		3.18	
A × B	1.45		0.51		1.11		0.02		0.57		0.62	
T × A × B	0.02		0.50		1.38		8.23	*	0.01		0.00	
S × A × B	3.06		0.06		0.49		1.98		0.20		0.53	
T × S × A × B	1.72		0.41		0.08		2.59		0.05		0.06	

F-values column group: Soil Chemical Properties.

[A] Disturbance response = (disturbed measurement-undisturbed measurement)/(undisturbed measurement).
[B] Represents treatment = (T) tank traffic during wet or dry soil conditions, (S) Split = half of the plot treated (i.e., 5 passes 2003, plus 5 additional passes, repeated traffic, 2004), or left untreated for 2004 (i.e., 5 passes single traffic, 2003), (A) Area = subplot from which sample was collected (i.e., curve, straight-a-way).
*, ** Denotes significance at the $p \leq 0.05$, 0.01 probability levels, respectively.

Table 2.9. Analysis of variance (F-values) for disturbance response[A] of soil chemical properties in the silt loam soil, 2007.

	F-values					
	Soil Chemical Properties					
Effect[B]	P (mg kg^{-1})	K (mg kg^{-1})	Ca (mg kg^{-1})	pH	Total C (g kg^{-1})	Total N (g kg^{-1})
Treatment (T)	0.33	1.22	0.38	93.69 **	70.24 **	149.52 **
Split (S)	0.89	0.01	0.05	0.17	0.00	0.01
T × S	1.44	0.13	0.10	0.36	0.85	0.39
Area (A)	4.08 †	9.89 *	10.64 *	10.37 *	38.74 **	34.11 **
T × A	0.11	0.52	0.80	8.73 *	0.59	0.26
S × A	8.61 *	3.31	4.76 †	7.33 *	17.25 **	15.16 **
T × S × A	0.25	2.08	0.51	3.65 †	0.91	0.62
Burn (B)	1.11	0.16	0.05	0.15	0.06	0.15
T × B	5.20 †	1.27	3.36	2.79	1.53	1.85
S × B	0.72	3.39	0.24	0.01	10.86 *	15.47 **
T × S × B	3.56	3.01	0.04	1.96	12.19 **	8.76 *
A × B	2.11	1.95	0.04	0.02	1.07	0.87
T × A × B	0.27	0.00	2.16	0.84	3.29	3.80 †
S × A × B	0.00	0.47	2.25	0.01	0.03	0.25
T × S × A × B	8.62 *	3.38	2.95	0.14	15.82 **	16.03 **

[A] Disturbance response = (disturbed measurement-undisturbed measurement)/(undisturbed measurement).
[B] Represents treatment = (T) tank traffic during wet or dry soil conditions, (S) Split = half of the plot treated (i.e., 5 passes 2003, plus 5 additional passes, repeated traffic, 2004), or left untreated for 2004 (i.e., 5 passes single traffic, 2003), (A) Area = subplot from which sample was collected (i.e., curve, straight-a-way).
†, *, ** Denotes significance at the $p \leq 0.10$, 0.05, 0.01 probability levels, respectively.

CHAPTER 3 - Composition and Response of Soil Microbial and Invertebrate Communities to Tracked Vehicle Disturbance

Peggy S. Althoff, T.C. Todd, M.B. Kirkham, S.J. Thien, P.S. Gipson and M.A. Callaham, Jr.

Peggy S. Althoff, M.B. Kirkham, and S.J. Thien, Dept. Of Agronomy; T.C. Todd, Dept. Of Plant Pathology; P.S. Gipson, U.S.G.S. Kansas Cooperative Fish and Wildlife Research Unit, Kansas State University; Manhattan, KS, 66506. M.A. Callaham, Jr., USDA Forest Service, GA.

For submission to Journal of Applied Soil Ecology.

ABSTRACT

Soil biota are important drivers of fundamental ecosystem processes such as decomposition, nutrient cycling, and maintenance of soil structure. This is especially true for grassland ecosytems such as the tallgrass prairie, where much of the net primary productivity in is allocated belowground and ultimately processed by heterotrophic soil organisms. Both soil microbes and soil fauna display perturbation responses that integrate the physical, chemical, and biological (i.e. food resource) changes in their environment and the structure of belowground microbial and faunal communities has been used widely as an indication of the ecological status of soils. A replicated small-plot study of tracked vehicle disturbance effects on tallgrass prairie soils and communities was initiated on Fort Riley in 2003. This chapter reports subsequent rates of recovery for a suite of plant and soil-quality indicators over a range of disturbances encompassing soil type, environmental conditions, and traffic intensity. Microbial biomass in disturbed areas remained lower than that observed for undisturbed areas through 2005, but frequently increased to levels greater than undisturbed controls by 2007. Disturbance also shifted microbial community composition, favoring gram-positive bacteria and actinomycetes over gram-negative bacterial and fungi. Nematode abundance, family richness, and trophic composition displayed disturbance effects through 2006 for curve areas and increased traffic intensity. Relative abundance of herbivores generally was reduced while microbivores increased in disturbed compared to undisturbed areas. Reductions in earthworm abundance remained severe (> 50%) for most treatments in 2005, but few significant effects were observed in subsequent years due to large variances in earthworm numbers. Nematode community structure provided a reliable and comprehensive assessment of the status of the soil food web and

represents an effective bioindicator for military training land mangers. In addition, given the dominant role of earthworms in ecosystem processes, it is recommended that this group be included in monitoring protocols.

INTRODUCTION

Ecosystems display characteristic structural and functional signatures in soil communities, suggesting that the biological status of soils should reflect soil quality as well as ecosystem health (Ritz et al., 2003). Belowground systems exhibit great complexity, with extremely high levels of biological diversity. It is the functional aspects of belowground systems, however, that appear to be the most descriptive, although there is a clear need for the identification and development of biological indicators (Loveland and Thompson, 2001; Ritz et al., 2003). Since the complexity of soil communities is related largely to the spatial heterogeneity and diversity of resources (Maire et al., 1999), disturbance of soil physical and chemical properties should have profound effects on both the structure and function of these communities. The rate of recovery in community structure and/or function provides a useful indicator of soil and, therefore, ecosystem resilience (Ritz et al., 2003).

Soil biota are important drivers of fundamental ecosystem processes such as decomposition, nutrient cycling, and maintenance of soil structure. Much of the net primary productivity in grassland ecosytems is allocated belowground and ultimately processed by heterotrophic soil organisms (Elliot et al., 1988). The tallgrass prairie, in particular, is characterized by high belowground productivity and large accumulations of soil organic matter and nutrients resulting in a large and diverse assemblage of soil biota (Ransom et al., 1998; Rice et al., 1998). The structure of belowground microbial and faunal communities has been used widely as an indication of the ecological status of soils (Linden et al., 1994). Soil fauna provide several advantages over microbial communities, however, because they reflect higher trophic levels in the soil food web, generally are easier to assess, and their populations are relatively stable (Neher, 2001). Nematodes are among the most popular soil faunal indicators because they represent a comprehensive array of functional or trophic groups occupying multiple positions in the soil food web (Yeates et al., 1993).

Macroinvertebrates, especially earthworms, play a dominant role in ecosystem processes. Earthworm burrowing and feeding activities result in improved aeration and water infiltration, incorporation of organic matter into the soil, and stabilization of soil aggregates (Tomlin et al., 1995; Edwards and Bohlen, 1996), leading to their designation as 'ecosystem engineers' (Jones et al., 1994). The tallgrass prairie soils of the Flint Hills region of eastern Kansas contain a mixture of native and exotic earthworm species which together account for most of the faunal biomass (James, 1995; Rice et al., 1998). Departures from historical disturbance regimes of frequent fire and grazing facilitate the expansion of exotic earthworms, possibly with the displacement of native species (Callaham and Blair, 1999; Callaham et al., 2003).

Mechanized military training provides a dramatic example of landscape-scale soil disturbance, impacting soil quality in many ways, most notably through displacement and compaction. The environmental impacts of military vehicle use have been reviewed recently by Anderson et al. (2005). Numerous studies have identified ecological processes susceptible to military training activities but additional research is needed to identify indicator variables for inclusion in monitoring programs on military lands. In an early comparison of training sites on Fort Riley with a native undisturbed tallgrass prairie site, soil invertebrates, including macro- and microarthropods, and native earthworm species, were identified as sensitive indicators of compaction resulting from mechanized maneuvers, even in the absence of observable effects on plant productivity (Schaeffer et al., 1990). A subsequent landscape-scale evaluation on Fort Riley identified nematode family richness as a strong indicator of disturbance due to mechanized maneuver training (Althoff et al., 2007). Althoff (2005) monitored the status of soil microbial and invertebrate communities following M1A1 tank traffic disturbance during wet and dry conditions in two soil types on Fort Riley, and observed dramatic reductions in both the abundance and richness of macroinvertebrate and nematode assemblages. Earthworms were the most sensitive group, with reductions in numbers approaching 100% in plots with the maximum disturbance regime.

Fire is a natural occurrence in the tallgrass prairie ecosystem and represents an effective tool for land managers (Wright, 1974; Collins and Gibson, 1990). Approximately one-third of Fort Riley is burned annually, including prescribed burns, and both naturally-occurring and training-related wildfires, resulting in a mosaic of vegetation patterns at the landscape level. In addition to the well-known effects of fire on plant community dynamics (see Chapter 1), burning influences belowground biota, including both microbial biomass and invertebrate consumer groups (Rice et. al., 1998). Burning enhances numbers of a variety of native soil taxa including earthworms, herbivorous macroarthropods, and herbivorous and microbivorous nematodes, while rendering soils more resistant to invasive earthworm species (Callaham et al., 2003; Todd, 1996; James, 1982; Seastedt and Ramundo, 1990; Seastedt, 1984a; Seastedt, 1984b).

Land maintenance on military training lands is currently guided by regulations set forth by the Integrated Training Area Management (ITAM) Program, which outlines procedures for achieving sustainable use of training lands (Army Regulation 350-4, 1988). A key component of this program, Range and Training Land Assessment (RTLA), provides information and recommendations regarding the condition of training lands to range managers to assist scheduling of training areas and monitoring of the effectiveness of rehabilitation projects (US Army Environmental Center, 2006).

Fort Riley Military Installation, located in the Flint Hills of northeastern Kansas, is a major training reservation, with seventy percent of its 40,434 ha used for mechanized maneuvers. Fort Riley started implementing portions of the assessment protocol under the Land Condition Trend Analysis (LCTA) Program, monitoring trends in plant communities related to military vehicle traffic patterns during 1994-2001 (Althoff et al., 2006). Assessment of soil quality indices, including physical, chemical, and biological properties began in 2002 (Althoff, 2005; Althoff and Thien, 2005; Althoff et al., 2007).

A replicated small-plot study of tracked vehicle disturbance effects on tallgrass prairie soils and communities was initiated on Fort Riley in 2003. The objectives were to evaluate rates of recovery in a suite of plant and soil-quality indicators over a range of disturbances encompassing soil type, environmental conditions, and traffic intensity. Results from the first two years are reported in Althoff (2005) and Althoff and Thien (2005). This manuscript reports longer-term trends in recovery of soil biota subsequent to military training disturbance.

MATERIALS AND METHODS

Site Description

Research was conducted at Fort Riley Military Installation, an Army base in operation since 1853, located in Clay, Geary, and Riley counties in the Flint Hills of northeastern Kansas (39°15'N, 96°50'W) (Pride, 1997; McCale and Young, 2000). The installation, located in a mesic, tallgrass-prairie ecosystem, uses 29,542 ha (70,926 ac) of its 40,434 ha (100,656 ac) for maneuver training. The Flint Hills grasslands encompass more than 1.6 million ha, covering much of eastern Kansas from near the Kansas-Nebraska border south into northeastern Oklahoma, and contain the largest remaining areas of untilled tallgrass prairie in North America

(Knapp and Seastedt, 1998). Hot summers and cold, dry winters characterize the climate. Mean monthly temperatures range from -2.7°C in January to 26.6°C in July. Annual precipitation averages 83.5 cm, with 75% of precipitation occurring during the growing season (Hayden, 1998). Fort Riley lands host three major vegetation communities: grasslands (ca. 32,200 ha), shrublands (ca. 6, 000 ha), and woodlands (ca. 1,600 ha). The soil at the study plots was classified as a Wymore series consisting of very deep, moderately drained, slowly or very slowly permeable soils that formed in loess (USDA, 1975). This soil series is found on most of the fort's training area. Wymore soils are classified as fine, smectitic, mesic Aquertic Argiudolls.

Experimental Treatments

A randomized complete block design composed of three treatments (a non-trafficked control, tank traffic during wet soil conditions, and tank traffic during dry soil conditions) and three replications (blocks) was established in each of two soil types, a silty clay loam and a silt loam, in 2003 (Althoff and Thien, 2005). An Abrams M1A1 main battle tank created disturbances by driving 5 circuits around a figure eight pattern in designated plots either during wet or dry soil conditions. The M1A1 weighs 57.2 t with a ground pressure of 0.00626 t/cm (13.8 pounds/sq inch). The tracks are approximately 63.5 cm (25 inches) wide and 4.57 m (15 feet) long. It has a maximum cross country speed of 48 km/h (30 mph). Tank speed was maintained at approximately 8 km/h (5 mph).

In 2004, one-half of each of the previously disturbed plots received 5 additional tank passes during wet or dry conditions similar to 2003. On a randomly selected half of the original figure eight, 5 additional passes were made with an M1A1 tank, producing a S-shaped pattern (Althoff, 2005). The second year of treatments allowed comparison of different levels of traffic intensity (one-time-traffic with 5 passes versus repeated traffic with a total of 10 passes). Two areas, a curve and straight-a-way, within each traffic intensity subplot were designated for sampling in 2005. Data from the first and second years of disturbance are reported in Althoff (2005) and Althoff and Thien (2005).

In April 2006, each whole plot was again split and a randomly selected half received a burn treatment (See figure 1.1, chapter 1). Curve and straight-a-way areas within each burn-intensity subplot were designated for sampling in 2006 and 2007.

Field Sampling and Laboratory Methods

Bulk soil samples for microbial and soil invertebrate community analyses were collected on 19 November 2005, 24 September 2006, and 20 June 2007. A 20 × 50-cm Daubenmire frame (Daubenmire, 1959) was positioned at each sampling area (curve and straight-a-way) and the soil was removed to a depth of 7.6 cm, placed in a 22-liter plastic bucket and covered with a lid. Samples were stored at 5°C (41°F) until further processing. All samples from disturbed areas were collected from the track pad, while control samples were collected from the undisturbed soil surface of control plots. Sampled depth, therefore, did not represent the same portion of the disturbed and undisturbed soil profiles.

Microbial Community Analyses

Microbial biomass was determined in the Microbial Lab, Department of Agronomy, Kansas State University using the fumigation-incubation technique described by Jenkinson and Powlson (1976). Bulk soil samples were mixed uniformly, and two 25-g subsamples were collected from each. One set was fumigated with chloroform and the other set was left unfumigated. The samples were incubated in 1-L mason jars for 10 days, and the CO_2 C concentration was measured using a Shimadzu GC-8A gas chromatograph. Nitrogen (NH_4 and NO_3) was extracted with 1 M KCL and analyzed on an Alpkem Autoanalyzer.

Microbial community composition was determined by phospholipid fatty acid (PLFA) analysis (White and Ringelberg, 1998) for the most disturbed plots (wet soil conditions, silt loam soil) in 2005. Lipids were extracted in a chloroform-methanol buffer from a 5-g subsample of each bulk soil sample, fractionated using silicic acid chromatography, and analyzed on a Shimadzu GC-8A gas chromatograph .

Soil Invertebrate Community Analyses

Earthworms and arthropods were hand-sorted, killed in boiling water, placed in 37% formalin for 2 days to set the proteins, and preserved in 70% ethanol for subsequent identification. Nematodes were extracted from 100 cm^3 soil subsamples by using a standard centrifugal-flotation technique (Jenkins, 1964) and identified to the family level to estimate family richness as an indicator of diversity. In addition to total abundance and family richness, enrichment profiles of the nematode communities were constructed (Ferris and Bongers, 2006). The enrichment profile depicts the proportional contribution of the total nematode community to plant, fungal, and bacterial channels, and provides a tool for monitoring the structure and function of the soil food web.

Statistical Analyses

A disturbance effect index was calculated for all variables using the following formula:

(*disturbed measurement-undisturbed measurement)/ (undisturbed measurement*).

This disturbance effect index was expressed as a percentage of the control and subjected to mixed-model analysis of variance using SAS (SAS Institute, Cary, NC, 2000). The data were analyzed as a strip-split-split plot with soil moisture condition as the whole plot treatment, stripped burn and traffic intensity subplots, correlated intensity subplots (5 passes vs. 10 passes) and correlated sub-subplots (curved vs. straight areas) with each subplot. The significance of the disturbance index was tested for individual treatment combinations using Least Squares Means (H_0: mean = 0).

RESULTS

Microbial Community

Microbial biomass in 2005 was largely influenced by sampling area, with greater (more negative, $p \leq 0.05$) disturbance indices for both C and N on curves compared to straight-a-ways across treatments in both soil types (Table 3.1, Fig. 3.1). Moisture condition at the time of traffic disturbance also continued to influence microbial biomass, with lower biomass C and N relative to control plots observed on average for the wet compared to the dry soil treatment. Overall, microbial biomass remained more disturbed in silty clay loam soil than in silt loam soil.

Area effects (curve vs. straight-a-way) continued to dominate microbial responses in 2006 and 2007 (Tables 3.2-3.5, Figs. 3.2-3.5). In contrast to 2005, however, this was more often the result of stimulation ($p \leq 0.10$) of microbial biomass in straight-a-ways compared to control plots than of continued suppression of microbial biomass in curve areas. Moisture condition at the time of disturbance remained a significant factor affecting microbial biomass N in silty clay loam soil 2007, with negative responses generally observed for the wet soil treatments and positive responses generally observed for the dry soil treatments (Table 3.4, Fig. 3.5).

Residual burning effects were observed for microbial biomass in 2007, with burned control plots exhibiting twice the biomass C of unburned control plots in silt loam soil (data not shown). Disturbance responses in these soils also were affected by burning, with stimulation ($p \leq 0.10$) of microbial biomass C relative to control plots observed, particularly for straight-a-ways, in the absence, but not presence, of burning (Table 3.5, Fig. 3.4). In silty clay loam soil, disturbance responses for microbial biomass C displayed interactions among burning, moisture condition, traffic intensity, and area effects (Table 3.4, Fig. 3.4).

Microbial community composition in 2005 displayed significant disturbance when tank traffic occurred during wet soil conditions in silt loam soil. PLFA biomass of gram positive bacteria was greater ($p \leq 0.10$) compared to undisturbed controls on curve and straight-a-way areas of both single and repeated traffic treatments, while biomass of gram negative bacteria was reduced compared to undisturbed controls in these same areas (Fig 3.6A). Actinomycetes and fungi exhibited non-significant increases in disturbed plots. These differences were reflected in Principal Components Analysis, with disturbed plots separating from control plots on the first principal component axis (Fig. 3.6B).

Soil Invertebrate Communities

Nematodes

Nematode densities in undisturbed control plots averaged 1.1 million m^{-2}, 1.0 million m^{-2}, and 0.4 million m^{-2} in 2005, 2006, and 2007, respectively, for the silty clay loam soil. In silt loam soil, nematode densities in undisturbed control plots averaged 2.0 million m^{-2}, 1.4 million m^{-2}, and 0.5 million m^{-2} in 2005, 2006, and 2007, respectively. Family richness values for 2005, 2006, and 2007 were 11, 15, and 12, respectively, in silty clay loam soil and 16, 14, and 12, respectively, in silt loam soil.

Total nematode abundance remained significantly affected ($p \leq 0.10$) only in plots with the greatest level of disturbance (curves of repeated traffic during wet soil conditions) in 2005 (Fig. 3.7). In silt loam soil, disturbance indices were greater (more negative, $p \leq 0.10$) on average for curve areas and for repeated traffic than for straight-a-way areas and single traffic, respectively (Table 3.1, Fig. 3.7). Patterns of disturbance effects remained similar in 2006 (Fig. 3.8), but no significant disturbance effects could be detected for individual treatments by 2007 (Fig. 3.9). There also were no consistent trends in main effects or interactions during 2006 and 2007 (Tables 3.2-3.5). A significant burn main effect ($p \leq 0.05$) was observed for nematode abundance in silt loam soil in 2007, with disturbance effects positive on average in the presence of burning and negative on average in the absence of burning (Table 3.5, Fig. 3.9).

Nematode family richness displayed a strong traffic intensity × area interaction ($p \leq 0.05$) for both soil types in 2005 (Table 3.1), with greater reductions in richness occurring on average for curve compared to straight-a-way areas in plots with repeated, but not single, traffic (Fig. 3.10). As for abundance, there were no consistent trends in disturbance effects for richness in 2006 and 2007 (Tables 3.2-3.5). Reductions ($p \leq 0.10$) in richness relative to control plots were observed for curve and straight-a-way areas, single and repeated traffic, wet and dry soil conditions, and burned and unburned plots in silty clay loam soil in 2006 (Fig. 3.11). In 2007, richness in silty clay loam soil was reduced only for the repeated traffic treatment in the absence of burning (Fig. 3.12). No significant reductions in richness were observed for silt loam soil in 2006 or 2007 (Figs. 3.11-3.12).

Enrichment profiles of nematode communities for 2005 and 2006 displayed separation of plots with the greatest disturbance (wet soil treatments and/or curve areas) from control plots due to lower herbivore relative abundance and higher bacterivore and/or fungivore relative abundances (Figs. 3.13-3.14). In 2007, enrichment profiles for control, but not disturbance, plots were strongly influenced by burning, with the most disturbed plots remaining separated from control plots only in the presence of burning (Fig. 3.15).

Macroinvertebrates

Earthworm communities consisted of both native (*Diplocardia* spp. and *Bimastos welchi*) and introduced European (*Aporrectodea trapezoides* and *Eisenia rosea*) species. Beetle larvae of the families Scarabaeidae and Carabidae dominated the macroarthropod communities.

Earthworm abundance remained 50%-100% reduced ($p \leq 0.10$) in all disturbance plots relative to control plots in silty clay loam soil in 2005 (Fig. 3.16A). In silt loam soil, in contrast, only disturbance treatments during wet soil conditions displayed lower earthworm abundances, and single traffic straight-a-ways during dry soil conditions exhibited higher earthworm abundances than control plots (Fig. 3.16B). Few significant reductions in earthworm abundance were observed in 2006 and 2007 due to large within-treatment variance, but there were increased ($p \leq 0.10$) abundances in some dry disturbance treatments in both soil types (Figs. 3.17-3.18). No differences in numbers of native vs. exotic earthworm taxa were observed during the recovery period. Trends for macroarthropod and total macroinvertebrate abundances generally were similar to those described for earthworm abundances (Figs. 3.19-3.24). There was a soil moisture condition × area interaction ($p \leq 0.05$) for total macroinvertebrate abundance in silty clay loam soil in 2005, reflecting greater disturbance effects for straight-a-ways during wet compared to dry soil conditions (Table 3.1, Fig. 3.22A). A burn effect for total macroinvertebrate abundances in silty clay loam soil, and burn × disturbance treatment interactions in silt loam soil, were observed in 2006 (Tables 3.2-3.3). Disturbance effects were more severe across treatments in the presence of burning in silty clay loam soil, while disturbance indices on straight-a-ways in silt loam soil were negative in the presence of burning but positive in the absence of burning (Fig. 3.23).

Macroarthropod richness displayed a soil moisture condition × area and traffic intensity × area interactions ($p \leq 0.10$) in silty clay loam soil in 2005, reflecting greater disturbance effects for straight-a-ways during wet compared to dry soil conditions, and for repeated vs. single traffic on curve areas, respectively (Table 3.1, Fig. 3.25A). There were no significant disturbance effects for macroarthropod richness in silt loam soil in 2005.

DISCUSSION

Tallgrass prairie soil biotic communities exhibited significant sensitivity to tank traffic, with measurable effects still present three years later in plots with the greatest level of disturbance. Vehicle traffic exerts multiple impacts on the soil ecosystem, including destruction of vegetation, displacement of topsoil along with accompanying soil organic matter, and compaction, which in turn reduces water infiltration and water-holding capacity. Additionally bare soil is susceptible to greater temperature and moisture fluctuations. All of these effects likely combined to produce the patterns of disturbance and recovery observed for the soil organisms in this study. Microbial biomass, for example, responds rapidly to changes in soil organic matter and to environmental fluctuations (Rice et al., 1996, 1998). Throughout the present study, microbial biomass estimates closely reflected the status of total soil C and, therefore, soil organic matter (see Chapter 2), suggesting that resource availability was the primary driver. Significant increases in microbial biomass C and N were frequently observed for straight-a-way areas. Much of the substrate in soils is unavailable to microorganisms due to physical protection mechanisms (e.g., aggregation) and disturbance releases these substrates, resulting in a flush of nutrients through decomposition, (Watts et al., 2000). Another potential mechanism for increased microbial biomass following traffic disturbance is the observation that, while compaction reduces macropores (> 30 µm diameter), micropores (0.2 – 30 µm diameter) are increased. The latter comprise the habitable- sized pores for microorganisms (Shestak and Busse, 2005).

Resource availability also is likely to be the main factor involved in the observed changes in microbial community composition. Microbial community structure in grasslands is correlated with soil physio-chemical properties, including organic matter content, and plant community structure (Grayston et al., 2004). Studies have shown that greater resource (carbon) availability is associated with increases in Gram-negative bacteria and fungi and decreases in Gram-positive bacteria and actinomycetes (Griffiths et al., 1999; Fierer et al., 2003). The disturbance-related reductions in soil C observed throughout most of this study would be expected to suppress Gram-negative bacteria and fungi while stimulating Gram-positive bacteria and actinomycetes, which, with the exception of fungi, is precisely what was observed. Thus recovery of the original microbial community structure would occur only after recovery of soil organic matter which remained lower in plots with the greatest level of disturbance three years after the initial treatment.

Nematode community composition similarly reflected resource availability, but in this case the most notable disturbance responses were by herbivorous (root-feeding) taxa. Herbivores typically comprise 30%-40% of the nematode community (Ransom et al., 1998; Blair et al., 2000) and are responsive to changes in both the quantity and quality of root inputs (Rice et al., 1998; Blair et al., 2000). Nematode community structure also reflects changes in the microbial community, and a measure of the relative abundances of herbivorous, fungivorous, and bacterivorous taxa serves as a useful indicator of soil food web status (Ferris et al., 2001; Ferris and Bongers, 2006). Nematode assemblages of the tallgrass prairie display a characteristic pattern, with low relative abundances of bacterivores compared to the other trophic groups (Todd et al., 2006). During the recovery process reported in this study, microbial-feeding taxa frequently increased in relative abundance at the expense of herbivorous taxa, suggesting that the latter group exhibits slower recovery rates. This observation is consistent with known life histories, with microbivores generally exhibiting shorter life cycles and more rapid population growth (Ferris and Bongers, 2006). As for the plant and soil microbial communities, disturbance effects on the structure of the nematode community were still observable at the end of the study. Nematode family richness is another potential indicator of disturbance on military lands (Althoff et al., 2007). In my study, family richness also was a sensitive indicator of M1A1 tank traffic effects, but was somewhat soil-type dependent (i.e. more prolonged reduction were observed in silty clay loam soil).

Earthworms (as well as other macroinvertebrates) were nearly eliminated from disturbed areas following tank traffic (Althoff, 2005) and generally remained low throughout the present study, although individual treatments displayed recovery and even increases in earthworm densities relative to the control. Vegetation destruction, litter removal along with the accompanying changes in soil moisture and temperature regime, and soil compaction likely combined to produce the dramatic responses observed for this group. Given the important effects that earthworms have on soil structure (Tomlin et al., 1995; Edwards and Bohlen, 1996), their absence has particularly significant implications for recovery of the soil ecosystem. Furthermore, it has been shown that differing land management practices can either favor or limit expansion of exotic earthworm species in tallgrass prairie (Callaham et al., 2003), with unknown consequences. Differences in feeding ecology and behavior are known to exist between native and exotic earthworm species (James and Cunningham, 1989; Callaham et al., 2001), suggesting that the two groups are not interchangeable. Where native and exotic species coexist, their combined effects are determined by their relative abundance, fitness, and differences in ecological strategies (James and Hendrix, 2004). Exotic taxa are abundant on Fort Riley, but the impact of military training activities on earthworm community structure and the implications for ecosystem processes remain to be determined.

Similar disturbance patterns to those described above were documented for the soil biotic communities in this study. Disturbance was consistently greater on curve areas and for tank traffic during wet soil conditions in both soil types as reported for plant communities (Chapter 3) and soil physical and chemical properties (Chapter 2). Burning effects on recovery rates were inconsistent, but fire is known to impact all of the soil biotic communities discussed here (Todd, 1996; Rice et al., 1998; Callaham et al., 2003). In particular, fire may be important in regulating the structure of tallgrass prairie biotic during the recovery period (Callaham et al., 2003), which may lead to greater resiliency and thus more sustainable training lands. These results need to be factored into management plans for training activities, with established criteria for meeting short- and long-term goals for site maintenance.

Both soil microbes and soil fauna display perturbation responses that integrate the physical, chemical, and biological (i.e. food resource) changes in their environment (Nannipieri et al., 1990; Rice et al., 1996; Neher, 2001). In contrast to Shestak and Busse (2005), who reported tolerance of microbial communities to compaction in forest ecosystems and a poor link between physical and biological indices of soil health, biological communities were reliable indicators of military training disturbance in tallgrass prairie. Soil fauna provide several advantages over microbial communities, however, because they reflect higher trophic levels in the soil food web, generally are easier to assess, and their populations are relatively stable (Neher, 2001). In this study, nematode community structure provided a reliable and comprehensive assessment of the status of the soil food web and represents an effective bioindicator for military training land mangers. In addition, given the dominant role of earthworms in ecosystem processes, it is recommended that this group be included in monitoring protocols.

ACKNOWLEDGEMENTS

Funding for this project was provided by the U.S. Army Military Installation, Integrated Training Area Management (ITAM) Program. We value Philip B. Woodford (ITAM) Coordinator, Chris Otto, (ITAM), Lee Breidenstein (Range Control), Monte Cales (NRCS, Fort Riley) Tony Davis, Troy Livingston, (GPS), Fred Siebe and staff (MPRC Gunnery Complex), and M1A1 tank crews, from Fort Riley Military Installation, for their effort and support. We are indebted to Keith Arnold, Bradley Feldhausen, Lance Noll, and Travis Halter for their assistance in collecting the soil samples and to Jamie Aikins for microbial biomass analyses.

REFERENCES

Althoff, P.S. 2005. Evaluation of soil quality indicators following disturbance by an Abrams M1A1 Main Battle Tank. M.S. Thesis. Kansas State University, Manhattan, KS, 136 pp.

Althoff, P.S., and S.J. Thien. 2005. Impact of M1A1 main battle tank disturbance on soil quality, invertebrates, and vegetation characteristics. Journal of Terramechanics 42:159-176.

Althoff, D.P., P.S. Althoff, N.D. Lambrecht, P.S. Gipson, J.S. Pontius, and P.B. Woodford. 2007. Soil Properties and perceived disturbance of grasslands subjected to mechanized military training: evaluation of an index. Land Degradation and Development 18:269-288.

Althoff, D.P., P.S. Gipson, J.S. Pontius, and P.B. Woodford. 2006. Plant community and bare ground trends on Fort Riley, Kansas: Implications for monitoring of a highly disturbed landscape. Transactions of the Kansas Academy of Science 109:101-106.

Anderson, A.B., G. Wang, S. Fang, G.Z. Gertner, B. Guneralp, and D. Jones. 2005. Assessing and predicting changes in vegetation cover associated with military land use activities using field monitoring data at Fort Hood, Texas. Journal of Terramechanics 42:207-229.

Army Regulation 350-4. 1988. Integrated Training Area Management (ITAM). Unclassified. Headquarters Department of the Army Washington, DC.

Blair, J.M., T.C. Todd, and M.A.Callaham Jr. 2000. Responses of grassland soil invertebrates to natural and anthropogenic disturbances. Pp 43-71 *In* D.C. Coleman and P.F. Hendrix (ed.). Invertebrates as webmasters in ecosystems. CABI Publishing New York, NY.

Callaham Jr. M.A., J.M. Blair, T.C. Todd, D.J. Kitchen, and M.R. Whiles. 2003. Macroinvertebrates in North American tallgrass prairie soils: effects of fire, mowing, and fertilization on density and biomass. Soil Biol. and Chemistry 35:1079-1093.

Callaham, M.A., Jr., and J.M. Blair. 1999. Influence of differing land management on the invasion of North American tallgrass prairie soils by European earthworms. Pedobiologia 43:507-512.

Callaham, M.A., Jr., and J.M. Blair and P.F. Hendrix. 2001. Different behavioral patterns of the earthworms *Octolasion tyrtaeum* and *Diplocardia* spp. In tallgrass prairie soils: potential influences on plant growth. Biology and Fertility of Soils 34:49-56

Collins, S.L., and D.J. Gibson. 1990. Effects of fire on community structure in tallgrass and mixed-grass prairie. Pp 81-98 *In* S.L. Collins and L.L. Wallace (ed.). Fire in North American tallgrass prairies. University of Oklahoma Press, Norman, Publishing Division of the University.

Daubenmire, R. 1959. Measurement of species diversity using canopy coverage classes. Northwest Science 33:43-66.

Edwards, C.A., and P.J. Bohlen. 1996. Biology and ecology of earthworms, third ed, Chapman & Hall, London.

Elliott, E.T., H.W. Hunt, and D.E. Walter. 1988. Detrital foodweb interactions in North American grassland ecosystems. Agriculture, ecosystems and environment 24:41-56.

Ferris, H., and T. Bongers. 2006. Nematode indicators of organic enrichment. Journal of Nematology 38:3-12.

Ferris, H., T. Bongers, and R.G.M. de Goede. 2001. A framework for soil food web diagnostics: extension of the nematode faunal analysis concept. Applied Soil Ecology 18:13-29.

Fierer, N., J.P. Schimel, P.A. Holden. 2003. Variations in microbial community composition through two soil depth profiles. Soil Biology & Biohemistry 35:167-176.

Grayston, S.J., C.D. Campbell, R.D. Bardgett, J.L. Mawdsley, C.D. Clegg, K. Ritz, B.S. Griffiths, J.S. Rodwell, S.J. Edwards, W.J. Davies, D.J. Elston, and P. Millard. 2004. Assessing shifts in microbial community structure across a range of grasslands of differing management intensity using CLPP, PLFA, and community DNA techniques. Applied Soil Ecology 25:63-84

Griffiths, B.S., K. Ritz, N. Ebblewhite, and G. Dobson. 1999. Soil microbial community structure: Effects of substrate loading. Soil Biology & Biochemistry 31:145-153.

Hayden, B.P. 1998. Regional climate and the distribution of tallgrass prairies. Pp 19-34 *In* A.K. Knapp, J.M. Briggs, D.C. Hartnet, and S.L. Collins (eds.), Grassland dynamics: long-term ecological research in tallgrass prairie. Oxford University Press, NY, NY, USA.

James S.W. 1982. Effects of fire and soil type on earthworm populations in a tallgrass prairie. Pedobiologia 24:37-40.

James, S.W., and M.R. Cunningham. 1989. Feeding ecology of some earthworms in Kansas tallgrass prairie. American Midland Naturalist 121:78-83.

James, S.W. 1995. Systematics, biogeography, and ecology of nearctic earthworms from eastern, central, southern, and southwester USA. Pp 29-51 *In* Hendrix, P.F., (ed.), Earthworm Ecology and Biogeography in North America, Lewis Publishers,.

James, S.W. and P.F. Hendrix. 2004. Invasion of exotic earthworms into North America and other regions. Pp 75-88 *In* C.A. Edwards (2nd ed.), Earthworm Ecology, Boca Raton, FL.

Jenkins, W.R. 1964. A rapid centrifugal-flotation technique for separating nematodes from soil. Plant Disease Reporter 48:692.

Jenkinson, D.S., and D.S. Powlson. 1976. The effects of biocidal treatments on metabolism in soil. Fumigation with chloroform. Soil Biol. Biochemistry 8:167-177.

Knapp, A.K., and T.R. Seastedt. 1998. Grasslands, Konza Prairie, and long-term ecological research. Pp 3-15 *In* A.K. Knapp, J.M. Briggs, D.C. Hartnet, and S.L. Collins (eds.), Grassland dynamics: long-term ecological research in tallgrass prairie. Oxford University Press, NY, NY, USA.

Linden, D.R., P.F. Hendrix, D.C. Coleman, and P.C.J. van Vliet. 1994. Faunal Indicators of soil quality. Pp 91-106. *In* J. W. Doran et al. (ed.). Defining Soil Quality for a Sustainable Environment. SSSA Special Publication 35.

Loveland, P.J., and T.R.E. Thompson. 2001. Identification and development of a set of national indicators for soil quality. In R&D Technical Report P5-053/2/TRBristol Environmental Agency.

Maire, N. D., D. Borcard, E. Laczko, and W. Matthey. 1999. Organic matter cycling in grassland soils of the Swiss Jura mountains: biodiversity and strategies of the living communities. Soil Biology and Biochemistry 31:1281-1293.

McKale, W., and W.D. Young. 2000. Fort Riley Citadel of the Frontier West, Kansas State Historical Society Topeka, Kansas.

Nannipieri, P., S. Grego, and B. Ceccanti. 1990. Ecological significance of the biological activity in soil. Pp 293-355 *In* J-M. Bollag and G. Stotzky, eds. Soil Biochemistry, vol. 6. New York, NY: Marcel Dekker.

Neher, D.A. 2001. Role of nematodes in soil health and their use as indicators. Journal of Nematology 33:161-168.

Pride, W.F. The History of Fort Riley. 1997. Manhattan, KS: U.S. Cavalry Museum and Fort Riley Historical and Archaeology Society.

Ransom, M.D., C.W. Rice, T.C. Todd, and W.A. Wehmueller. 1998. Soils and soil biota. Pp 48-66 *In* A.K. Knapp, J.M. Briggs, D.C. Hartnet, and S.L. Collins (eds.), Grassland dynamics: long-term ecological research in tallgrass prairie. Oxford University Press, NY, NY, USA.

Rice, C.W., T.B. Moorman, and M. Beare. 1996. Role of microbial biomass carbon and nitrogen in soil quality. Pp 203-215. *In* J.W. Doran and A.J. Jones (eds.) Methods for Assessing Soil Quality. SSSA Special Publication 49. Madison, WI.

Rice, C.W., T.C. Todd, J.M. Blair, T.R. Seastedt, R.A. Ramundo, and G.W.T. Wilson. 1998. Belowground biology and processes. Pp. 244-264 *In* A.K. Knapp et al. (eds), Grassland Dynamics, Oxford University Press, New York,.

Ritz, K., M. McHugh, and J. Harris. 2003. Biological diversity and function in soil: Contemporary perspectives and implications in relation to the formulation of effective indicators. Agricultural impacts on soil erosion and soil biodiversity: Developing indicators for policy analysis. Proceedings from an OECD Expert Meeting, Rome, Italy, March.

SAS Institute Inc. 2000. SAS/STAT user’s guide. Version 9.01. SAS Institute Inc., Cary NC, USA.

Schaeffer, DJ, Seastedt RR, Gibson DJ, Hartnett DC, James SW, Kaufman DW, Schwab AP, Herricks EE, Novak EW. 1990. Field bioassessments for selecting test systems to evaluate military training lands in tallgrass prairie. Ecosystem Health. V. Environmental Management 14:81-93. Springer-Verlag New York Incorporated.

Seastedt, T.R., and R.A. Ramundo. 1990. The influence of fire on belowground processes of tallgrass prairie. Pp. 99-117 *in* S.L. Collins and L.L. Wallace, eds. Fire in North American tallgrass prairies. University of Oklahoma Press, Norman.

Seastedt, T.R. 1984a. Microarthropods of burned and unburned tallgrass prairie. Journal of the Kansas Entomological Society 57:468-476.

Seastedt, T.R. 1984b. Belowground macroarthropods of annually burned and unburned tallgrass prairie. American Midland Naturalist 111:405-408.

Shestak, C.J. and M.D. Busse. 2005. Compaction alters physical but not biological indices of soil health. Soil Science Society of America Journal 69:236-246.

Todd, T.C. 1996. Effects of management practices on nematode community structure in tallgrass prairie. Applied Soil Ecology 3:235-246.

Todd, T.C., T.O. Powers, and P.G. Mullin. 2006. Sentinel nematodes of land-use change and restoration in tallgrass prairie. Journal of Nematology 38:20-27.

Tomlin, A.D., M.J. Shipitalo, W.M. Edwards, and R. Protz. 1995. Earthworms and their influence on soil structure and infiltration. Pp 159-183 *In* P.F. Hendrix (ed.). Earthworm ecology and biogeography in North America. Lewis Publication. Boca Raton, FL.

US Army Environmental Center. 2006. Sustainable range program: Range and training land assessment program. https://srp.army.mil/itam/rtla.

USDA, Soil Conservation Service in cooperation with Kansas Agricultural Experiment Station. 1975. Soil Survey of Riley and Part of Geary County, Kansas.

Watts, C.W., S. Eich, and A.R. Dexter. 2000. Effects of mechanical energy inputs on soil respiration at the aggregate and field scales. Soil and Tillage Research 53:231-243.

White, D., and D. Ringleberg. 1998. Signature lipid biomarker analysis. Pp 255-272. *In*: Techniques in microbial ecology. R. Burlage, R. Atlas, D. Stahl, G. Geesey, and G. Sayler (Eds.). Oxford University Press, Oxford, U.K.

Wright, H.A. 1974. Range burning. Journal of Range Management 27:5-11.

Yeates, G.W., T. Bongers, R.G.M. de Goede, D.W. Freckman, and S.S. Georgieva. 1993. Feeding habits in soil nematode families and genera—an outline for soil ecologists. Journal of Nematology 25:315-331.

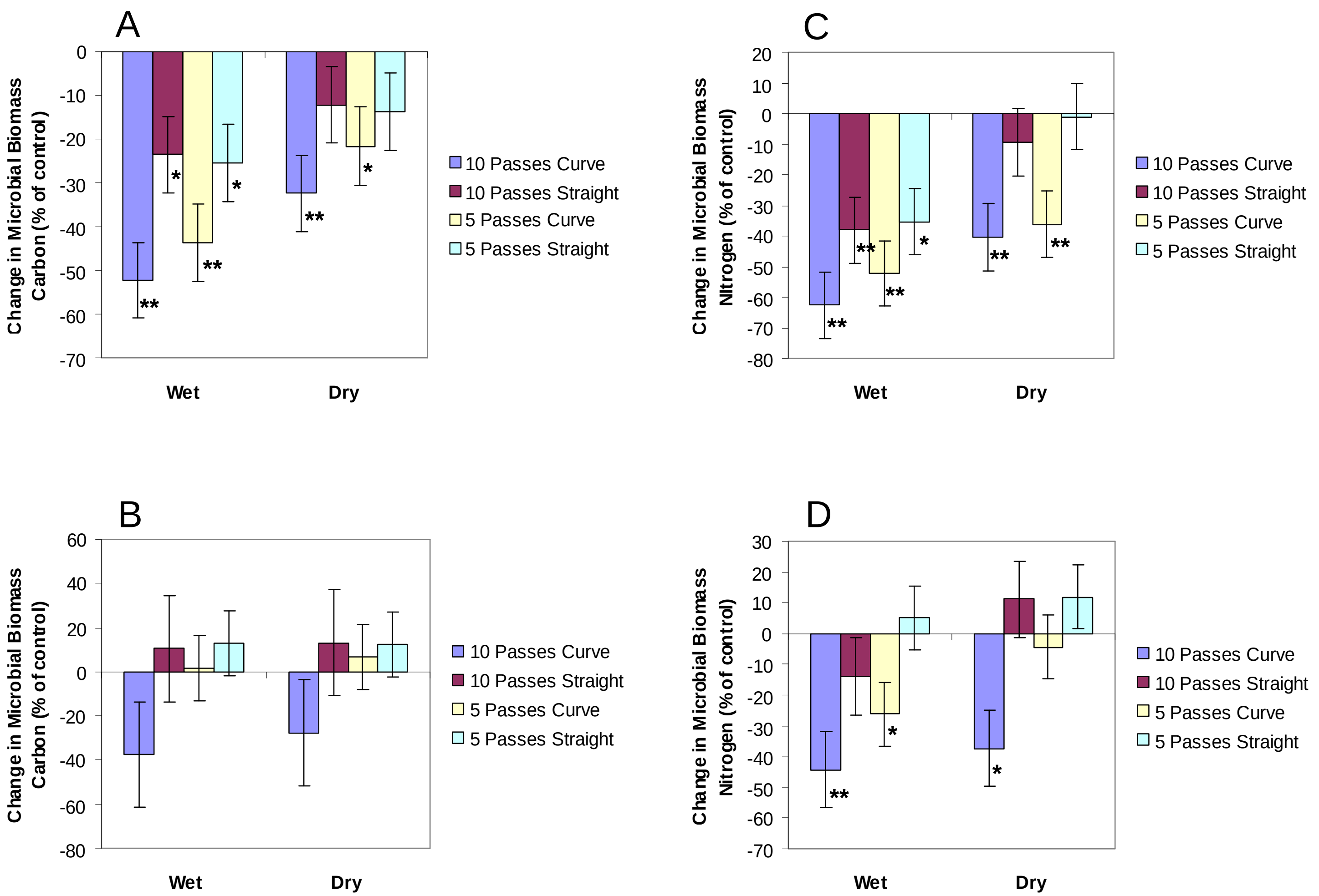


Figure 3.1. Disturbance response for microbial biomass carbon in (A) silty clay loam soil, (B) silt loam soil, and microbial biomass nitrogen in (C) silty clay loam soil and (D) silt loam soil, 2005. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. *, ** indicate $p \leq 0.05$, 0.01, respectively. Microbial biomass C averaged 1219 and 1088 mg kg^{-1} for controls in silty clay loam soil and silt loam soil, respectively, and microbial biomass N averaged 266 and 266 mg kg^{-1} for controls in silty clay loam soil and silt loam soil, respectively.

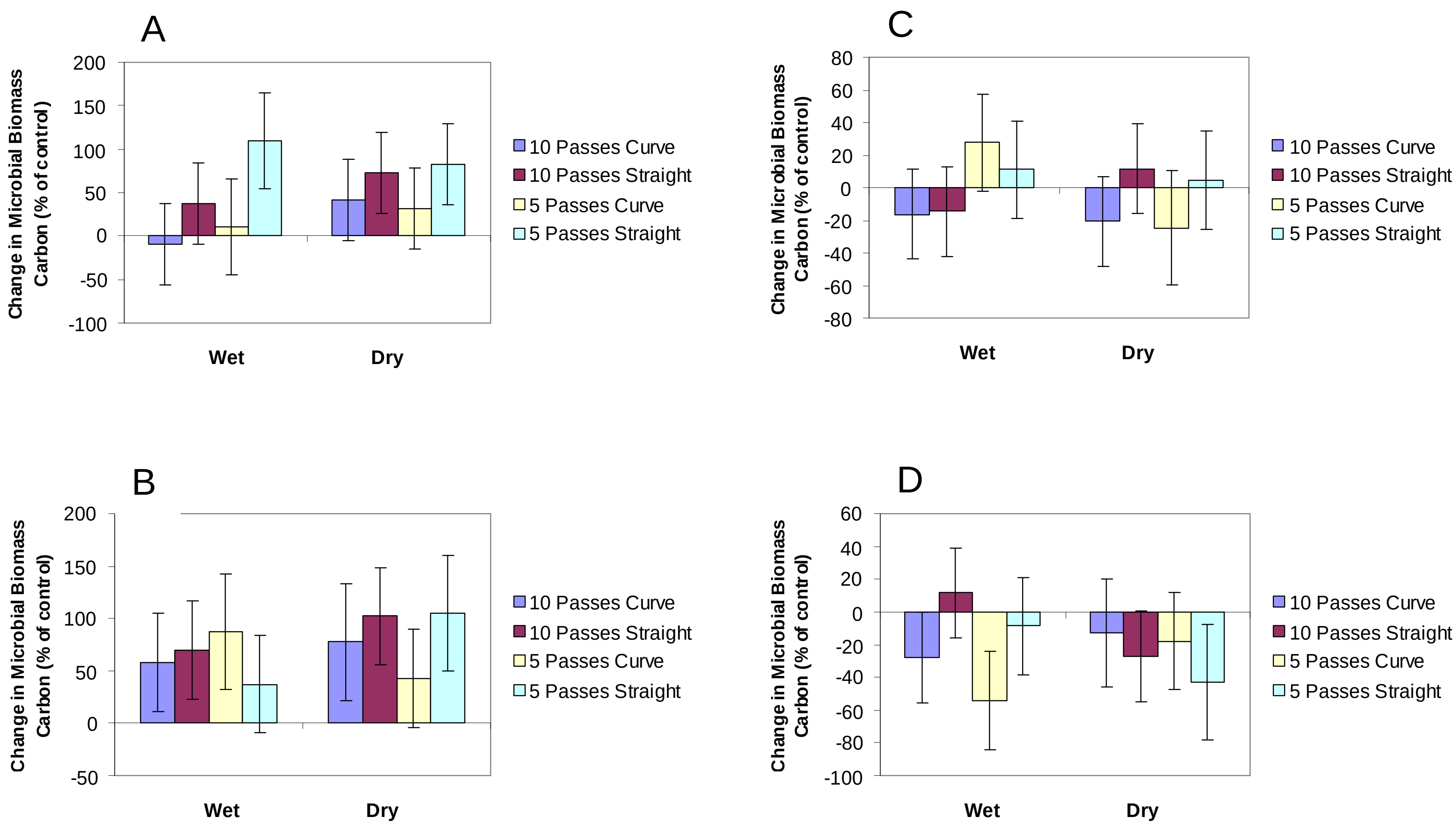


Figure 3.2. Disturbance response for microbial biomass carbon in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2006. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. Microbial biomass C averaged 318 and 233 mg kg^{-1} for burned and unburned controls, respectively, in silty clay loam soil and 504 and 559 mg kg^{-1} for burned and unburned controls, respectively, in silt loam soil.

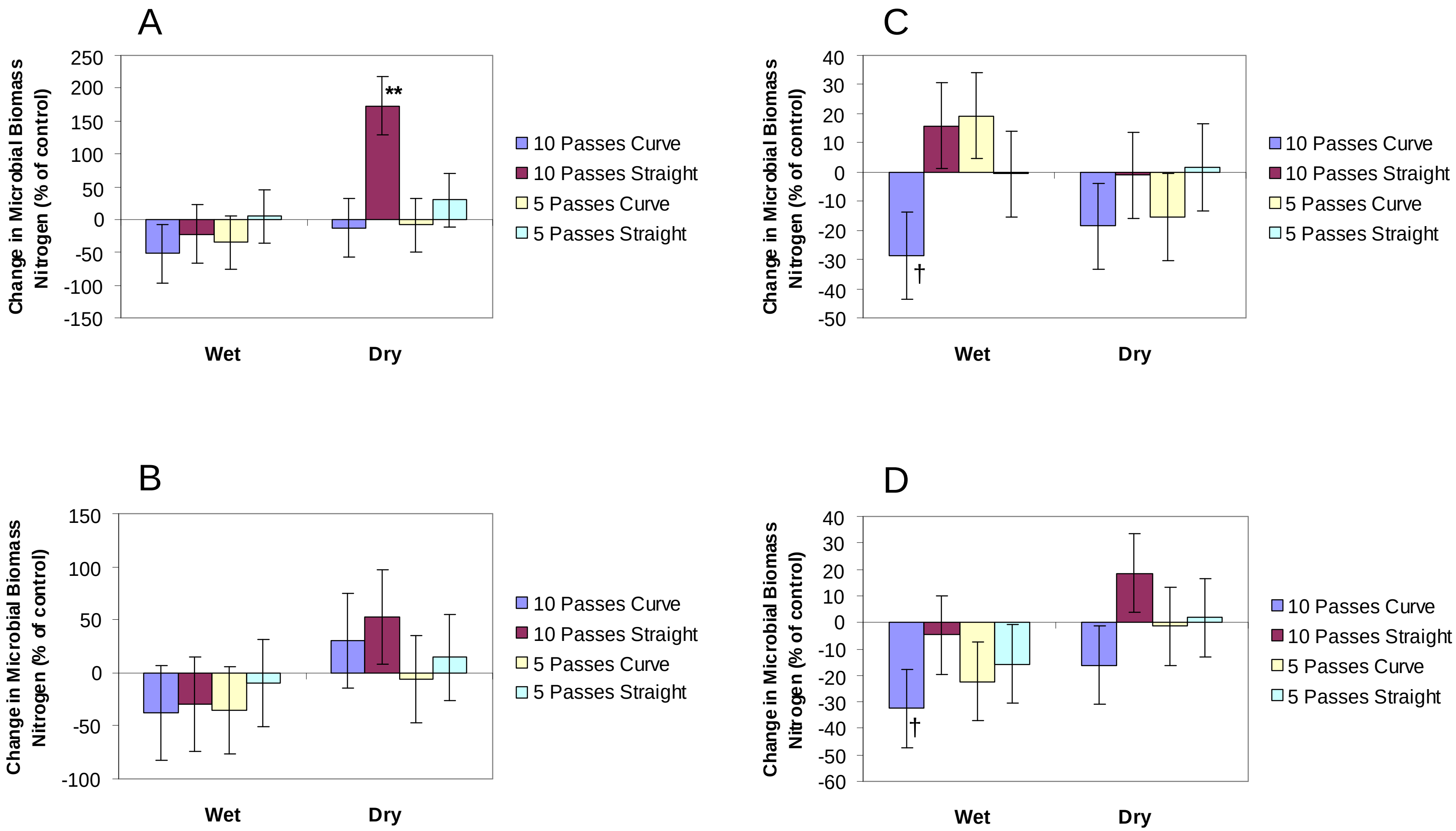


Figure 3.3. Disturbance response for microbial biomass nitrogen in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2006. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, ** indicate $p \leq 0.10, 0.01$, respectively. Microbial biomass N averaged 135 and 123 mg kg^{-1} for burned and unburned controls, respectively, in silty clay loam soil and 172 and 191 mg kg^{-1} for burned and unburned controls, respectively, in silt loam soil.

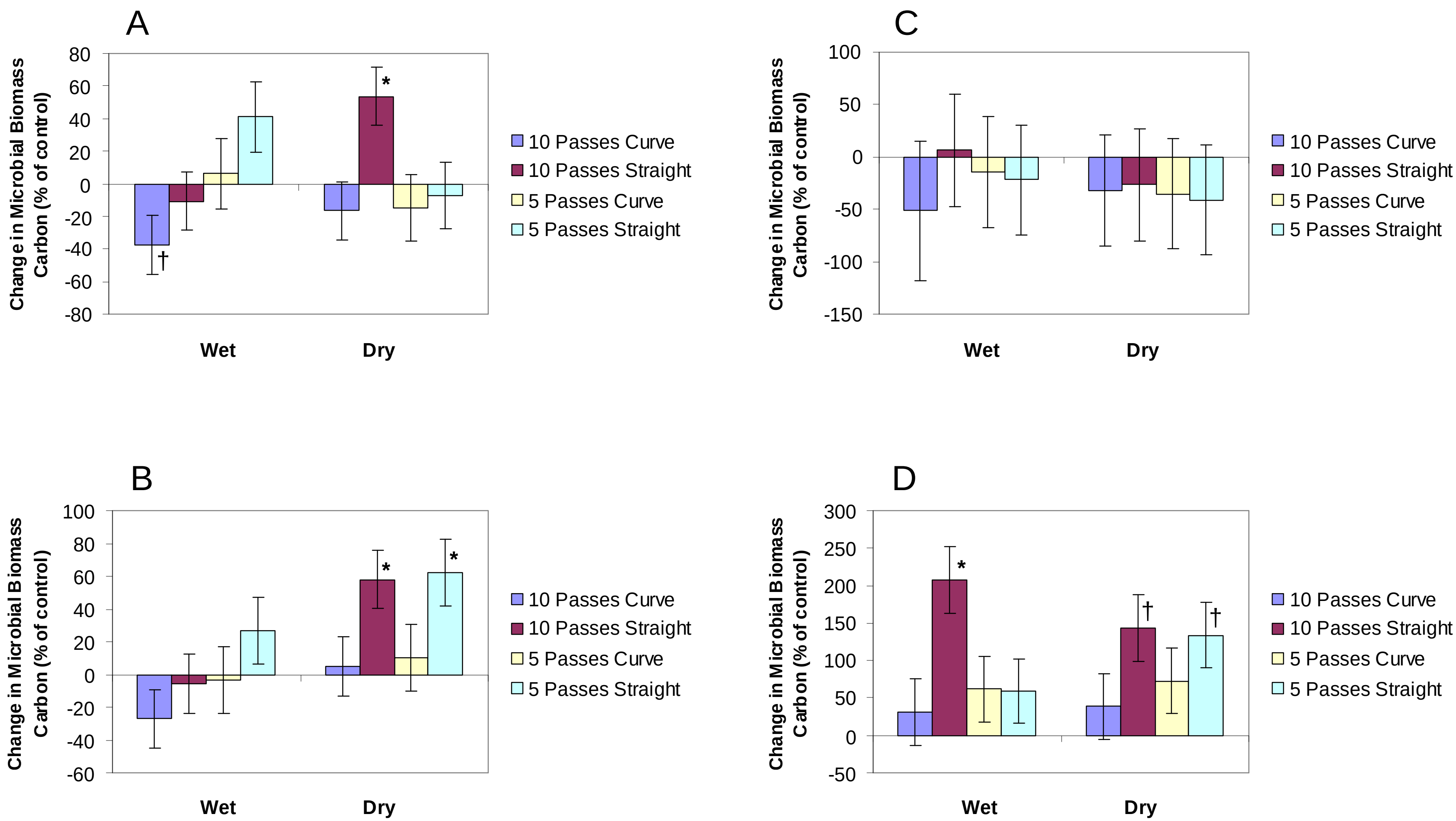


Figure 3.4. Disturbance response for microbial biomass carbon in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2007. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, * indicate $p \leq 0.10, 0.05$, respectively. Microbial biomass C averaged 467 and 508 mg kg^{-1} for burned and unburned controls, respectively, in silty clay loam soil and 691 and 318 mg kg^{-1} for burned and unburned controls, respectively, in silt loam soil.

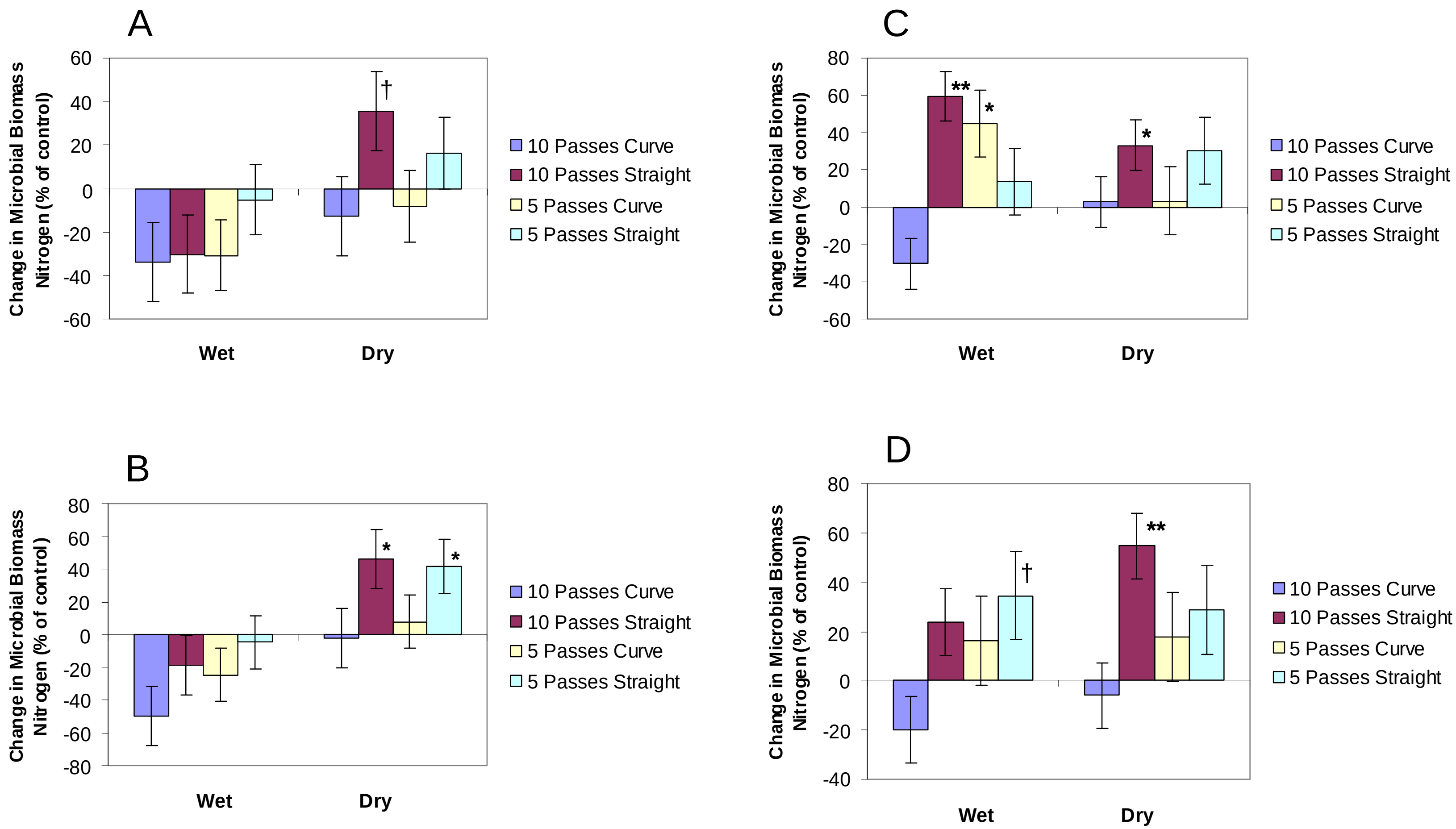


Figure 3.5. Disturbance response for microbial biomass nitrogen in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2007. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, *, ** indicate $p \leq 0.10, 0.05, 0.01$, respectively. Microbial biomass N averaged 116 and 135 mg kg^{-1} for burned and unburned controls, respectively, in silty clay loam soil and 157 and 149 mg kg^{-1} for burned and unburned controls, respectively, in silt loam soil.

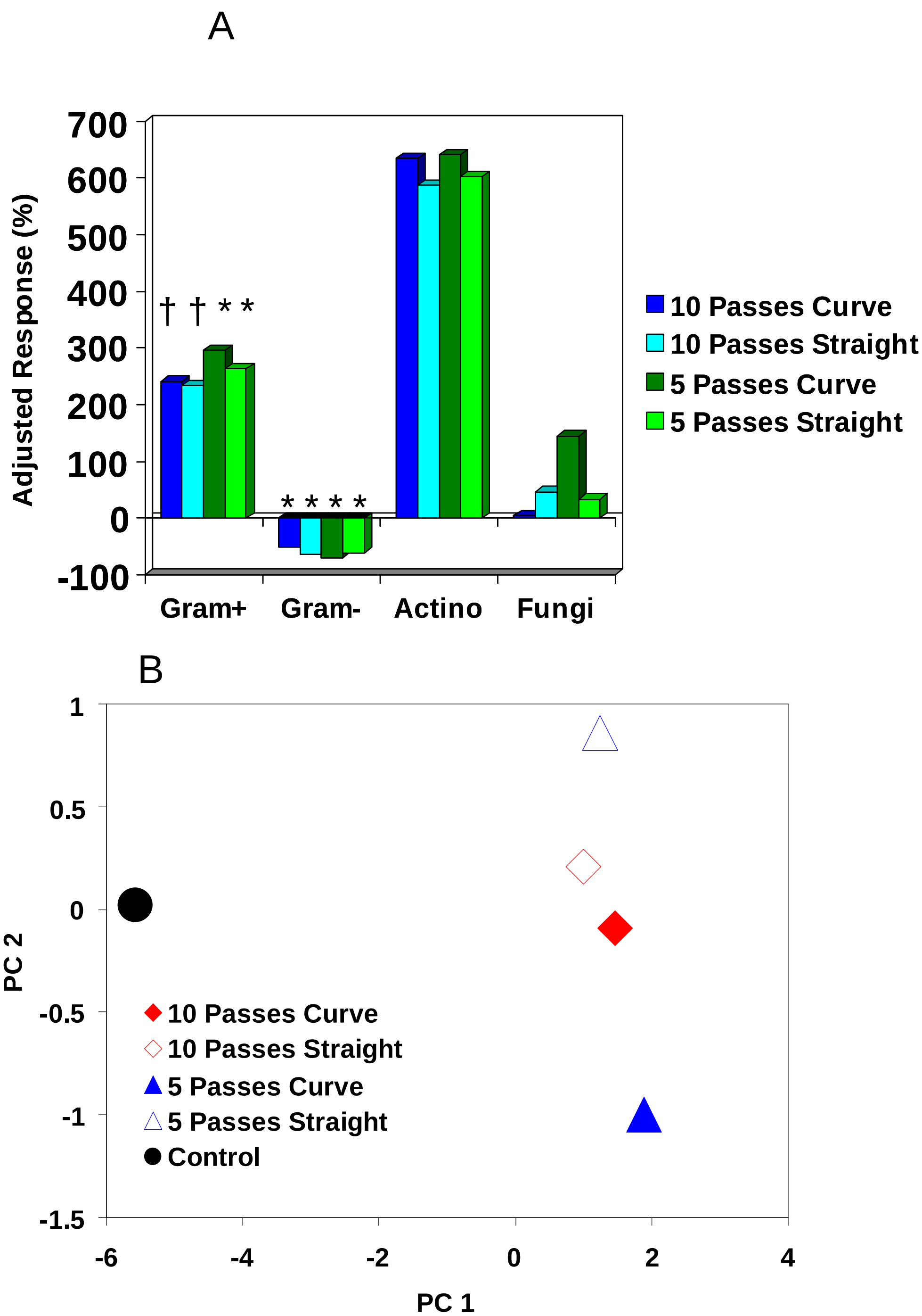


Figure 3.6. Microbial community responses to 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet soil moisture conditions in silt loam soil, 2005. A) Disturbance response of PLFA groups. B) Separation of treatments on the first and second principal components based on Principal Components Analysis of PLFA data. †, *, ** indicate $p \leq 0.10$, 0.05, 0.01, respectively.

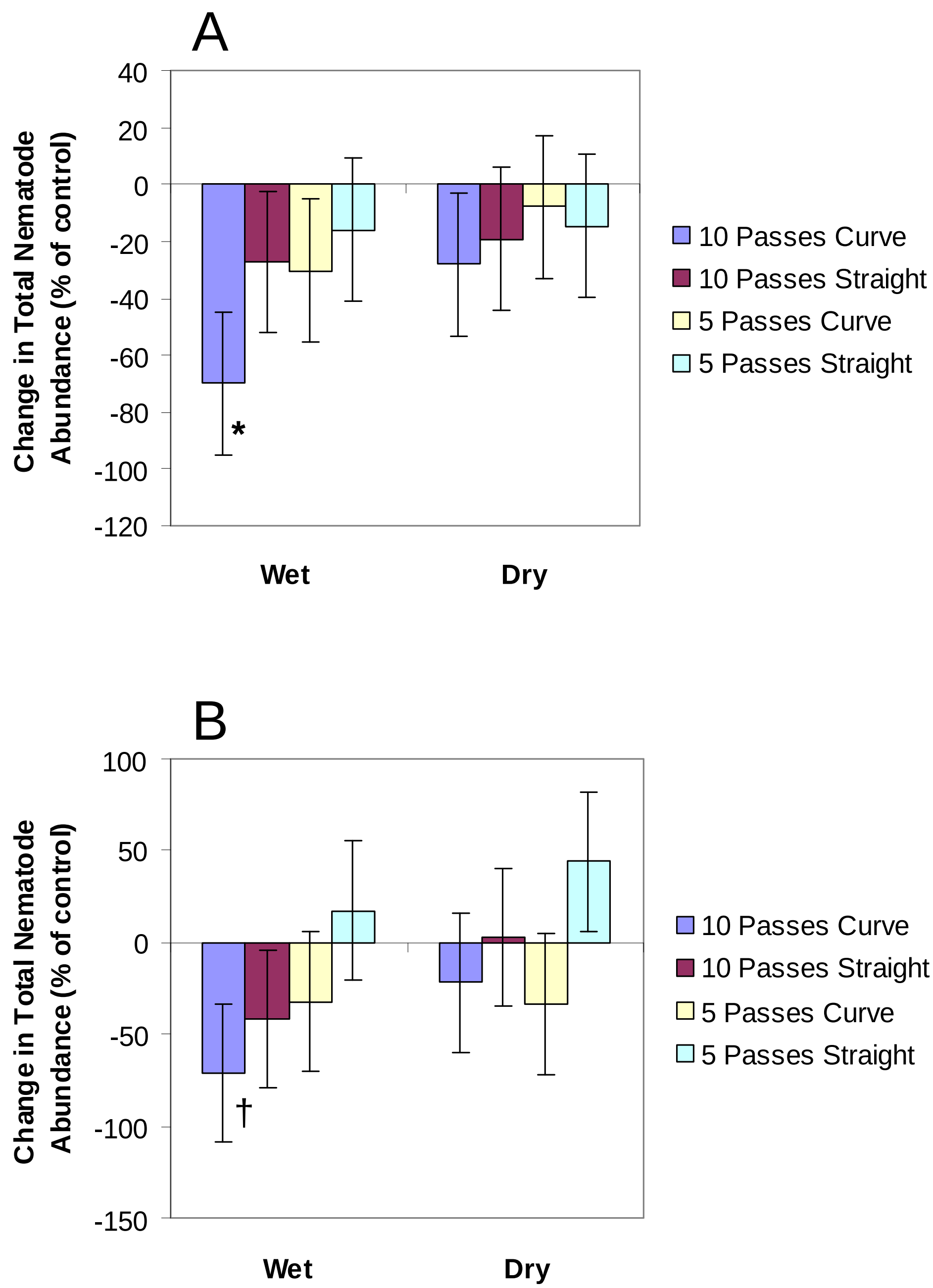


Figure 3.7. Disturbance response for total nematode abundance in (A) silty clay loam soil and (B) silt loam soil, 2005. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, * indicate $p \leq 0.10$, 0.05, respectively. Total nematode abundance averaged 1.19 and 1.91 million m^{-2} for controls in silty clay loam soil and silt loam soil, respectively.

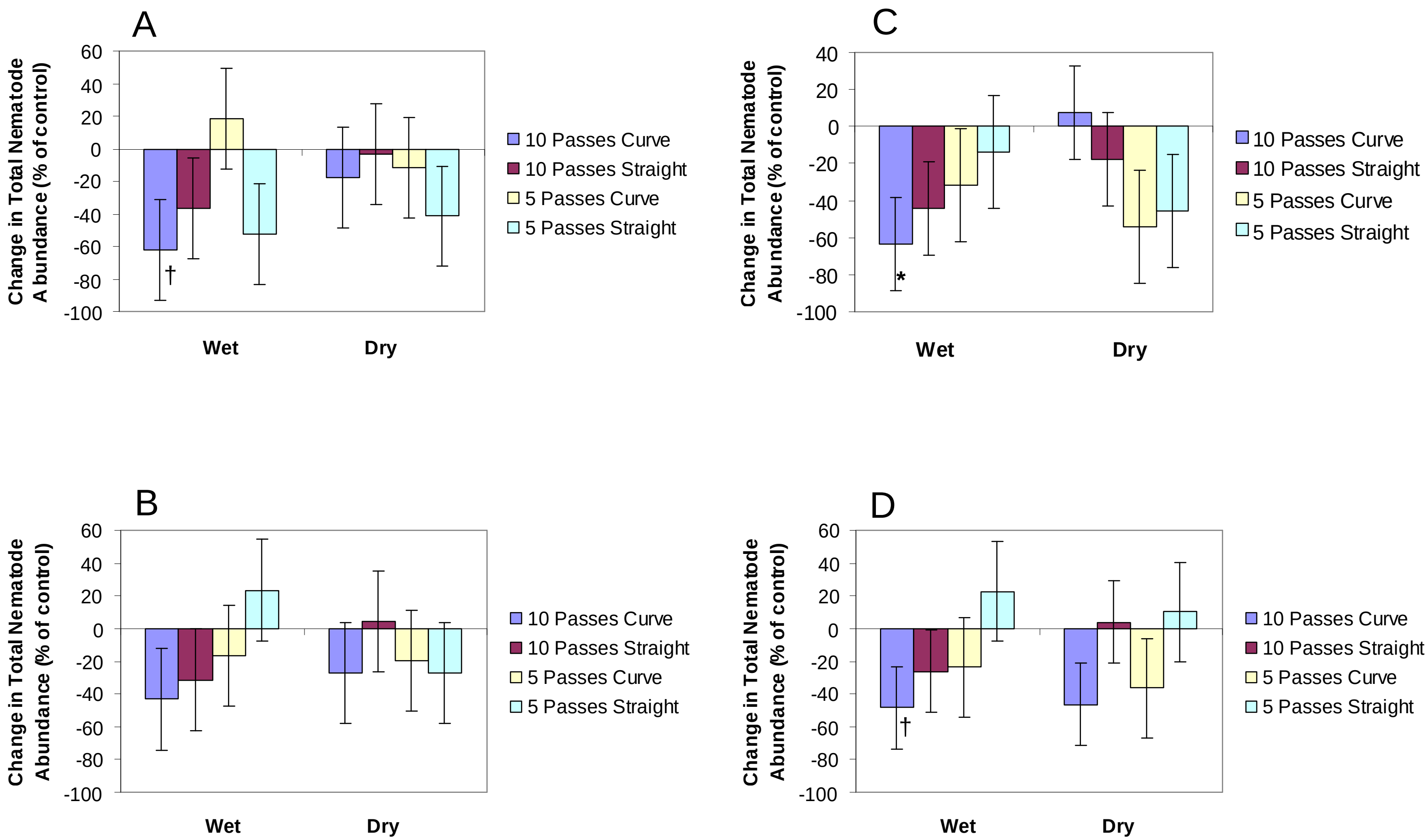


Figure 3.8. Disturbance response for total nematode abundance in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2006. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, * indicate $p \leq 0.10$, 0.05, respectively. Total nematode abundance averaged 0.88 and 1.30 million m^{-2} for burned and unburned controls, respectively, in silty clay loam soil and 0.85 and 1.93 million m^{-2} for burned and unburned controls, respectively, in silt loam soil.

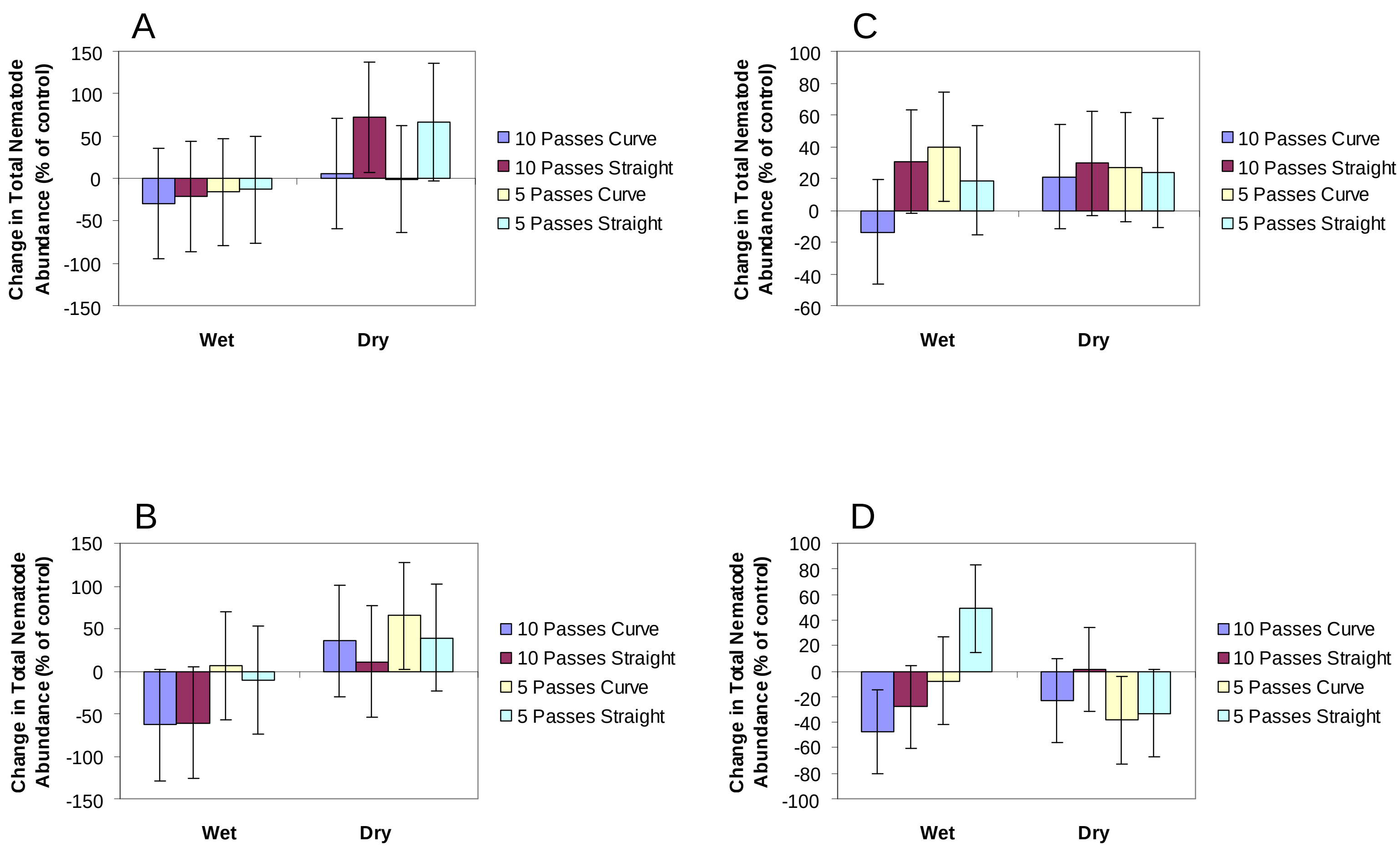
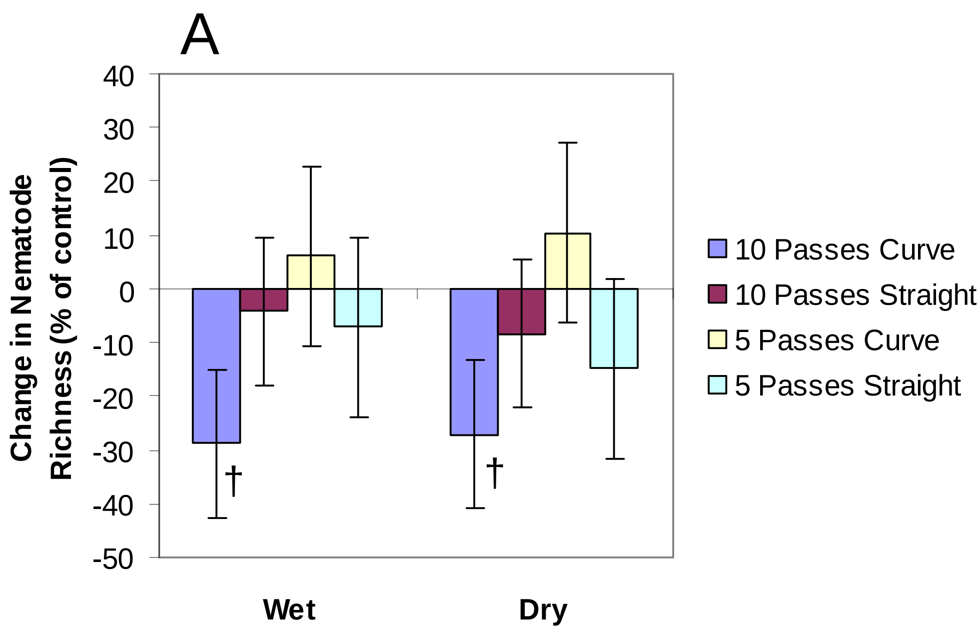


Figure 3.9. Disturbance response for total nematode abundance in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2007. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. Total nematode abundance averaged 0.28 and 0.72 million m^{-2} for burned and unburned controls, respectively, in silty clay loam soil and 0.54 and 0.45 million m^{-2} for burned and unburned controls, respectively, in silt loam soil.



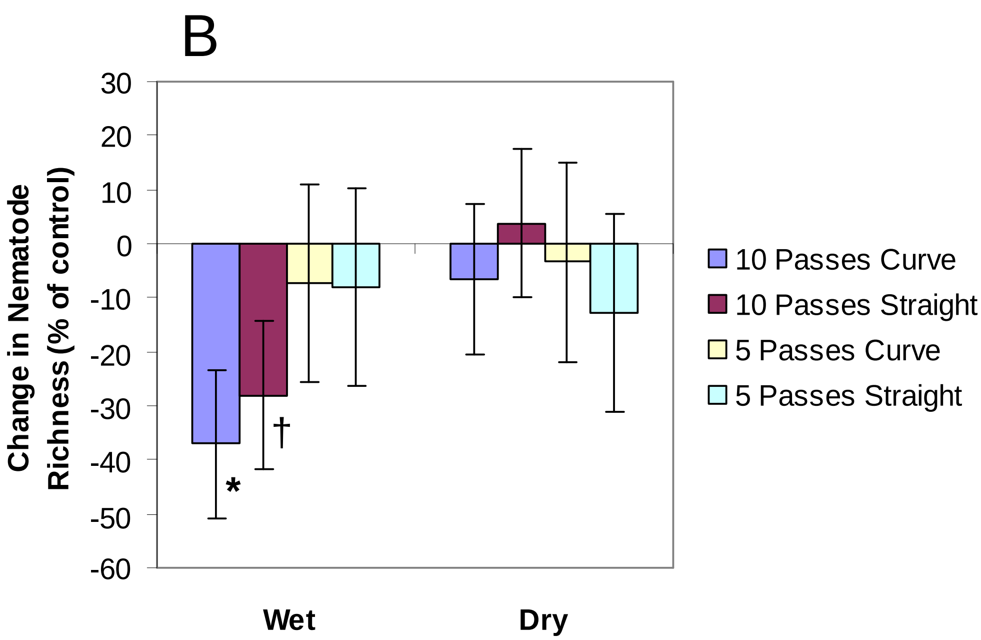


Figure 3.10. Disturbance response for nematode family richness in (A) silty clay loam soil and (B) silt loam soil, 2005. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, * indicate $p \leq 0.10$, 0.05, respectively. Nematode family richness averaged 11 and 16 for controls in silty clay loam soil and silt loam soil, respectively.

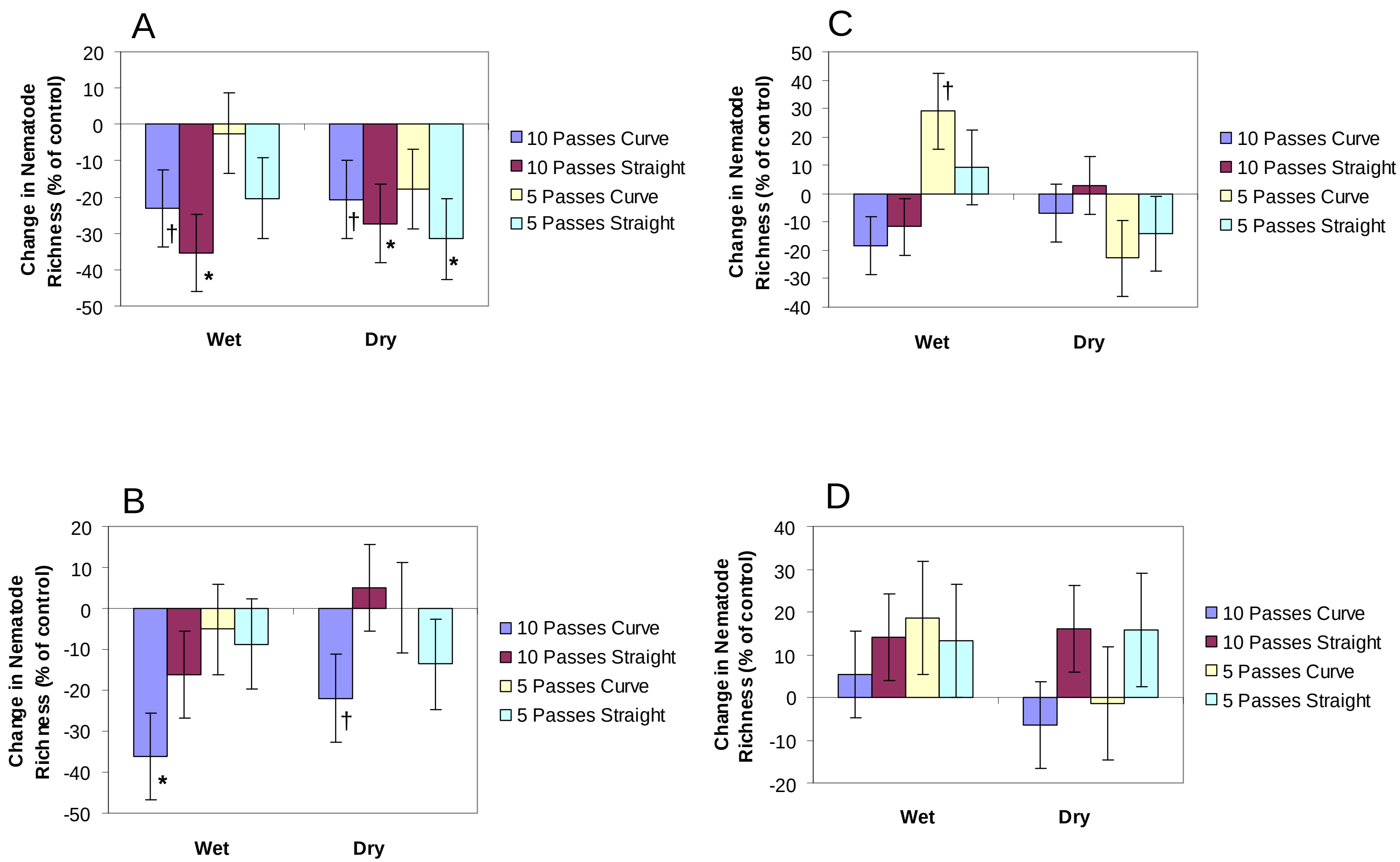


Figure 3.11. Disturbance response for nematode family richness in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2006. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, * indicate $p \leq 0.10$, 0.05, respectively. Nematode family richness averaged 13 and 16 for burned and unburned controls, respectively, in silty clay loam soil and 13 and 15 for burned and unburned controls, respectively, in silt loam soil.

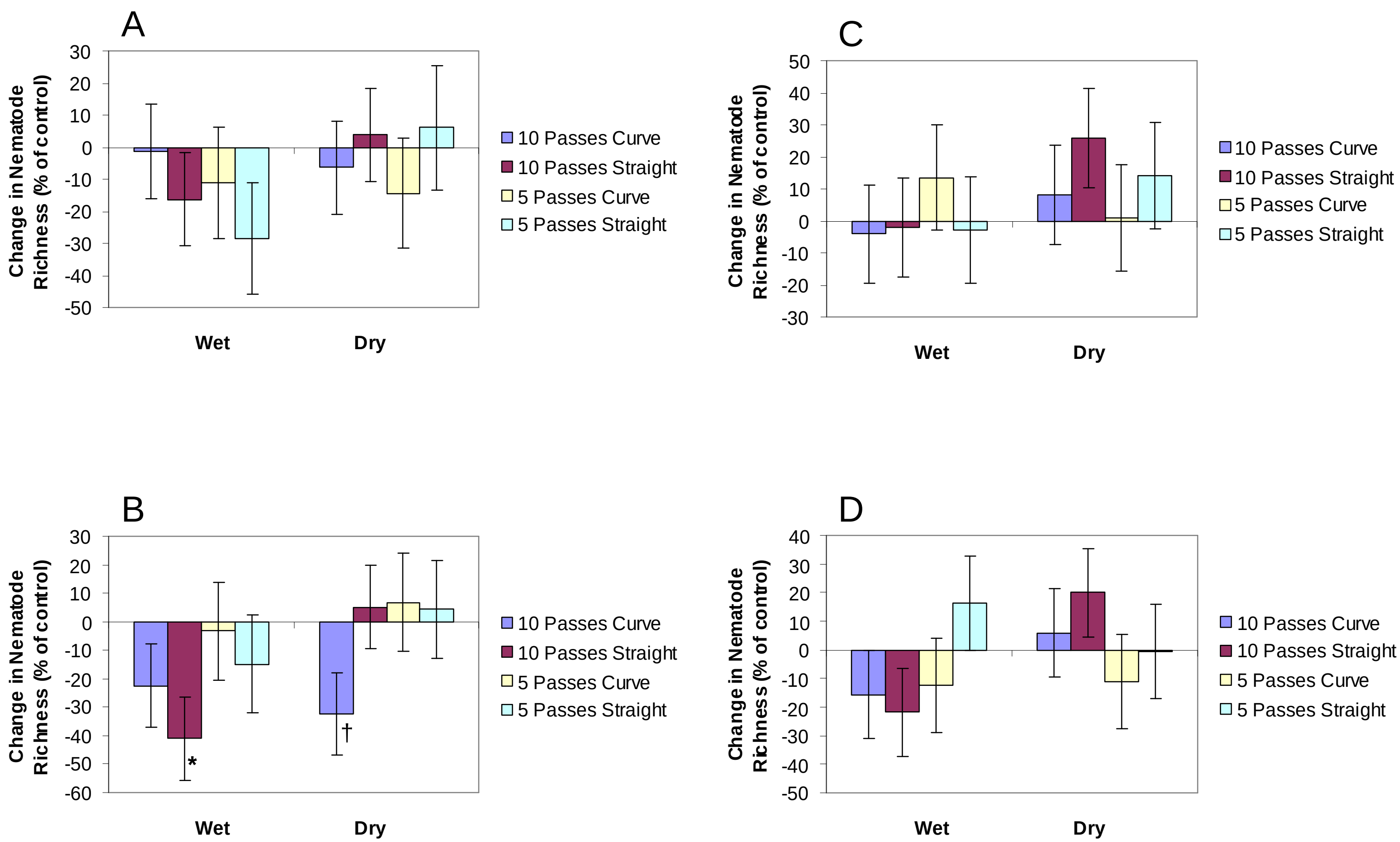


Figure 3.12. Disturbance response for nematode family richness in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2007. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, * indicate $p \leq 0.10$, 0.05, respectively. Nematode family richness averaged 12 and 12 for burned and unburned controls, respectively, in silty clay loam soil and 13 and 11 for burned and unburned controls, respectively, in silt loam soil.

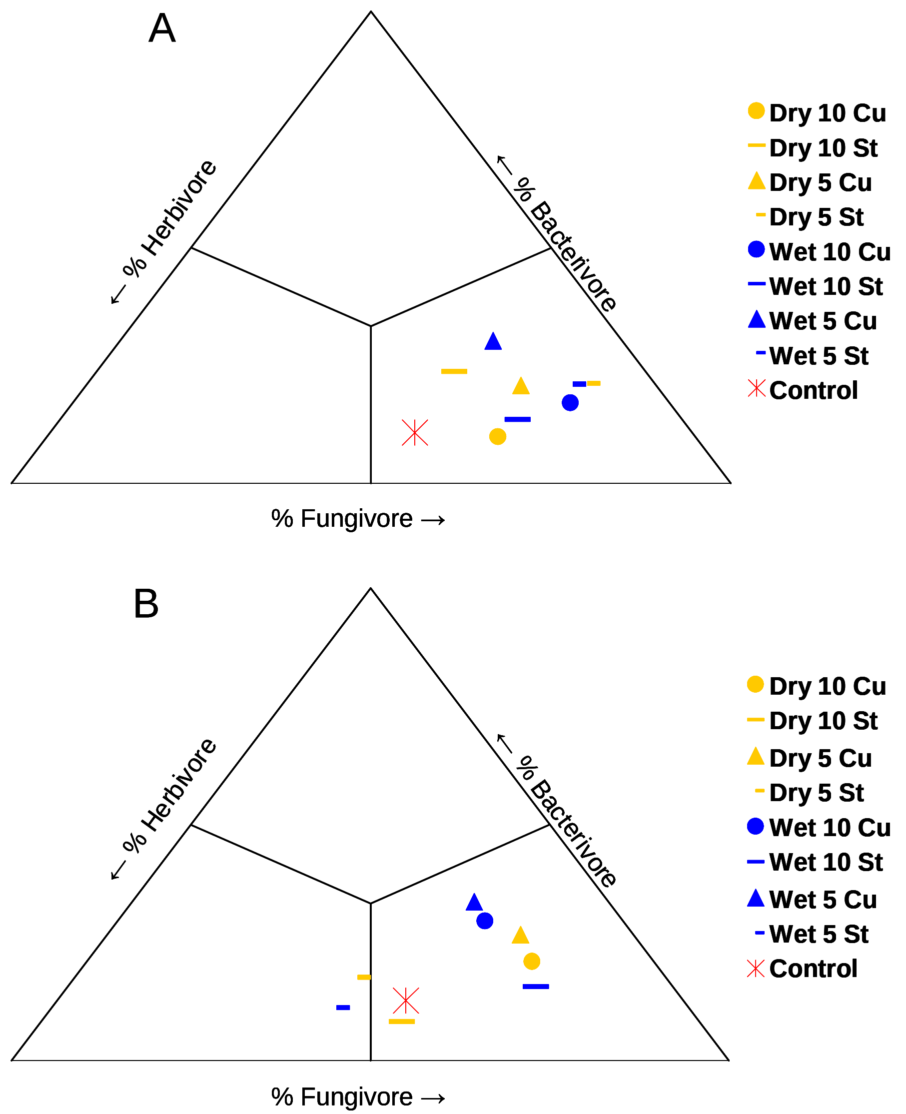


Figure 3.13. Nematode enrichment profile for (A) silty clay loam soil and (B) silt loam soil, 2005. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Cu = curve area, St = straight-a-way area.

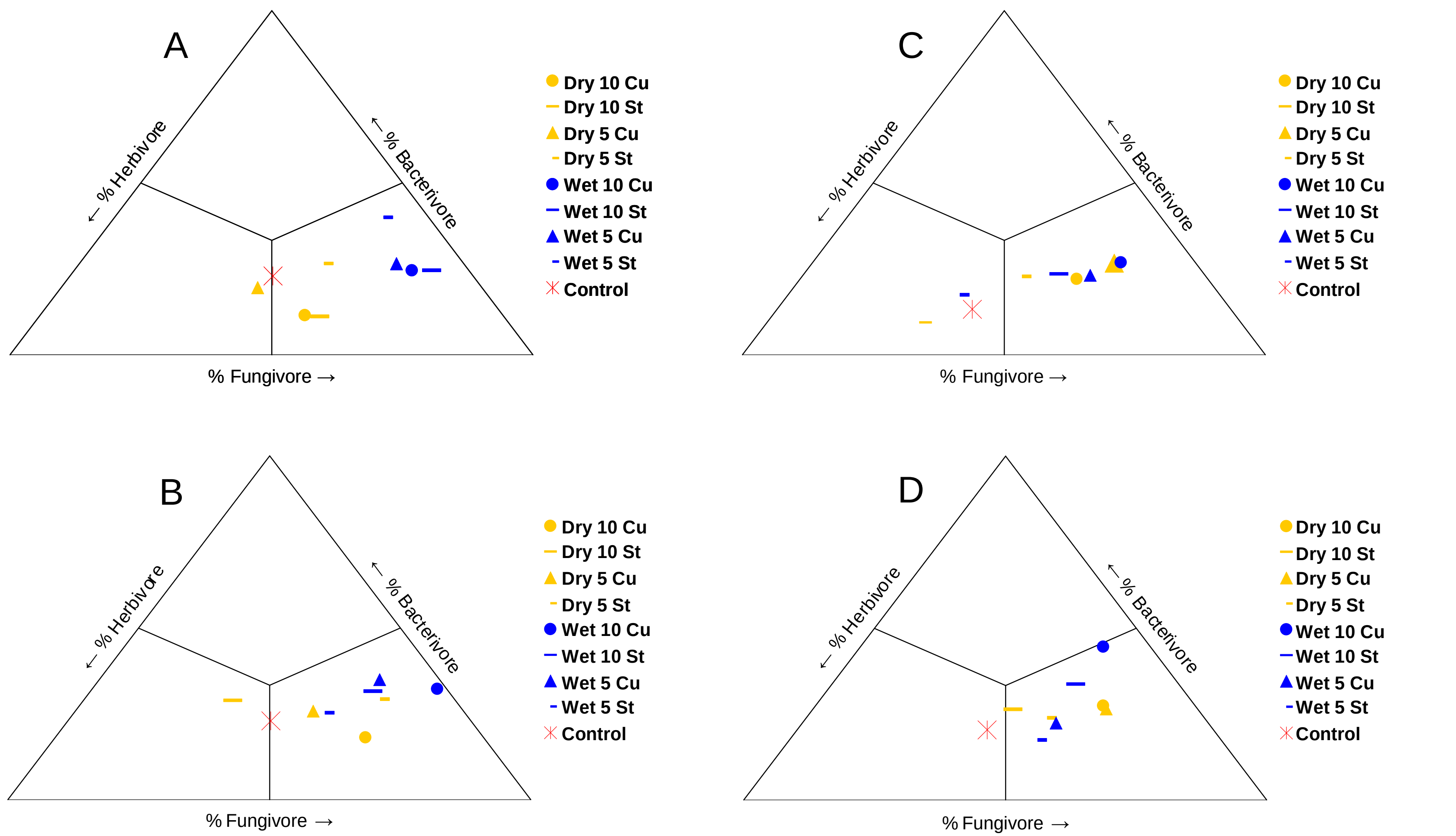


Figure 3.14. Nematode enrichment profile for (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2006. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Cu = curve area, St = straight-a-way area.

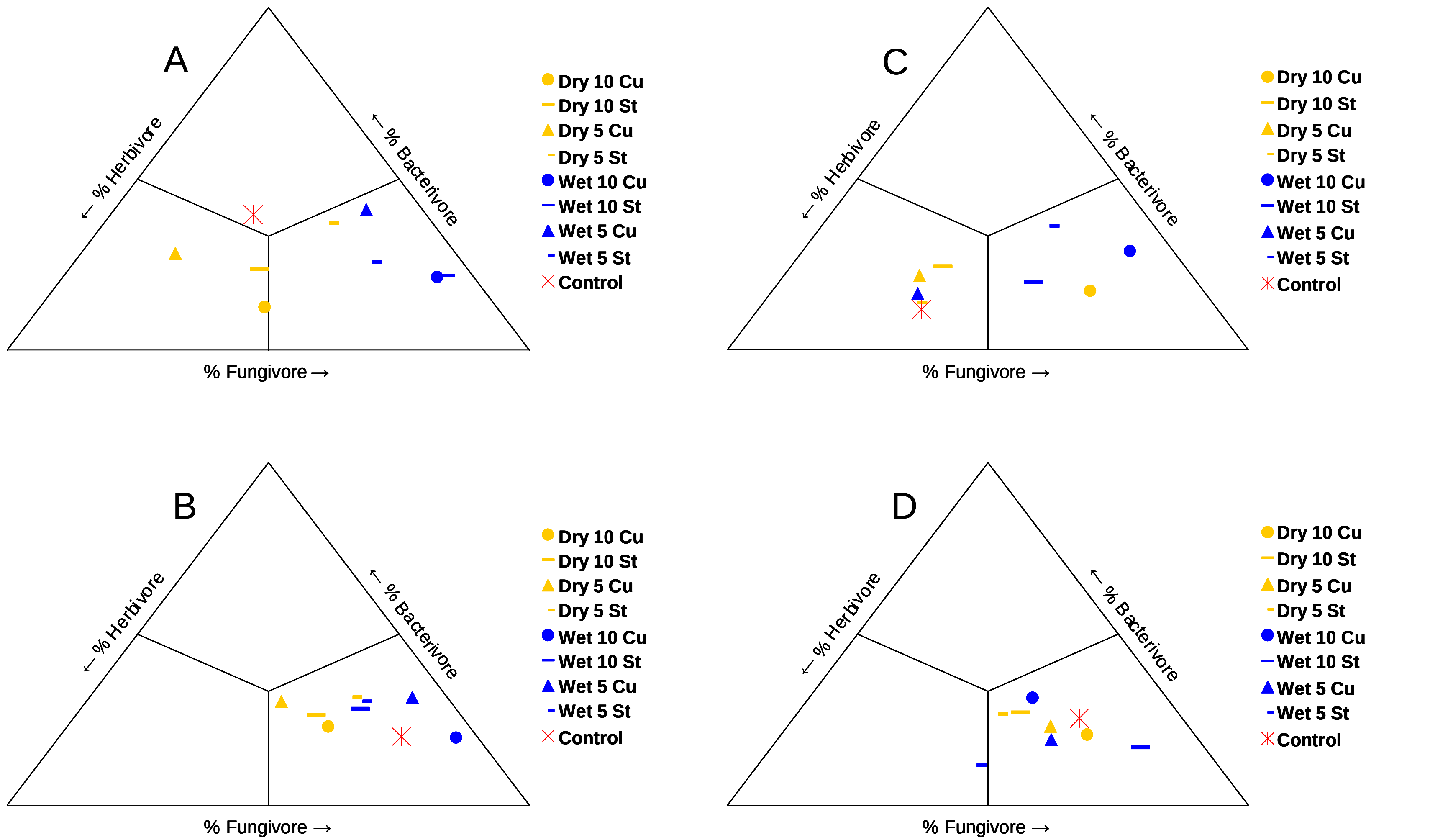


Figure 3.15. Nematode enrichment profile for (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2007. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Cu = curve area, St = straight-a-way area.

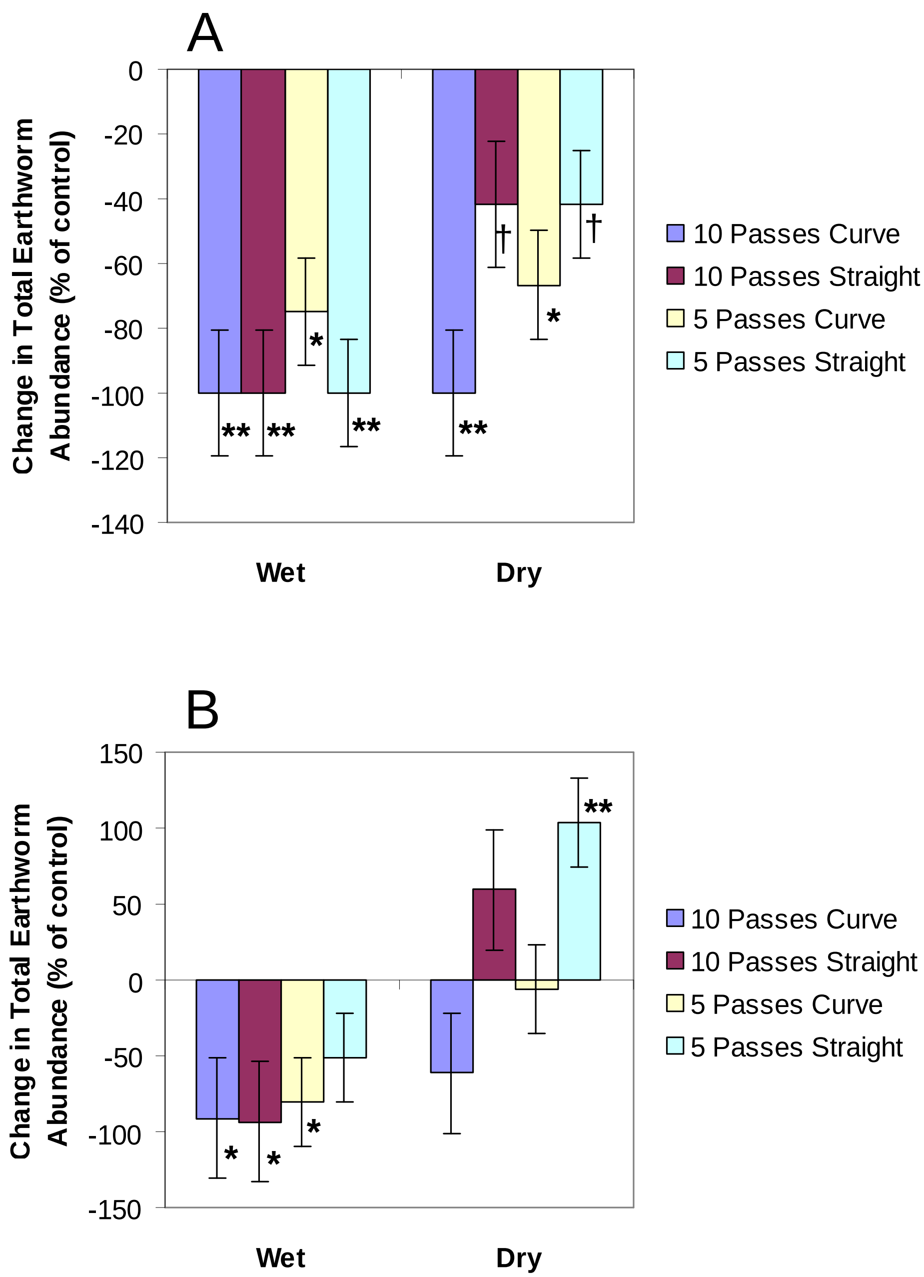


Figure 3.16. Disturbance response for earthworm abundance in (A) silty clay loam soil and (B) silt loam soil, 2005. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, *, ** indicate $p \leq 0.10, 0.05, 0.01$, respectively. Earthworm abundance averaged 27 and 93 m^{-2} for controls in silty clay loam soil and silt loam soil, respectively.

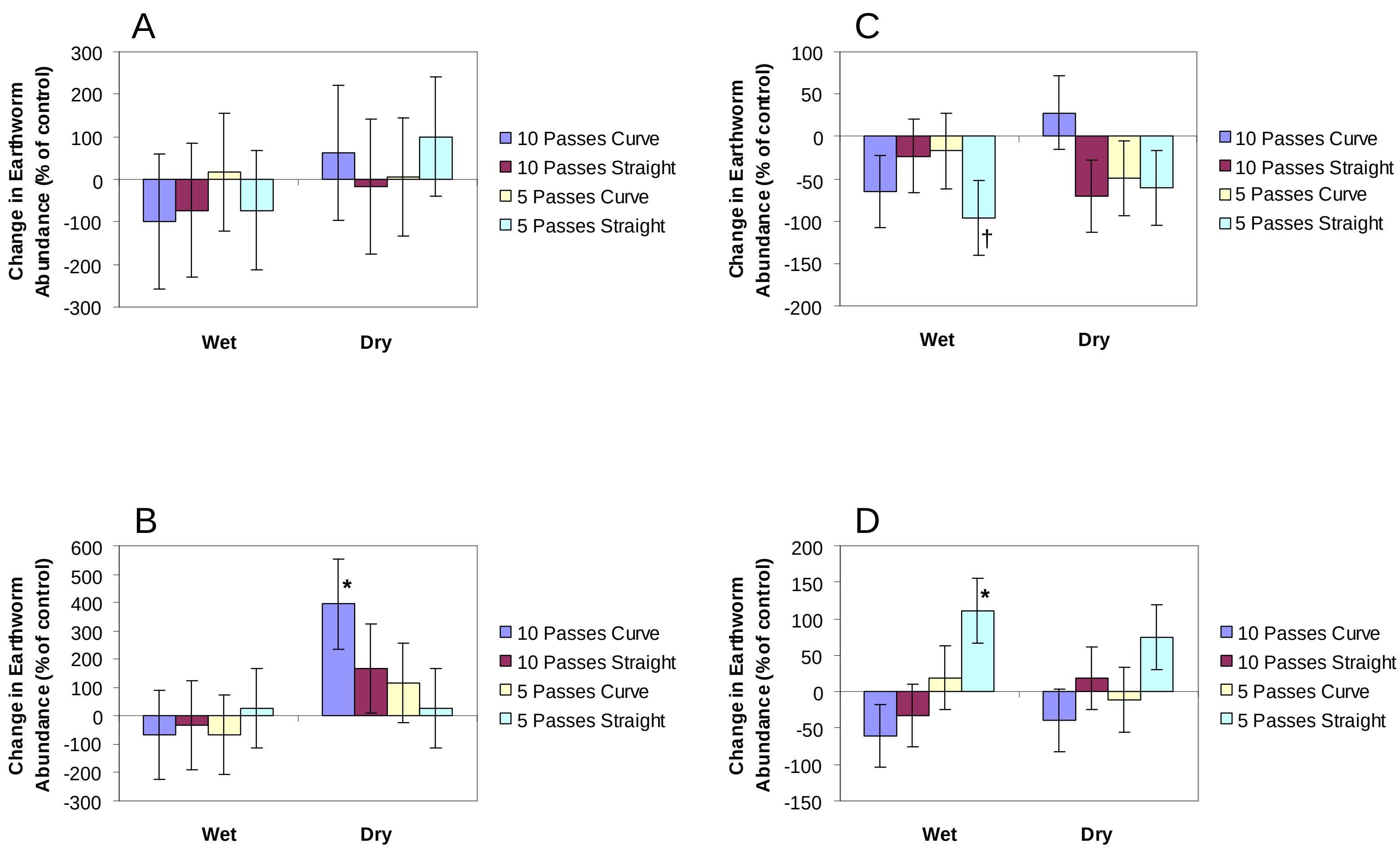


Figure 3.17. Disturbance response for earthworm abundance in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2006. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, * indicate $p \leq 0.10$, 0.05, respectively. Earthworm abundance averaged 20 and 40 m^{-2} for burned and unburned controls, respectively, in silty clay loam soil and 77 and 140 m^{-2} for burned and unburned controls, respectively, in silt loam soil.

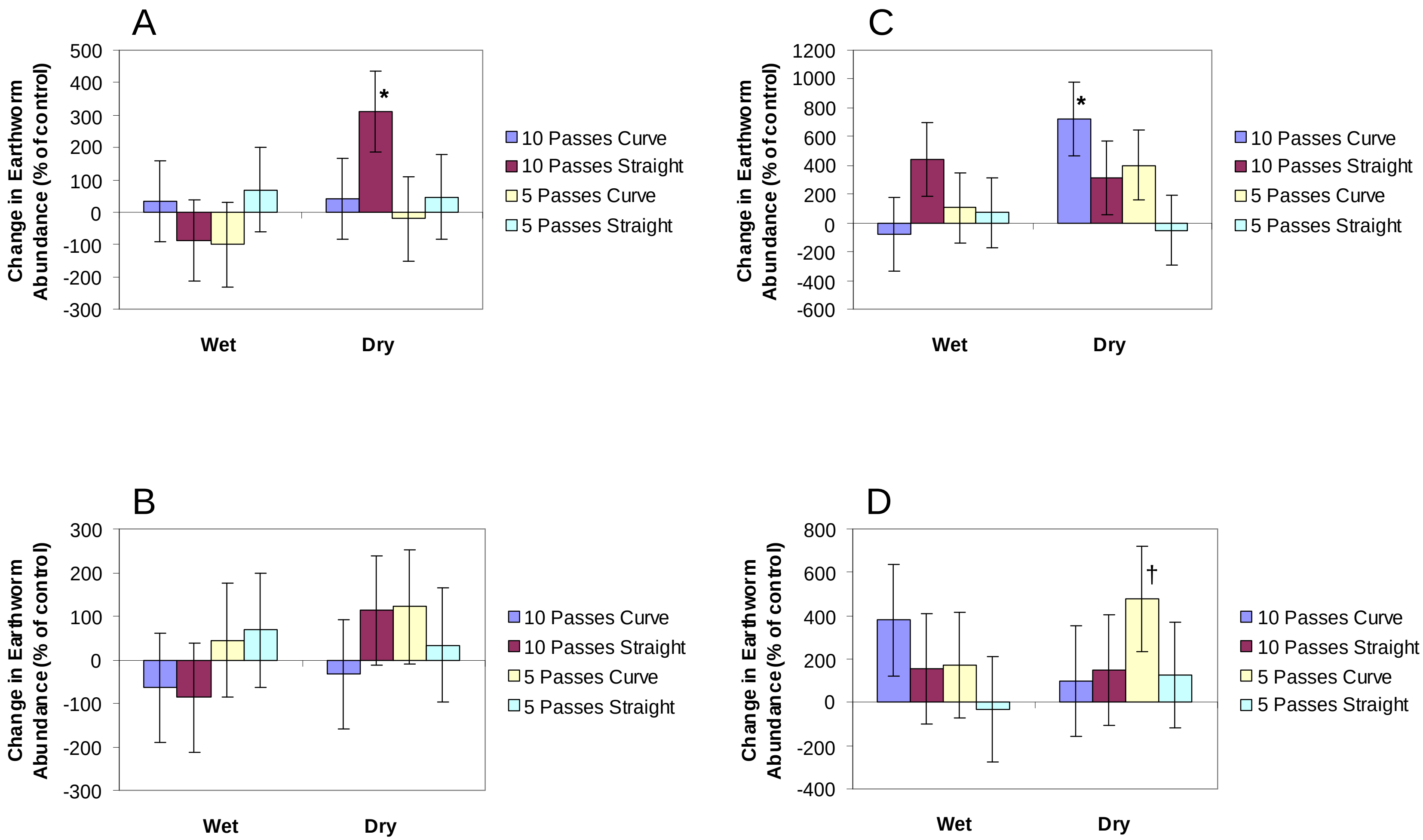


Figure 3.18. Disturbance response for earthworm abundance in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2007. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. †, * indicate $p \leq 0.10$, 0.05, respectively. Earthworm abundance averaged 10 and 23 m^{-2} for burned and unburned controls, respectively, in silty clay loam soil and 23 and 60 m^{-2} for burned and unburned controls, respectively, in silt loam soil.

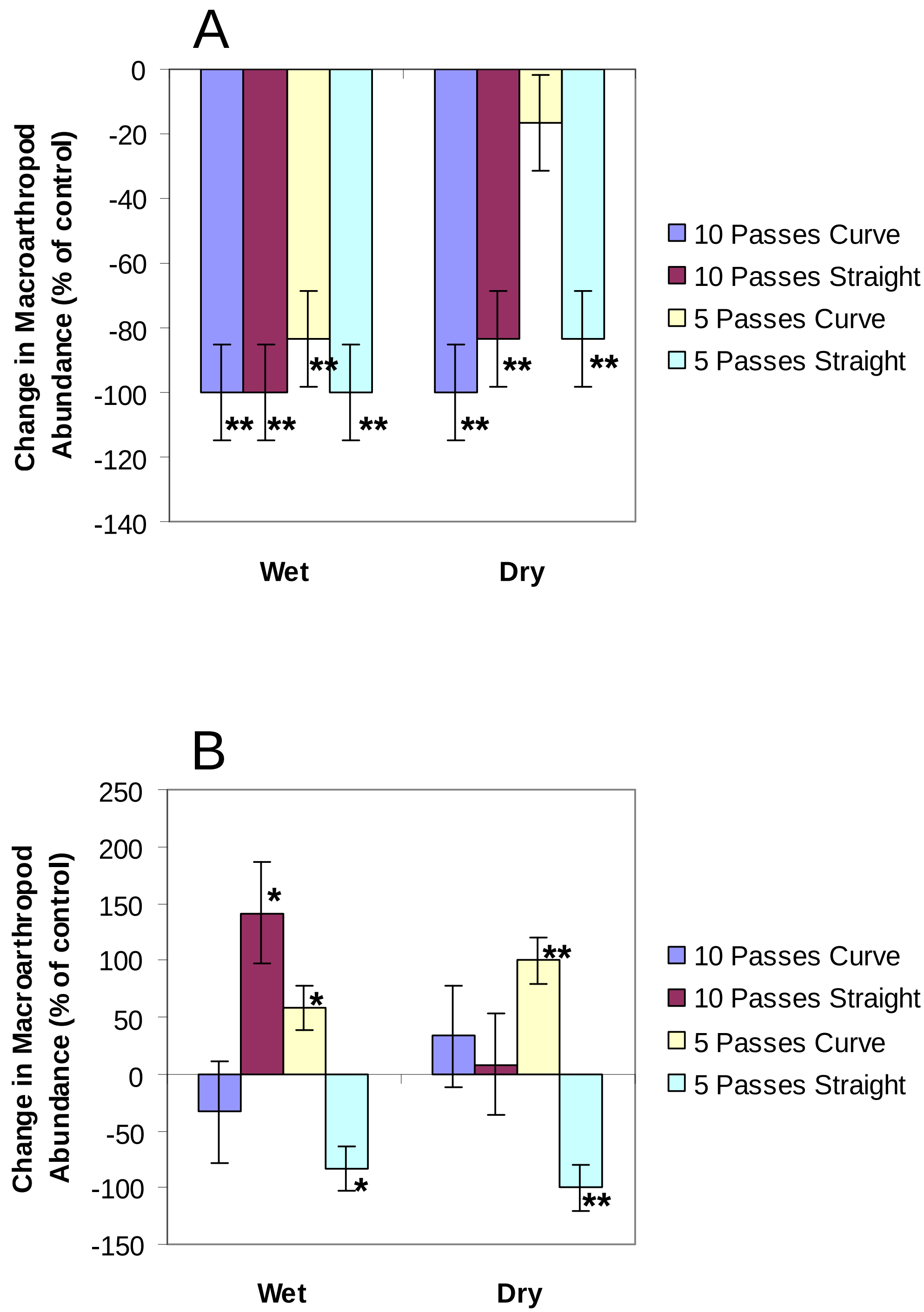


Figure 3.19. Disturbance response for macroarthropod abundance in (A) silty clay loam soil and (B) silt loam soil, 2005. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. *, ** indicate $p \leq 0.05$, 0.01, respectively. Macroarthropod abundance averaged 13 and 17 m^{-2} for controls in silty clay loam soil and silt loam soil, respectively.

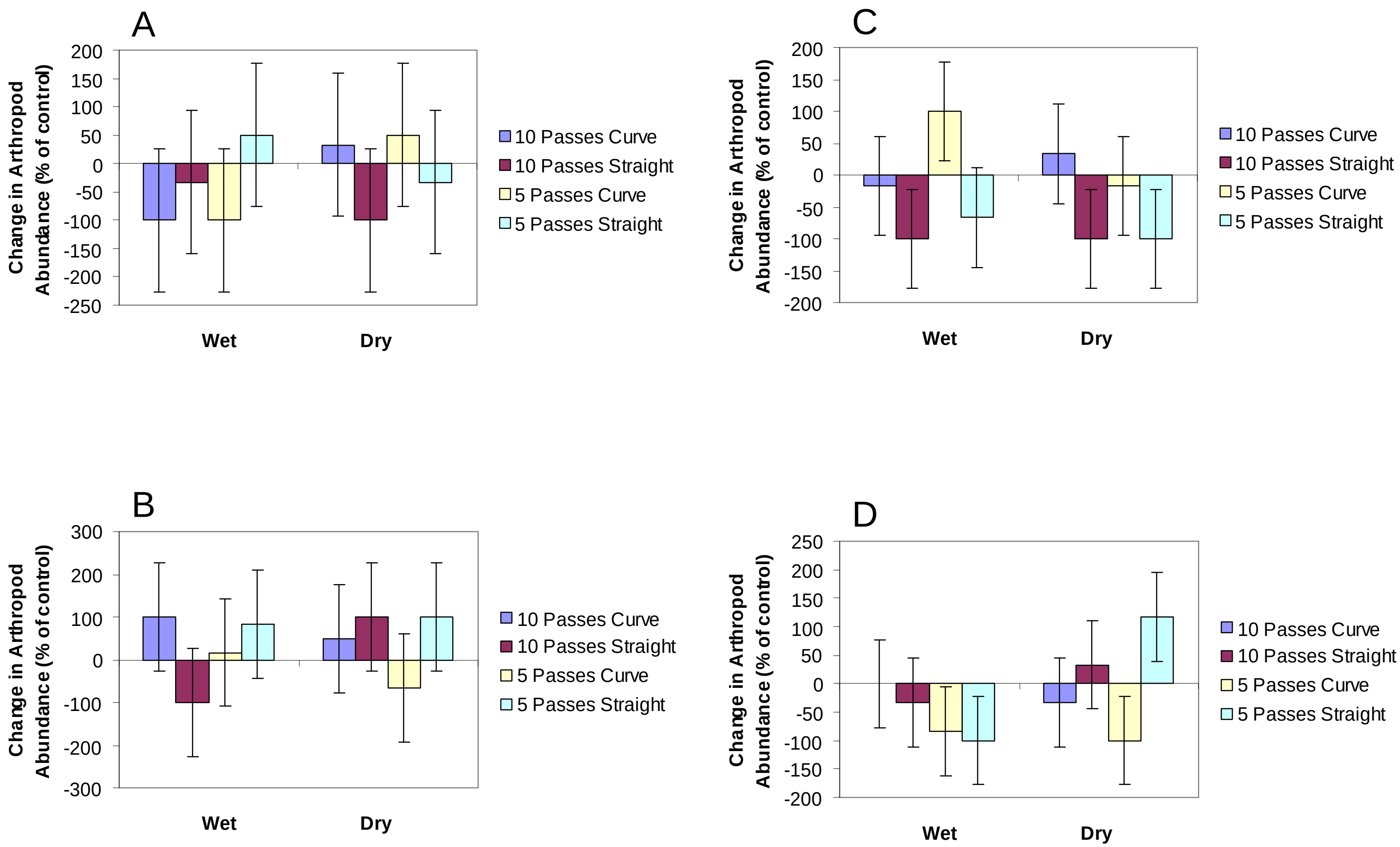


Figure 3.20. Disturbance response for macroarthropod abundance in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2006. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. Macroarthropod abundance averaged 3 and 17 m^{-2} for burned and unburned controls, respectively, in silty clay loam soil and 3 and 17 m^{-2} for burned and unburned controls, respectively, in silt loam soil.

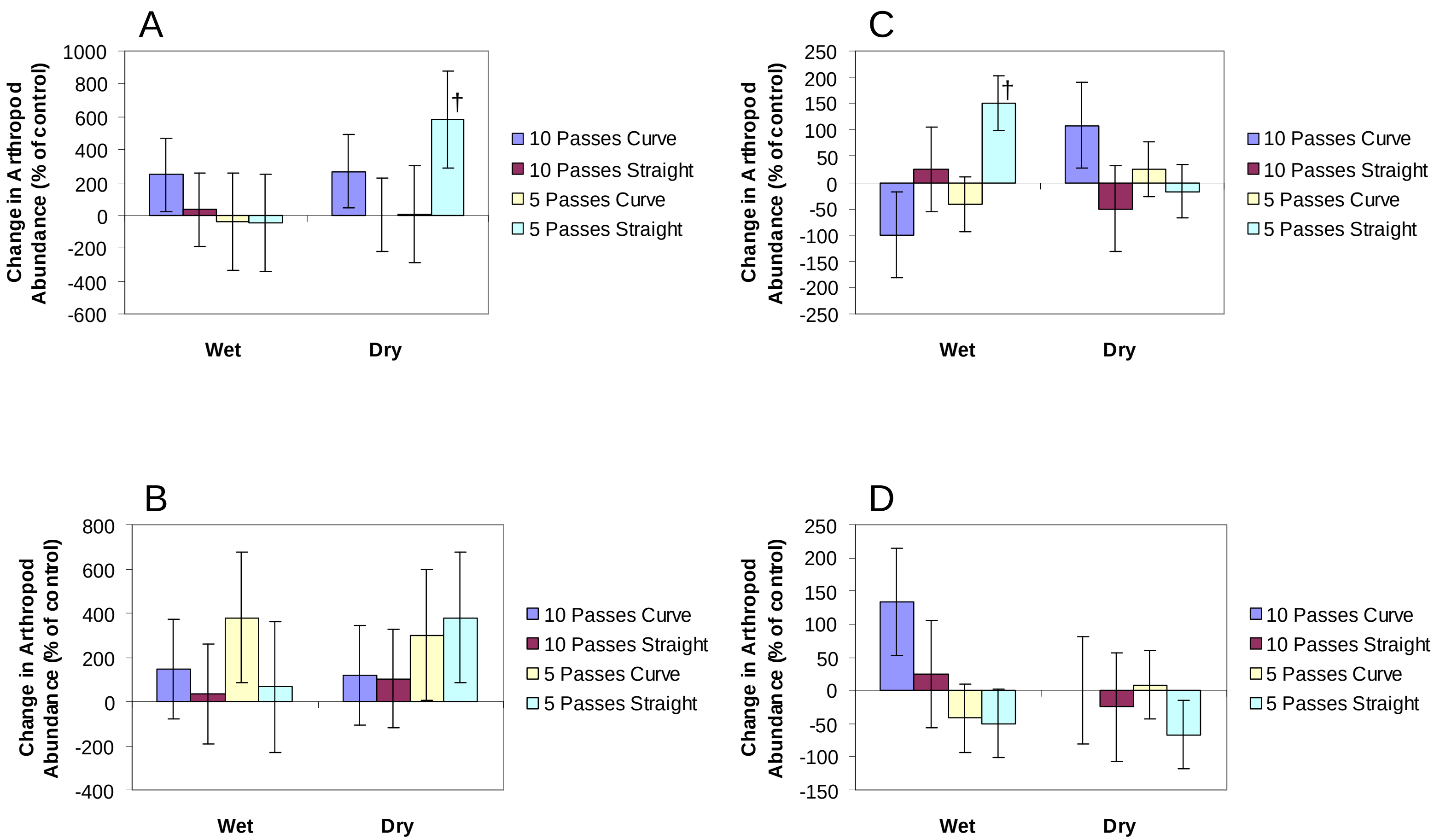


Figure 3.21. Disturbance response for macroarthropod abundance in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2007. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. † indicates $p \leq 0.10$. Macroarthropod abundance averaged 20 and 13 m^{-2} for burned and unburned controls, respectively, in silty clay loam soil and 17 and 7 m^{-2} for burned and unburned controls, respectively, in silt loam soil.

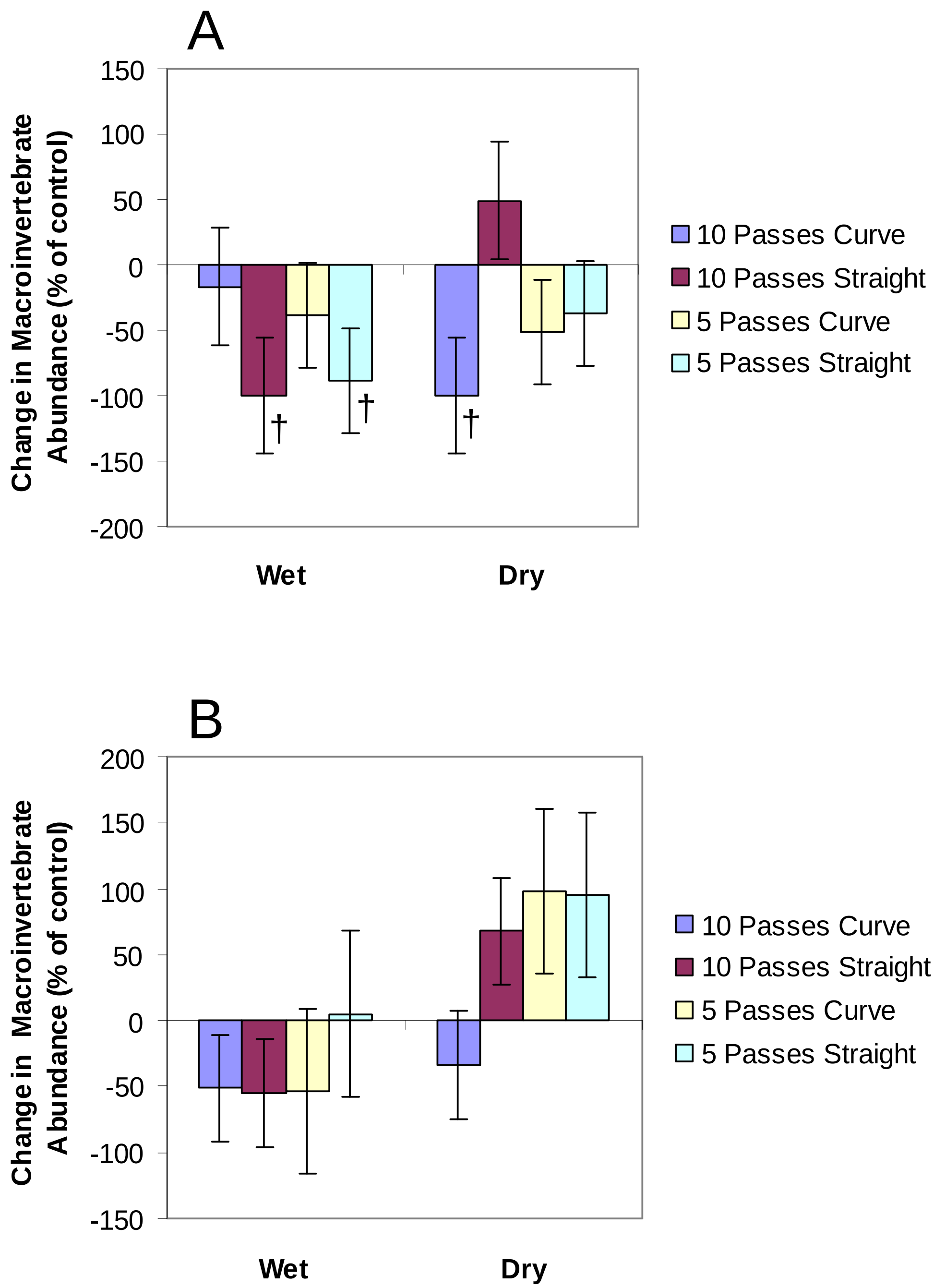


Figure 3.22. Disturbance response for macroinvertebrate abundance in (A) silty clay loam soil and (B) silt loam soil, 2005. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. † indicates $p \leq 0.10$. Macroinvertebrate abundance averaged 40 and 110 m^{-2} for controls in silty clay loam soil and silt loam soil, respectively.

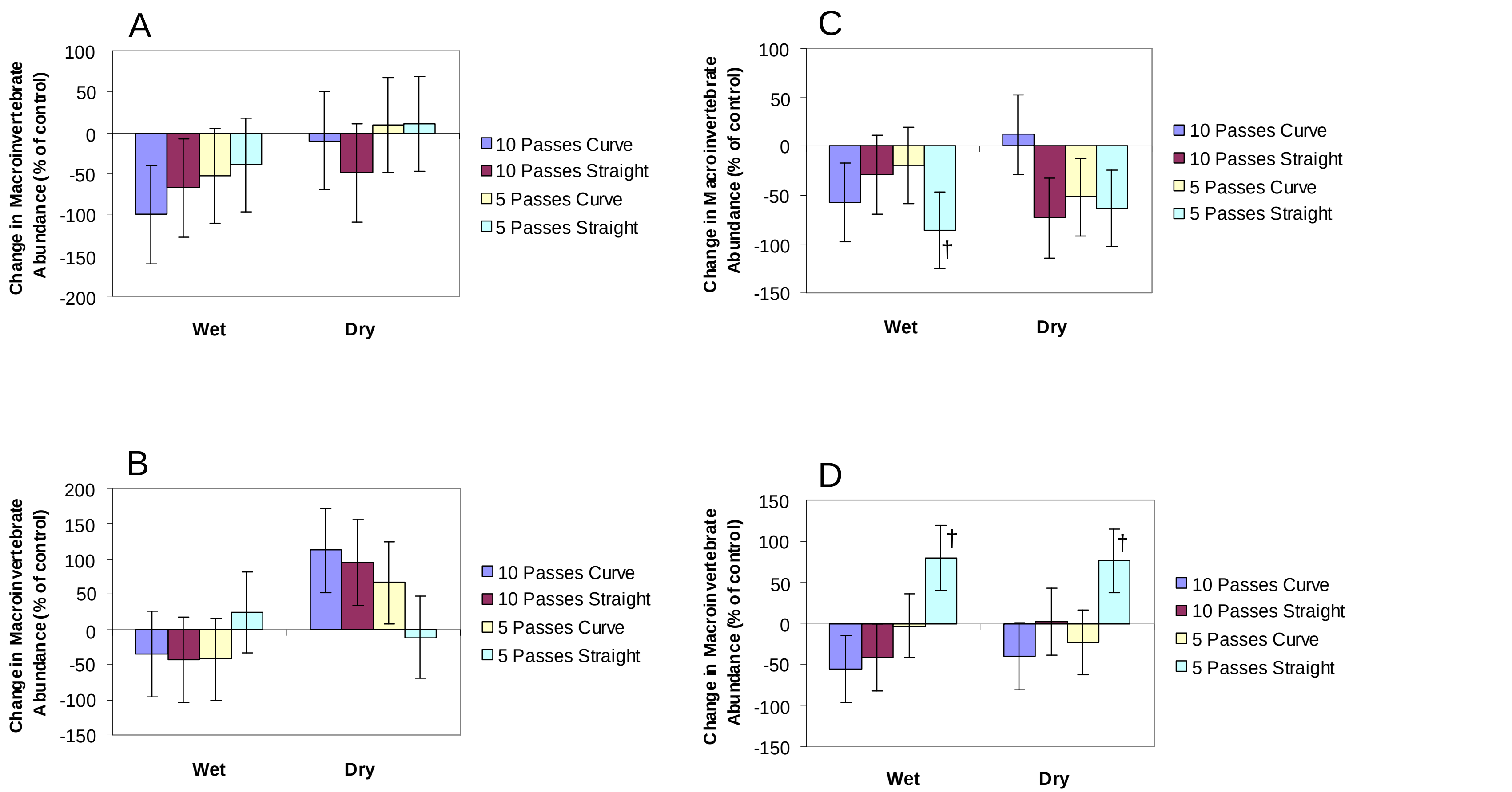


Figure 3.23. Disturbance response for macroinvertebrate abundance in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2006. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. † indicates $p \leq 0.10$. Macroinvertebrate abundance averaged 13 and 47 m^{-2} for burned and unburned controls, respectively, in silty clay loam soil and 70 and 147 m^{-2} for burned and unburned controls, respectively, in silt loam soil.

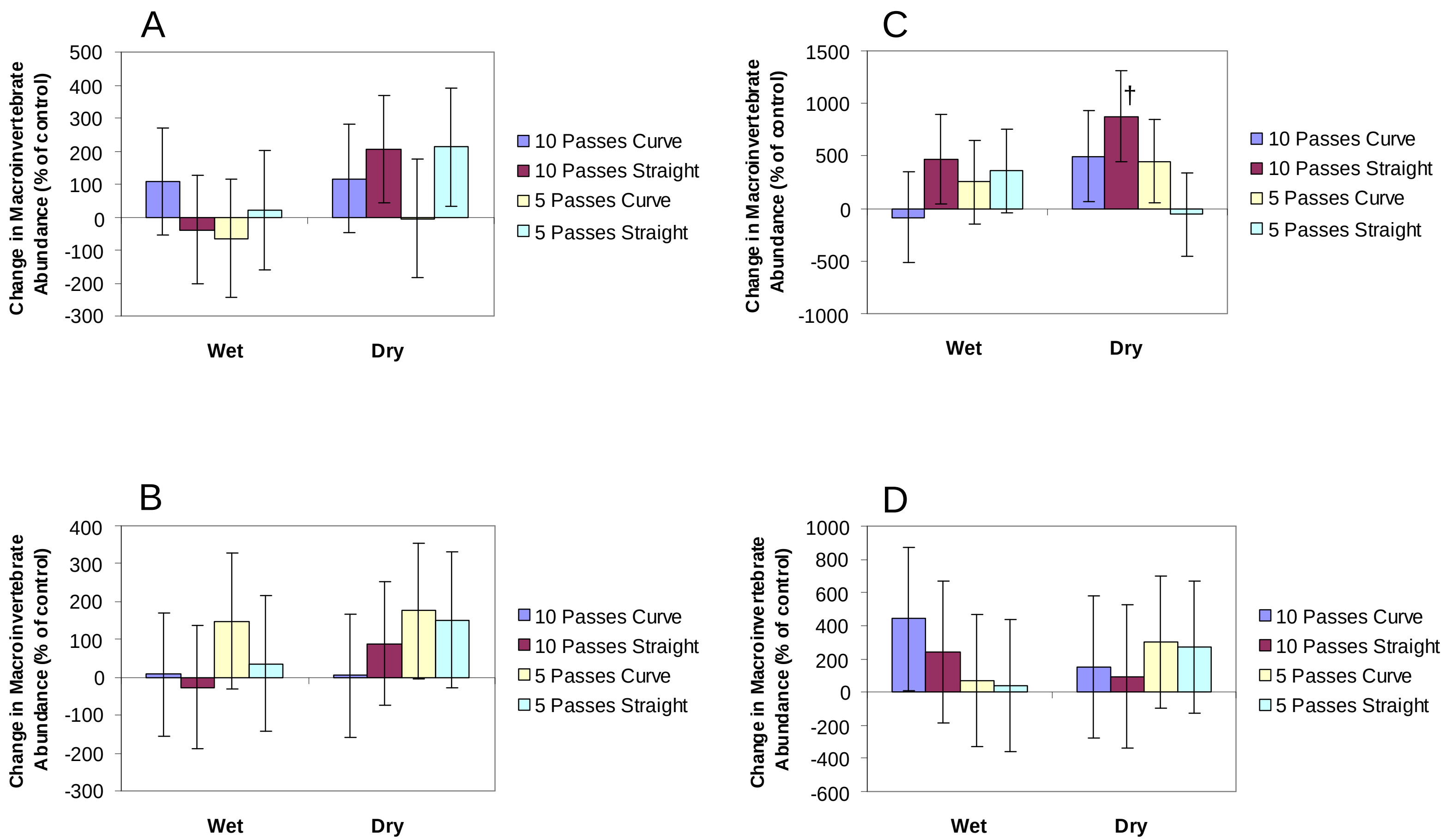


Figure 3.24. Disturbance response for macroinvertebrate abundance in (A) burned silty clay loam soil, (B) unburned silty clay loam soil, (C) burned silt loam soil and (D) unburned silt loam soil, 2007. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. † indicates $p \leq 0.10$. Macroinvertebrate abundance averaged 30 and 37 m^{-2} for burned and unburned controls, respectively, in silty clay loam soil and 40 and 67 m^{-2} for burned and unburned controls, respectively, in silt loam soil.

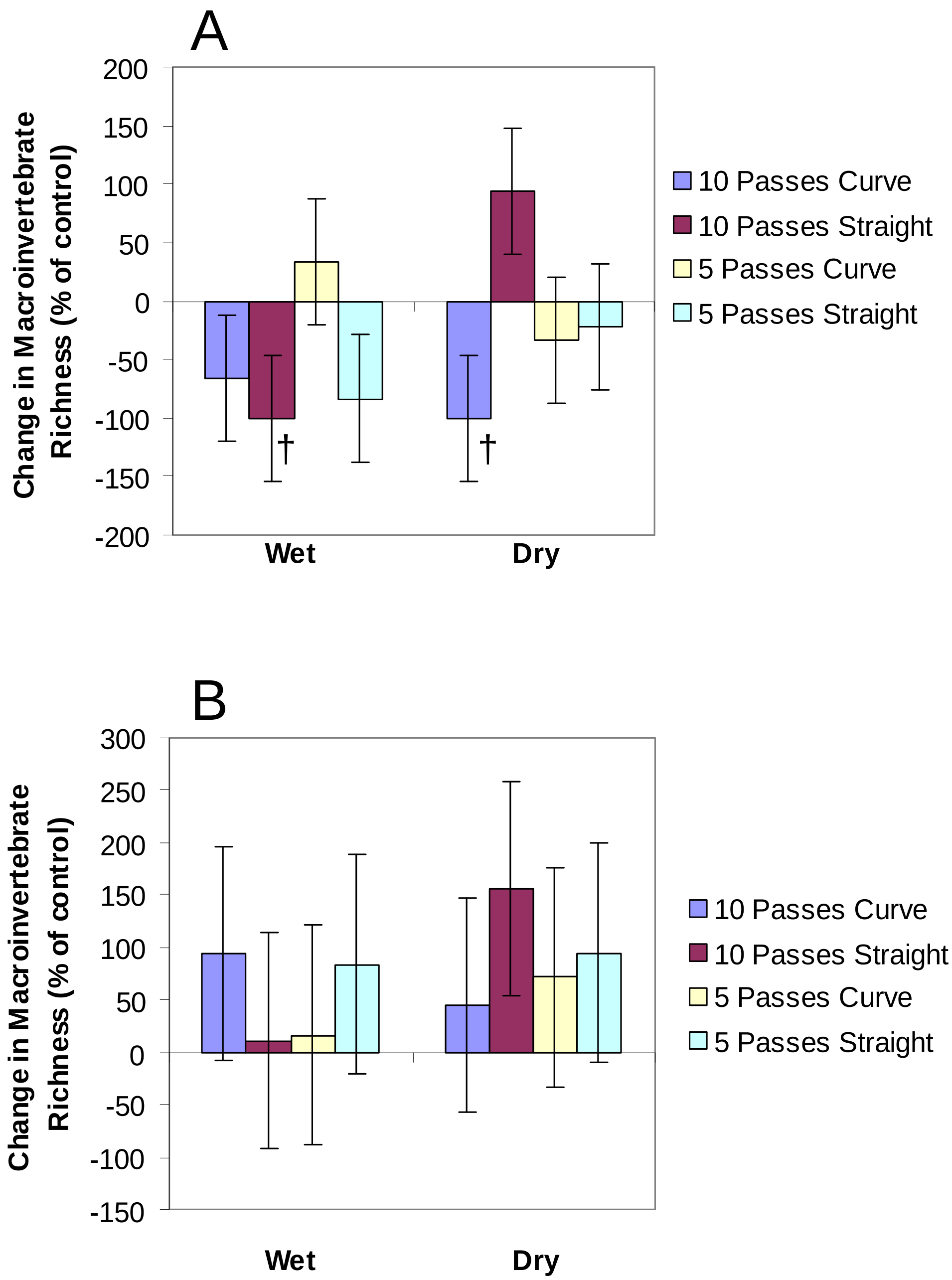


Figure 3.25. Disturbance response for macroinvertebrate richness in (A) silty clay loam soil and (B) silt loam soil, 2005. Disturbance treatments consisted of 5 passes (2003) or 10 passes (5 additional passes on one-half of the plot in 2004) with an Abrams M1A1 Main Battle Tank during wet and dry soil moisture conditions. Data are means ± standard error. † indicates $p \leq 0.10$. Macroinvertebrate richness averaged 2 and 3 for controls in silty clay loam soil and silt loam soil, respectively.

Table 3.1. Analysis of variance (F-values) for the disturbance response[A] of biological soil quality indicators in the silty clay loam and silt loam soils, 2005.

	F-values											
	Macroinvertebrates				Nematodes				Microbial biomass			
Effect[B]	Abundance		Richness		Abundance		Richness		Carbon		Nitrogen	
					Silty Clay Loam							
Treatment (T)	4.07		1.46		1.04		0.09		10.89	†	16.94	*
Split (S)	0.36		0.27		1.42		2.11		0.61		2.20	
T × S	0.11		1.68		0.15		0.00		0.02		0.00	
Area (A)	0.06		0.19		0.84		0.33		6.71	*	10.26	**
T × A	5.23	*	7.64	*	0.74		0.14		0.43		0.54	
S × A	0.60		4.30	†	0.53		7.87	*	0.62		0.01	
T × S × A	1.66		0.60		0.05		0.06		0.00		0.12	
					Silt Loam							
Treatment (T)	3.21		0.61		2.25		3.28		0.04		1.74	
Split (S)	3.71		0.04		9.01	*	1.69		1.95		4.38	†
T × S	0.82		0.02		2.93		4.86	†	0.02		0.01	
Area (A)	1.90		0.41		4.69	†	0.18		6.86	*	33.56	**
T × A	0.16		0.68		0.09		0.62		0.10		0.02	
S × A	0.14		0.11		0.76		6.06	*	3.12		2.05	
T × S × A	2.27		1.71		0.22		0.80		0.00		2.28	

[A] Disturbance response = (disturbed measurement-undisturbed measurement)/(undisturbed measurement).
[B] Represents treatment = (T) tank traffic during wet or dry soil conditions, (S) Split = half of the plot treated (i.e., 5 passes 2003, plus 5 additional passes, repeated traffic, 2004), or left untreated for 2004 (i.e., 5 passes single traffic, 2003), (A) Area = subplot from which sample was collected (i.e., curve, straight-a-way).
[†], *, ** Denotes significance at the $p \leq 0.10$, 0.05, 0.01 probability levels, respectively.

Table 3.2. Analysis of variance (F-values) for the disturbance response[A] of biological soil quality indicators in the silty clay loam soil, 2006.

	F-values									
	Macroinvertebrates			Nematodes				Microbial biomass		
Effect[B]	Abundance		Richness	Abundance	Richness			Carbon	Nitrogen	
Treatment (T)	4.65			0.09	0.19			0.37	4.57	
Split (S)	0.05			0.41	8.40	*		0.08	0.63	
T × S	0.59			2.15	42.18	**		0.59	2.27	
Area (A)	0.01			0.01	0.20			1.75	6.05	*
T × A	0.89			0.00	0.03			0.16	1.18	
S × A	0.02			1.34	2.67			0.05	0.64	
T × S × A	0.09			0.01	0.21			0.18	1.38	
Burn (B)	5.11	†		0.65	3.02			0.96	0.43	
T × B	0.44			0.54	1.61			0.00	0.30	
S × B	1.45			0.08	0.03			0.38	0.08	
T × S × B	0.12			0.01	0.00			0.16	0.33	
A × B	0.05			2.42	2.87			0.72	2.07	
T × A × B	0.12			0.52	0.10			1.45	0.92	
S × A × B	0.00			2.17	1.19			0.21	1.04	
T × S × A × B	0.88			2.15	0.15			0.69	0.84	

[A] Disturbance response = (disturbed measurement-undisturbed measurement)/(undisturbed measurement).
[B] Represents treatment = (T) tank traffic during wet or dry soil conditions, (S) Split = half of the plot treated (i.e., 5 passes 2003, plus 5 additional passes, repeated traffic, 2004), or left untreated for 2004 (i.e., 5 passes single traffic, 2003), (A) Area = subplot from which sample was collected (i.e., curve, straight-a-way).
[†], *, ** Denotes significance at the $p \leq 0.10$, 0.05, 0.01 probability levels, respectively.

Table 3.3. Analysis of variance (F-values) for the disturbance response[A] of biological soil quality indicators in the silt loam soil, 2006.

	F-values					
	Macroinvertebrates		Nematodes		Microbial biomass	
Effect[B]	Abundance	Richness	Abundance	Richness	Carbon	Nitrogen
Treatment (T)	0.11		0.21	1.66	0.15	0.19
Split (S)	1.54		0.25	0.99	0.00	0.56
T × S	0.58		3.66	4.30	0.13	0.37
Area (A)	0.52		5.17 †	2.04	0.77	7.95 *
T × A	0.01		0.25	4.14 †	0.21	0.10
S × A	0.53		0.41	1.90	0.06	6.37 *
T × S × A	1.23		0.03	1.03	0.00	1.54
Burn (B)	6.31 †		2.34	7.77 *	2.71	0.91
T × B	0.02		0.72	0.32	0.03	7.33 †
S × B	5.54 †		2.30	0.46	1.70	0.73
T × S × B	0.11		5.39 †	12.05 **	1.25	0.31
A × B	6.75 *		3.56	2.03	0.00	0.08
T × A × B	0.51		4.04 †	0.03	4.25	0.02
S × A × B	1.04		0.03	0.09	0.03	0.07
T × S × A × B	1.57		2.36	0.40	0.11	2.94

[A] Disturbance response = (disturbed measurement-undisturbed measurement)/(undisturbed measurement).
[B] Represents treatment = (T) tank traffic during wet or dry soil conditions, (S) Split = half of the plot treated (i.e., 5 passes 2003, plus 5 additional passes, repeated traffic, 2004), or left untreated for 2004 (i.e., 5 passes single traffic, 2003), (A) Area = subplot from which sample was collected (i.e., curve, straight-a-way).
[†], *, ** Denotes significance at the $p \leq 0.10$, 0.05, 0.01 probability levels, respectively.

Table 3.4. Analysis of variance (F-values) for the disturbance response[A] of biological soil quality indicators in the silty clay loam soil, 2007.

	F-values											
	Macroinvertebrates				Nematodes				Microbial biomass			
Effect[B]	Abundance		Richness		Abundance		Richness		Carbon		Nitrogen	
Treatment (T)	0.42				2.03		6.06		7.08		125.70	**
Split (S)	0.11				0.65		0.53		2.79		0.71	
T × S	0.00				0.17		0.02		10.74	*	1.18	
Area (A)	0.11				0.27		0.00		28.15	**	17.28	**
T × A	1.78				0.32		4.64	†	1.54		1.75	
S × A	0.14				0.02		0.11		0.70		0.24	
T × S × A	0.10				0.02		0.32		2.09		0.76	
Burn (B)	0.01				0.07		0.24		3.80		1.67	
T × B	0.35				0.14		0.24		4.95	†	1.42	
S × B	2.02				1.20		3.40		1.01		0.41	
T × S × B	0.01				0.04		0.35		13.21	*	0.05	
A × B	0.50				1.84		0.01		0.38		0.37	
T × A × B	0.14				1.07		0.00		1.70		0.07	
S × A × B	1.35				0.01		0.46		4.75	†	0.23	
T × S × A × B	0.03				0.01		2.28		4.46		0.72	

[A] Disturbance response = (disturbed measurement-undisturbed measurement)/(undisturbed measurement).
[B] Represents treatment = (T) tank traffic during wet or dry soil conditions, (S) Split = half of the plot treated (i.e., 5 passes 2003, plus 5 additional passes, repeated traffic, 2004), or left untreated for 2004 (i.e., 5 passes single traffic, 2003), (A) Area = subplot from which sample was collected (i.e., curve, straight-a-way).
[†], *, ** Denotes significance at the $p \leq 0.10$, 0.05, 0.01 probability levels, respectively.

Table 3.5. Analysis of variance (F-values) for the disturbance response[A] of biological soil quality indicators in the silt loam soil, 2007.

	F-values											
	Macroinvertebrates				Nematodes				Microbial biomass			
Effect[B]	Abundance		Richness		Abundance		Richness		Carbon		Nitrogen	
Treatment (T)	0.23				0.02		53.90	*	0.01		0.06	
Split (S)	0.38				0.55		0.00		0.26		0.56	
T × S	0.05				2.53		95.60	**	0.94		0.72	
Area (A)	0.02				1.34		0.81		3.93		15.97	**
T × A	0.37				0.45		0.79		0.27		0.02	
S × A	0.71				0.26		0.01		2.31		10.17	*
T × S × A	0.31				0.00		0.19		2.91		2.22	
Burn (B)	0.76				7.50	*	1.44		12.82	†	0.02	
T × B	0.49				0.90		0.01		0.17		1.32	
S × B	0.14				0.05		0.01		0.18		0.20	
T × S × B	4.04	†			2.02		1.18		2.29		0.19	
A × B	0.40				0.50		0.25		2.20		0.19	
T × A × B	0.77				0.10		1.18		0.15		0.08	
S × A × B	1.28				0.75		0.81		0.55		1.46	
T × S × A × B	0.08				1.57		1.71		0.53		12.28	*

[A] Disturbance response = (disturbed measurement-undisturbed measurement)/(undisturbed measurement).

[B] Represents treatment = (T) tank traffic during wet or dry soil conditions, (S) Split = half of the plot treated (i.e., 5 passes 2003, plus 5 additional passes, repeated traffic, 2004), or left untreated for 2004 (i.e., 5 passes single traffic, 2003), (A) Area = subplot from which sample was collected (i.e., curve, straight-a-way).

†, *, ** Denotes significance at the $p \leq 0.10$, 0.05, 0.01 probability levels, respectively.

CHAPTER 4 - Evaluation of Land Rehabilitation and Maintenance (LRAM) Practices Following Disturbance by a Light Medium Tactical Vehicle (LMTV)

Peggy S. Althoff, P.S. Gipson, S.J. Thien, T.C. Todd, and M.B. Kirkham.

Peggy S. Althoff, M.B. Kirkham, and S.J. Thien, Dept. Of Agronomy; T.C. Todd, Dept. Of Plant Pathology; P.S. Gipson, U.S.G.S. Kansas Cooperative Fish and Wildlife Research Unit, Kansas State University; Manhattan, KS, 66506.

For submission to Agronomy Journal.

ABSTRACT

The Land Rehabilitation and Maintenance (LRAM) Program, a component of the Army's Integrated Training Area Management (ITAM) Program, is responsible for repairing and maintaining military training lands. The goal of the LRAM Program is to ensure sustainable use of the land for future training while providing a safe and realistic training environment. A replicated small-plot study to evaluate the effectiveness of LRAM procedures following wheeled vehicle disturbance was initiated for the dominant soil types on Fort Riley in the tallgrass prairie of northeastern Kansas. The objectives were to compare LRAM practices including reseeding with native C_3 vs. C_4 mixes, and leveling and mulching, to determine if these practices improve the rate of recovery of selected soil quality indicators. Ten passes with a 2 t Light Medium Tactical Vehicle (LMTV) in a figure-eight pattern were made during wet soil conditions. Curve areas of each figure eight were divided into four plots randomly receiving one of the following remediation treatments: (1) disk leveling followed by mulching with approximately 2 t of prairie hay/acre, (2) leveling, followed by seeding of a C_3 grass mix at a rate of 7 g/m^2, followed by mulching, (3) leveling, followed by seeding of a C_4 grass mix also at a rate of 7 g/m^2, followed by mulching, or (4) no remediation. Soil compaction, plant production, and soil invertebrate (nematode) community structure were evaluated at the end of the first growing season. Significant compaction (compared to control plots) was observed for all treatments in the upper 5 cm depths for silty clay loam soil and in the upper 10 cm depths for silt loam soil but soil strength did not vary ($p > 0.05$) among treatments in either soil type. Total vegetation biomass in silt loam soil, but not silty clay loam soil, was improved ($p \leq 0.05$) for treatments that included leveling and mulching compared to the no remediation treatment. Total nematode abundance and family richness were not affected by any treatment in the silty clay loam soil but both were

reduced ($p \leq 0.10$) in plots receiving no remediation treatment compared to control plots in silt loam soil. The no remediation treatment was separated from all other treatments in the silt loam soil based on a lower proportion of herbivorous taxa and a higher proportion of fungivorous taxa, while all treatments had significantly greater proportions of bacterivorous taxa than control plots. Leveling produced immediate improvements in safety and erosion risks resulting from mechanized maneuvers. There also was evidence for enhanced recovery of vegetation biomass and soil function (e.g. food web structure) following leveling and mulching, but not reseeding, in the silt loam soil. More rapid recovery of above- and belowground prairie communities should result in greater sustainability in military training lands.

INTRODUCTION

Fort Riley is a premier training site for the Army's mechanized forces, with 29,542 ha of maneuver area available for battalion-level exercises. The Fort is located at the northern end of the Flint Hills, the largest remaining expanse tallgrass prairie. Much of the installation still is vegetated by native species including big bluestem (*Andropogon gerardii*), little bluestem (*Schizachyrium scoparium*), switchgrass (*Panicum virgatum*), and indiangrass (*Sorghastrum nutans*). The USDA Soil Conservation Service (1996) mapped 36 soil series on Fort Riley and taxonomically categorized them into six soil associations with many of these highly erodible. Heavy mechanized training has the potential to cause extensive damage to this ecosystem.

The Land Rehabilitation and Maintenance (LRAM) Program, a component of the Army's Integrated Training Area Management (ITAM) Program, is responsible for repairing and maintaining military training lands. This program is managed by United States Department of Agriculture, Natural Resources Conservation Service (USDA-NRCS) through a Memorandum of Agreement with Fort Riley. The primary objectives of the LRAM Program are to address the following land management concerns: troop safety, maneuver damage, and soil erosion. This ensures sustainable use of the land for future training while providing a safe and realistic training environment. Land management practices include grading and shaping, gully checks and riprap, and reseeding and mulching of damaged areas (Cales et al., 2006; US Army Environmental Center, 2006).

A replicated small-plot study to evaluate the effectiveness of LRAM procedures following wheeled vehicle disturbance was initiated for the dominant soil types on Fort Riley in 2007. The objectives were to compare LRAM practices including reseeding with native C_3 vs. C_4 mixes, and leveling and mulching, to determine if these practices improve the rate of recovery of selected soil quality indicators. This manuscript reports short-term (first year) recovery patterns for vegetation cover, soil compaction, and soil food web structure.

MATERIALS AND METHODS

Site Description

Research was conducted at Fort Riley Military Installation, an Army base in operation since 1853, located in Clay, Geary, and Riley counties in the Flint Hills of northeastern Kansas (39°15’N, 96°50’W) (Pride, 1997; McCale and Young, 2000). The installation, located in a mesic, tallgrass-prairie ecosystem, uses 29,542 ha (70,926 ac) of its 40,434 ha (100,656 ac) for maneuver training. The Flint Hills grasslands encompass more than 1.6 million ha, covering much of eastern Kansas from near the Kansas-Nebraska border south into northeastern Oklahoma, and contain the largest remaining areas of untilled tallgrass prairie in North America (Knapp and Seastedt, 1998). Hot summers and cold, dry winters characterize the climate. Mean monthly temperatures range from -2.7°C in January to 26.6°C in July. Annual precipitation averages 83.5 cm, with 75% of precipitation occurring during the growing season (Hayden, 1998). Fort Riley lands host three major vegetation communities: grasslands (ca. 32,200 ha), shrublands (ca. 6, 000 ha), and woodlands (ca. 1,600 ha). The soil at the study plots was classified as a Wymore series consisting of very deep, moderately drained, slowly or very slowly permeable soils that formed in loess (USDA, 1975). This soil series is found on most of the fort’s training area. Wymore soils are classified as fine, smectitic, mesic Aquertic Argiudolls.

Experimental Treatments

The disturbance treatment consisted of 10 passes with a 2.3 t Light Medium Tactical Vehicle (LMTV) in a figure-eight pattern during wet soil conditions on 17 April, 2007. Vehicle speed was maintained at 10 km/h (6 mph). Remediation treatments were arranged in a randomized complete block with three replications in each of two soil types (silty clay loam and silt loam soils). All plots were burned in April 2006.

Curve areas of each figure eight were divided into four plots randomly receiving one of the following remediation treatments: (1) disk leveling followed by mulching with approximately 2 t of prairie hay/acre, using a Haybuster^{TM} mulcher (2) leveling, followed by seeding of a C_3 grass mix [47 % *Bromus inermis* (smooth brome), 45% *Agropyron smithii* (western wheatgrass)] at a rate of 7 g/m^2, followed by mulching, (3) leveling, followed by seeding of a C_4 grass mix [21% *Sorghastrum nutans* (indiangrass), 19% *Bouteloua curtipendula* (sideoats grama), 15% *Andropogon gerardii* (bigbluestem), 16% *Schizachyrium scoparium* (little bluestem), 14% *Panicum virgatum* (switchgrass)] also at a rate of 7 g/m^2, followed by mulching, or (4) no remediation (Fig. 4.1). Grass seed was hand-broadcast in a designated 3-m × 3-m area of each curve.

Field Sampling and Laboratory Methods

All samples and measurements were collected from within the 3-m × 3-m subplots of each curve and from randomly selected areas of the same size within control plots. Ridge height and rut depth of LMTV tracks were measured from each curve area using a transit and surveying rod (Spectra Precision Laserplane 500c transit, Dayton, Ohio; Surveying Rod, Crain Enterprises I, Rod City, USA) immediately following disturbance. Ridge height and rut depth are defined as the difference between the undisturbed surface height and the ridge top and track pad, respectively.

A Fieldscout SC 900 Soil Compaction Meter (Spectrum Technologies, Inc.) was used to measure penetration resistance and compaction. The programmed rate for insertion speed was 5.06cm/2 seconds as specified by ASAE-recommended standards. The maximum load and default value was 113 kg. Measurements were collected on October 22, 2007.

Vegetation biomass was sampled on 9 October 2007, using the Daubenmire frame (20 cm x 50 cm) technique (Daubenmire, 1959). Living plant biomass was clipped, sorted into grass or forb categories, dried 48 hours at 40^{o}C, and weighed (Althoff and Thien, 2005). Plant species composition and percentage bare ground were estimated prior to clipping.

Four 2.5-cm diameter soil cores were collected to a depth of 15 cm from each subplot on 9 October 2007 and mixed uniformly. Nematodes were extracted from 100 cm^3 soil subsamples by using a standard centrifugal-flotation technique (Jenkins, 1964) and identified to the family level to estimate family richness as an indicator of diversity. In addition to total abundance and family richness, enrichment profiles of the nematode communities were constructed (Ferris and Bongers, 2006). The enrichment profile depicts the proportional contribution of the total nematode community to plant, fungal, and bacterial channels, and provides a tool for monitoring the structure and function of the soil food web.

Statistical Analyses

A disturbance effect index was calculated for all variables using the following formula: (*disturbed measurement-undisturbed measurement)/ (undisturbed measurement*).

This disturbance effect index was expressed as a percentage of the control and subjected to mixed-model analysis of variance using SAS (SAS Institute, Cary, NC, 2000). The data were analyzed as a randomized complete block design with three replications per soil type. The significance of the disturbance index was tested for individual treatment combinations using Least Squares Means (H_0: mean = 0).

RESULTS

Significant rutting was observed on curves of LMTV figure eights in both the silty clay loam and silt loam soils (Fig. 4.2), with the greatest disturbance observed for the outside track. Rut depth for the outside track was similar for both soils, averaging 11 cm (Fig. 4.3 A), while ridge height averaged 11 cm and 16 cm for the silty clay loam and silt loam soil, respectively (Fig. 4.3 B). Penetrometer measurements indicated that significant compaction also occurred in both soil types. Penetrometer resistance did not vary ($p > 0.05$) among treatments in either soil type, but significant compaction (compared to control plots) was observed for all treatments in the upper 5 cm depths for silty clay loam soil and in the upper 10 cm depths for silt loam soil (Fig. 4.4). Increases in resistance at these depths averaged 630% and 178% for silty clay loam and silt loam soil, respectively.

Total vegetation biomass in control plots averaged 14.8 g m^{-2} in silty clay loam soil and 16.1 g m^{-2} in silt loam soil. Grasses comprised 75% and 99% of total vegetation biomass in silty clay loam and silt loam soil, respectively. No significant effects on grass or forb biomass were observed for any treatments in either soil type, or for total vegetation biomass in silty clay loam soil at the end of the 2007 growing season (Fig. 4.5). Total vegetation biomass in silt loam soil, however, was reduced ($p \leq 0.05$) for the no remediation treatment compared to treatments that included leveling and mulching (Fig. 4.5 C). No effects of seeding with either a cool-season C_3 or warm-season C_4 grass mix were observed after the first growing season.

Basal cover was not affected by remediation treatment in either soil type (Fig. 4.6 A), nor was plant species richness in the silty clay loam soil (Fig. 4.6 B). Species richness in the silt loam soil, however, was increased ($p \leq 0.05$) by reseeding with either a C_3 or a C_4 mix (Fig. 4.6 B). Table 4.1 includes a list of species found in each treatment. One or more of the dominant C4 tallgrass prairie grasses were present in all treatments regardless of reseeding. *Andropogon gerardii* frequently was the dominant grass present, particularly for the silt loam soil.

Total nematode abundance in control plots averaged 0.83 million m^{-2} in silty clay loam soil and 1.25 million m^{-2} in silt loam soil. Nematode family richness averaged 15 and 12 in silty clay loam and silt loam soil, respectively. Total nematode abundance and family richness were not affected by any treatment in the silty clay loam soil but both were reduced ($p \leq 0.10$) in plots receiving no remediation treatment compared to control plots in silt loam soil (Fig. 4.7). Nematode family richness in this treatment also generally was reduced ($p \leq 0.14$) compared to treatments that included leveling and mulching (Fig. 4.7 B). In enrichment profiles, the no remediation treatment was separated from all other treatments in the silt loam soil based on a lower proportion of herbivorous taxa and a higher proportion of fungivorous taxa (Fig. 4.8 B). All treatments had significantly greater proportions of bacterivorous taxa than control plots. As for vegetation biomass, no effects of seeding with either a cool-season C_3 or warm-season C_4 grass mix were observed.

DISCUSSION

As for the Abrams M1A1 tank (Althoff, 2005; Chapter 1 this Dissertation), severe rutting was observed for curve areas of the LMTV figure-eight track. Axle load is a major factor influencing rut depth for wheeled vehicles (Raper, 2005). In the silty clay loam and silt loam soils of Fort Riley, rut depth was equivalent between the tracked 57-t Abrams and the wheeled 2.3-t LMTV for the same number of passes and soil moisture conditions. Levels of compaction, as measured by penetrometer resistance, also were similar between these two vehicles. Both greater and similar soil pressures have been measured for wheeled vehicles compared to tracked vehicles of similar mass in agricultural soils (Taylor and Burt, 1975; Turner et al., 1997).

No effects of wheeled vehicle traffic or differences among remediation treatments were observed for above- or belowground biological indicators in silty clay loam soil. LMTV traffic in silt loam soil reduced ($p \leq 0.1$) both nematode abundance and family richness in the absence of remediation. In contrast, the same number of passes with an Abrams M1A1 tank during wet soil conditions reduced ($p \leq 0.05$) nematode abundance and family richness an equivalent amount in both silty clay loam and silt loam soils (Althoff, 2005). Remediation benefits also were observed in the silt loam soil, particularly for plant production. The combination of leveling and mulching increased ($p \leq 0.05$) total vegetation biomass over the no remediation treatment regardless of reseeding, suggesting that there may not be a benefit to the latter. Grasses have the greatest resistance and resilience to vehicle traffic impacts among plant forms (Yorks et al., 1997), and within the grasses, the ability to produce rhizomes enhances recovery (Palazzo et al., 2005). Because the dominant grasses of the tallgrass prairie are rhizomatous, it appears that reseeding is not necessary for reestablishment. The results of this study are preliminary, however, and any conclusions should be drawn with caution.

Land leveling has been observed to increase nutrient content and decrease organic matter content, as well as alter the relationships between soil chemical properties and microbial biomass (Brye et al., 2004). Microbial biomass was not measured directly in the present study, but observed changes in nematode community composition likely reflected the combined effects of vehicle disturbance and remediation procedures on microbial populations. The benefits of leveling (reduced surface rutting and erosion, in this case) must be weighed against its potential effects on soil properties and processes (Brye et al., 2004).

The goal of the LRAM program is to reduce long-term impacts of military training through improvements to vegetative cover and repairs to landscape damage (Cales et al., 2006; US Army Environmental Center, 2006). The remediation procedures utilized in this study did produce immediate improvements in safety and erosion risks from rutting due to mechanized maneuvers (i.e., disking levels rutted areas). There also was evidence for enhanced recovery of vegetation biomass and, thus aerial, if not basal, cover in the silt loam soil. Vertical vegetation structure in turn provides increased surface protection and reduces soil loss through erosion (Grantham et al., 2001). Reseeding did not have an effect on plant biomass but did appear to increase species richness in the silt loam soil, although since the seeded species were present in most plots, the apparent increase in species richness is more likely due to the leveling and mulching effects. Productivity, stability, and resilience have been hypothesized to increase with the diversity of ecosystems (Giller et al., 1997). Although diversity was not measured directly in this study, increased species richness resulting from remediation procedures could promote more rapid recovery of the plant community and, subsequently, soil structure and function.

ACKNOWLEDGEMENTS

Funding for this project was provided by the U.S. Army Military Installation, Integrated Training Area Management (ITAM) Program. I thank Philip B. Woodford (ITAM) Coordinator, Chris Otto, (ITAM), Lee Breidenstein (Range Control), Tony Davis, Troy Livingston, (GPS), Fred Siebe and staff (MPRC Gunnery Complex), and LMTV crew from Fort Riley Military Installation, for their effort and support. I am indebted to Monte Cales (NRCS, Fort Riley) for his assistance in the collection of rut depth measurements, and for disking and haying plots. Finally, I appreciate Dr. Paul Ayers (University of Tennessee) for providing a back-up penetrometer for the soil strength measurements and analyses.

REFERENCES

Althoff, P.S. 2005. Evaluation of soil quality indicators following disturbance by an Abrams M1A1 Main Battle Tank. M.S. Thesis. Kansas State University, Manhattan, KS, 136 pp.

Althoff, P.S., and S.J. Thien. 2005. Impact of M1A1 main battle tank disturbance on soil quality, invertebrates, and vegetation characteristics. Journal of Terramechanics 42:159-176.

Brye, K.R., N.A. Slaton, M. Mozaffari, M.C. Savin, R.J. Norman, and D.M. Miller. 2004. Short-term effects of land leveling on soil chemical properties and their relationships with microbial biomass. Soil Science Society of America Journal 68:924-934.

Cales, M., P.B. Woodford, and C. Otto. 2006. Fort Riley: Land Rehabilitation and Maintenance (LRAM). 15th Annual ITAM Workshop Manhattan, Kansas.

Daubenmire, R. 1959. Measurement of species diversity using canopy coverage classes. Northwest Science 3:43-66.

Ferris, H., T. Bongers, and R.G.M. de Goede. 2001. A framework for soil food web diagnostics: extension of the nematode faunal analysis concept. Applied Soil Ecology 18:13-29.

Giller, K.E., M.H. Beare. P. Lavelle, A.N. Izac, and M.J. Swift. 1997. Agricultural intensification, soil biodiversity and agroecosystem function. Applied Soil Ecology 6:3-16.

Grantham, W.P., E.F. Redente, C.F. Bagley, and M.W. Paschke. 2001. Tracked vehicle impacts to vegetation structure and soil erodibility. Journal of Range Management 4:711-716.

Hayden, B.P. 1998. Regional climate and the distribution of tallgrass prairies. Pp 19-34 *In* A.K. Knapp, J.M. Briggs, D.C. Hartnet, and S.L. Collins (eds.), Grassland dynamics: long-term ecological research in tallgrass prairie. Oxford University Press, NY, NY, USA.

Jenkins, W.R. 1964. A rapid centrifugal-flotation technique for separating nematodes from soil. Plant Disease Reporter 48:692.

Knapp, A.K., and T.R. Seastedt. 1998. Grasslands, Konza Prairie, and long-term ecological research. Pp 3-15 *In* A.K. Knapp, J.M. Briggs, D.C. Hartnet, and S.L. Collins (eds.), Grassland dynamics: long-term ecological research in tallgrass prairie. Oxford University Press, NY, NY, USA.

McKale, W., and W.D. Young. 2000. Fort Riley Citadel of the Frontier West, Kansas State Historical Society Topeka, Kansas.

Palazzo, A.J., K.B. Jensen, B.L. Waldron, and T.J. Cary. 2005. Effect of tank tracking on range grasses. J. Terramechanics 42:177-191.

Pride, W.F. The History of Fort Riley. 1997. Manhattan, KS: U.S. Cavalry Museum and Fort Riley Historical and Archaeology Society.

Raper, R.L. 2005. Agriculture traffic impacts on soil. Journal of Terramechanics 42:259-280.

SAS Institute Inc. 2000. SAS/STAT user's guide. Version 9.01. SAS Institute Inc., Cary NC, USA.

Taylor, J.H. and E.C. Burt. 1975. Track and tire performance in agricultural soils. Transactions SAE 8:3-6.

Turner, R.J., L.R. Shell, and F.M. Zoz. 1997. Field performance of rubber belted and MFWD tractors in Southern Alberta soils. Belt and tire traction in agricultural vehicles. Warrendale (PA): Society of Automotive Engineers. Pp 75-85.

US Army Environmental Center. 2006. Sustainable range program: Range and training land assessment program. https://srp.army.mil/itam/rtla.

USDA, Soil Conservation Service in cooperation with Kansas Agricultural Experiment Station. 1975. Soil Survey of Riley and Part of Geary County, Kansas.

Yorks, T.P., N.E. West, R.J. Mueller, and S.D. Warren. 1997. Toleration of traffic by vegetation: Life form conclusions and summary extracts from a comprehensive data base. Environmental Management 21:121-131.

Figure 4.1. Implementing Land Rehabilitation and Maintenance (LRAM) repairs on curve areas of Light Medium Tactical Vehicle (LMTV). (A) Disking, (B) mulching with prairie hay, (C) reseeding with native grass, and (D) production following one growing season.

Figure 4.2. Effect of 10 passes by a Light Medium Tactical Vehicle (LMTV) on (A) silty clay loam and (B)silt loam soils during wet conditions.

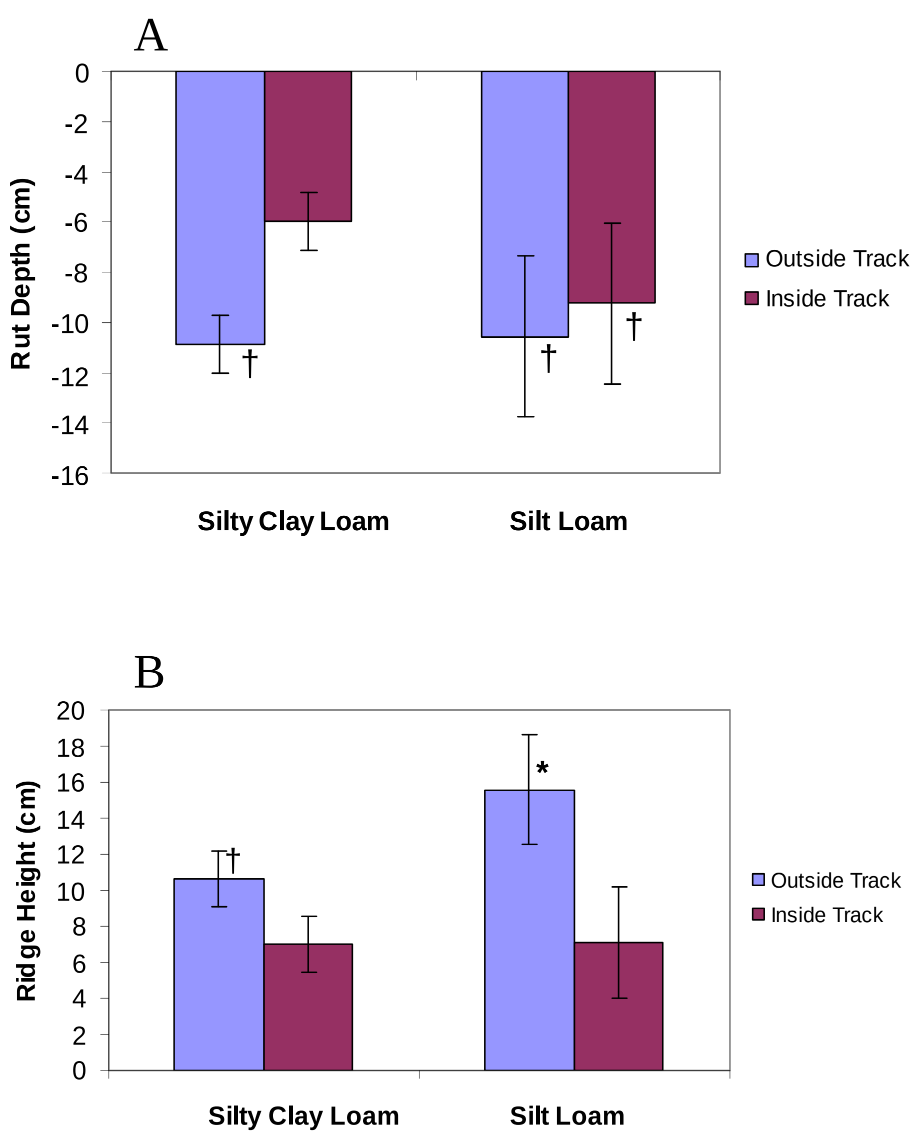


Figure 4.3. Soil disturbance from 10 passes with a wheeled Light Medium Tactical Vehicle (LMTV) during wet soil conditions in silty clay loam and silt loam soils. Transit measurements for (A) rut depth and (B) ridge height. Data are means ± standard error. †, * indicate $p \leq 0.10, 0.05$, respectively.

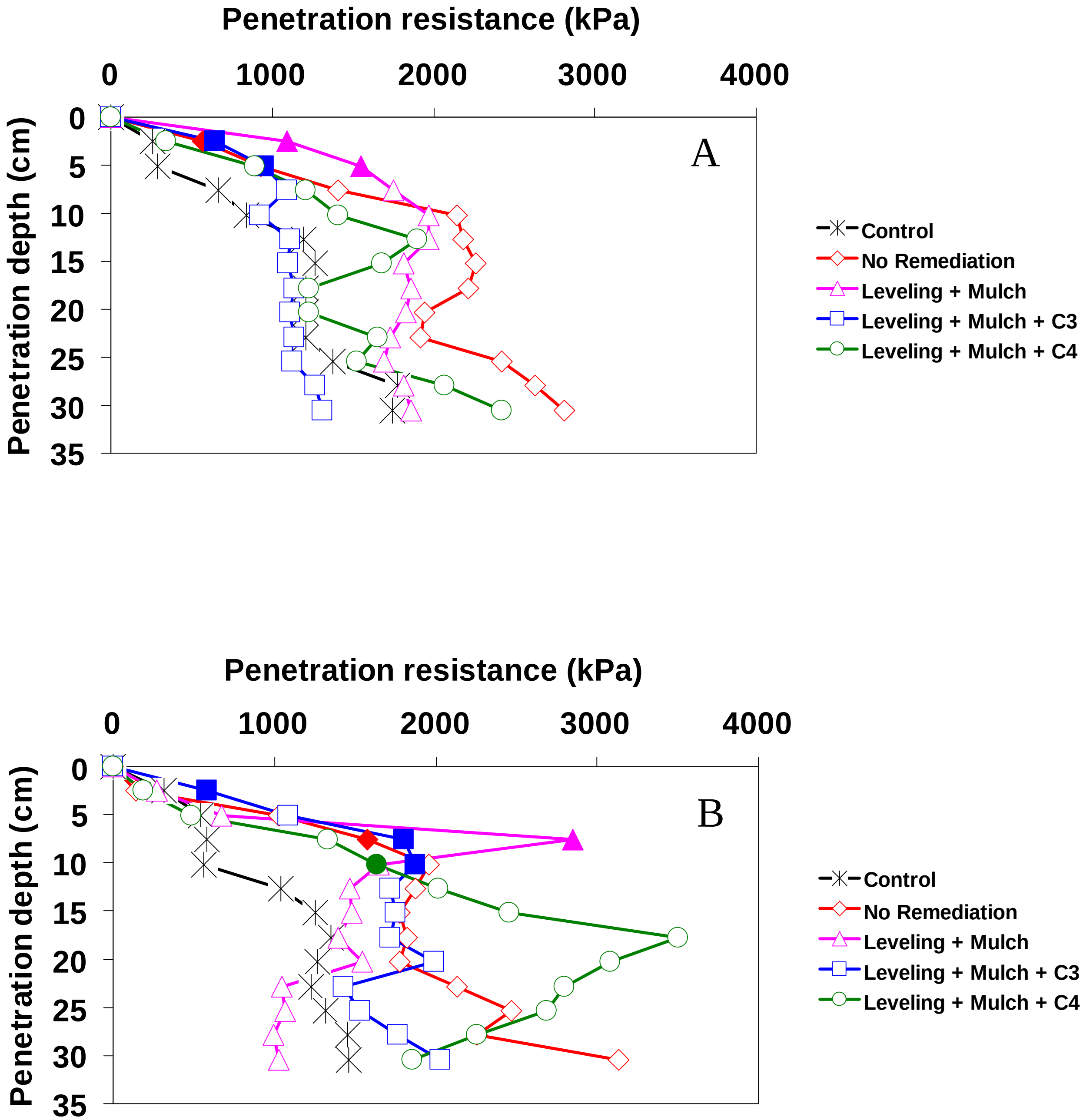


Figure 4.4. Effect of LRAM procedures on penetrometer resistance following 10 passes with a wheeled Light Medium Tactical Vehicle (LMTV) during wet soil conditions in (A) silty clay loam and (B) silt loam soils. Filled symbols indicate significant difference from the control at that depth ($p \leq 0.05$).

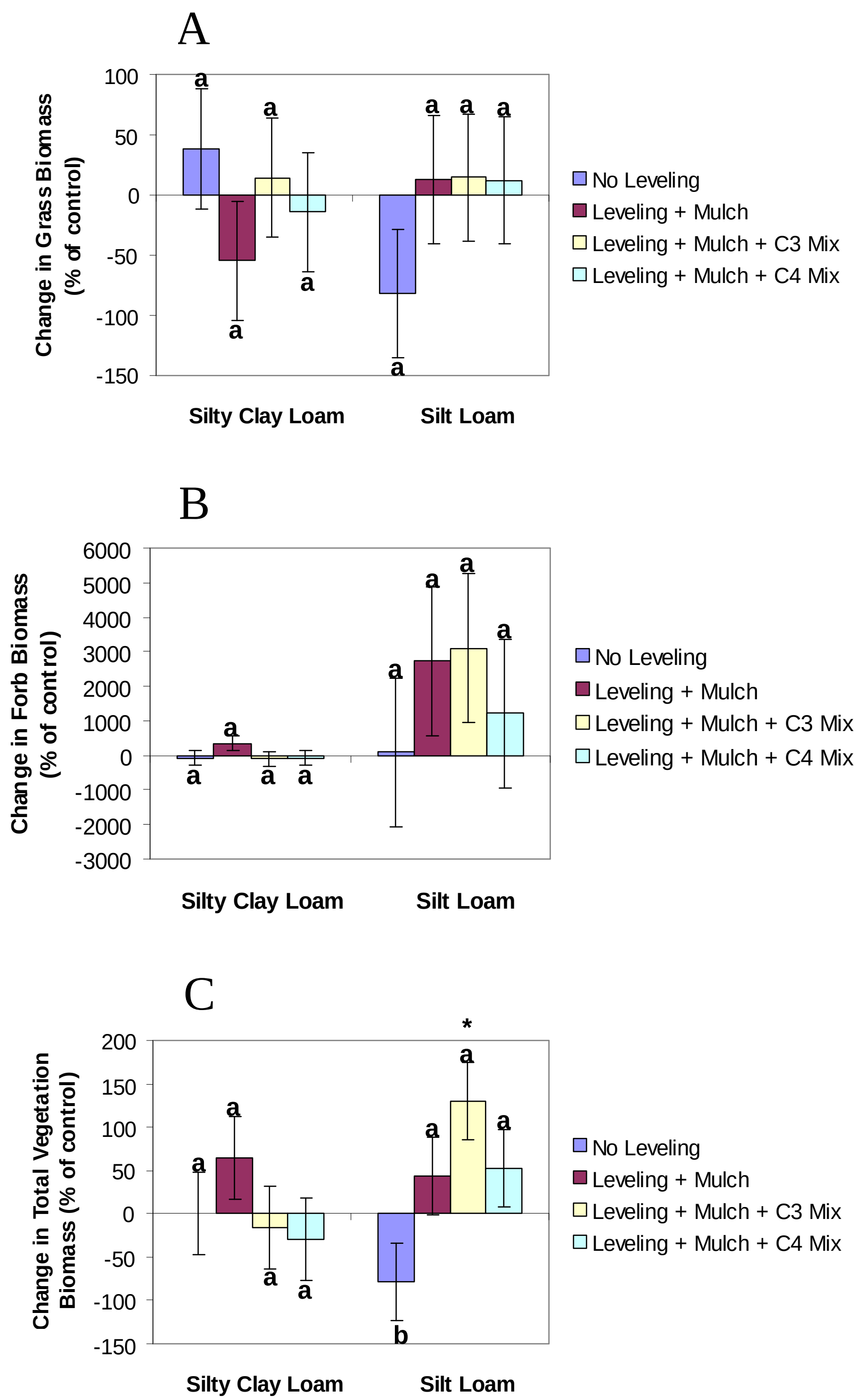
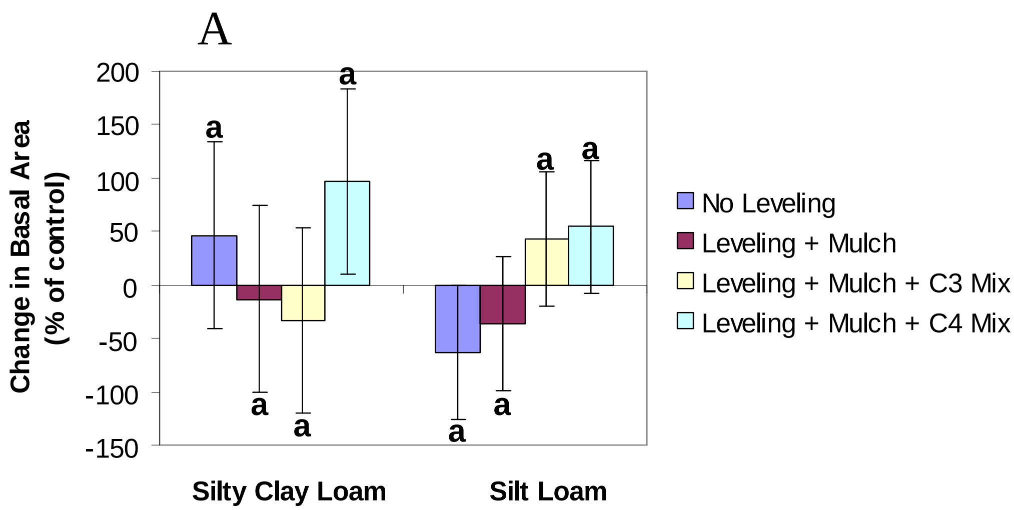


Figure 4.5. Effect of LRAM procedures on disturbance response for (A) grass biomass, (B) forb biomass, and (C) total vegetation biomass following 10 passes with a wheeled Light Medium Tactical Vehicle (LMTV) during wet soil conditions in silty clay loam and silt loam soils. Data are means ± standard error. * indicates a significant difference from the control at $p \leq 0.05$. Treatments within soil type with the same letter are not significantly different at $p \leq 0.05$. Grass, forb, and total biomass averaged 111, 37, and 148 g m^{-2}, respectively, for controls in silty clay loam soil and 160, 2, and 161 g m^{-2}, respectively, for controls in silt loam soil.



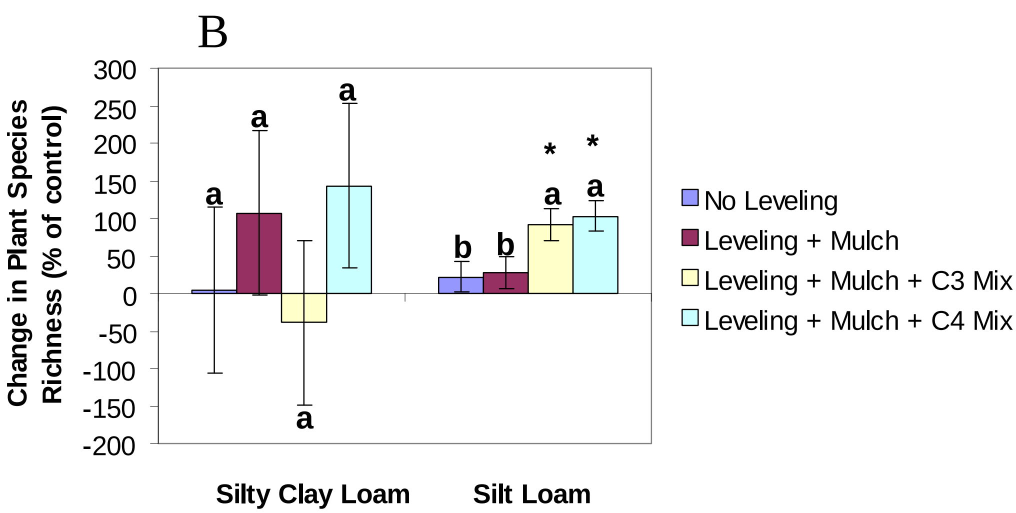


Figure 4.6. Effect of LRAM procedures on disturbance response for (A) basal area and (B) plant species richness following 10 passes with a wheeled Light Medium Tactical Vehicle (LMTV) during wet soil conditions in silty clay loam and silt loam soils. Data are means ± standard error. * indicates a significant difference from the control at $p \leq 0.05$. Treatments within soil type with the same letter are not significantly different at $p \leq 0.05$. Basal area averaged 5 and 7 % for controls in silty clay loam soil and silt loam soil, respectively. Species richness averaged 5 and 4 for controls in silty clay loam soil and silt loam soil, respectively.

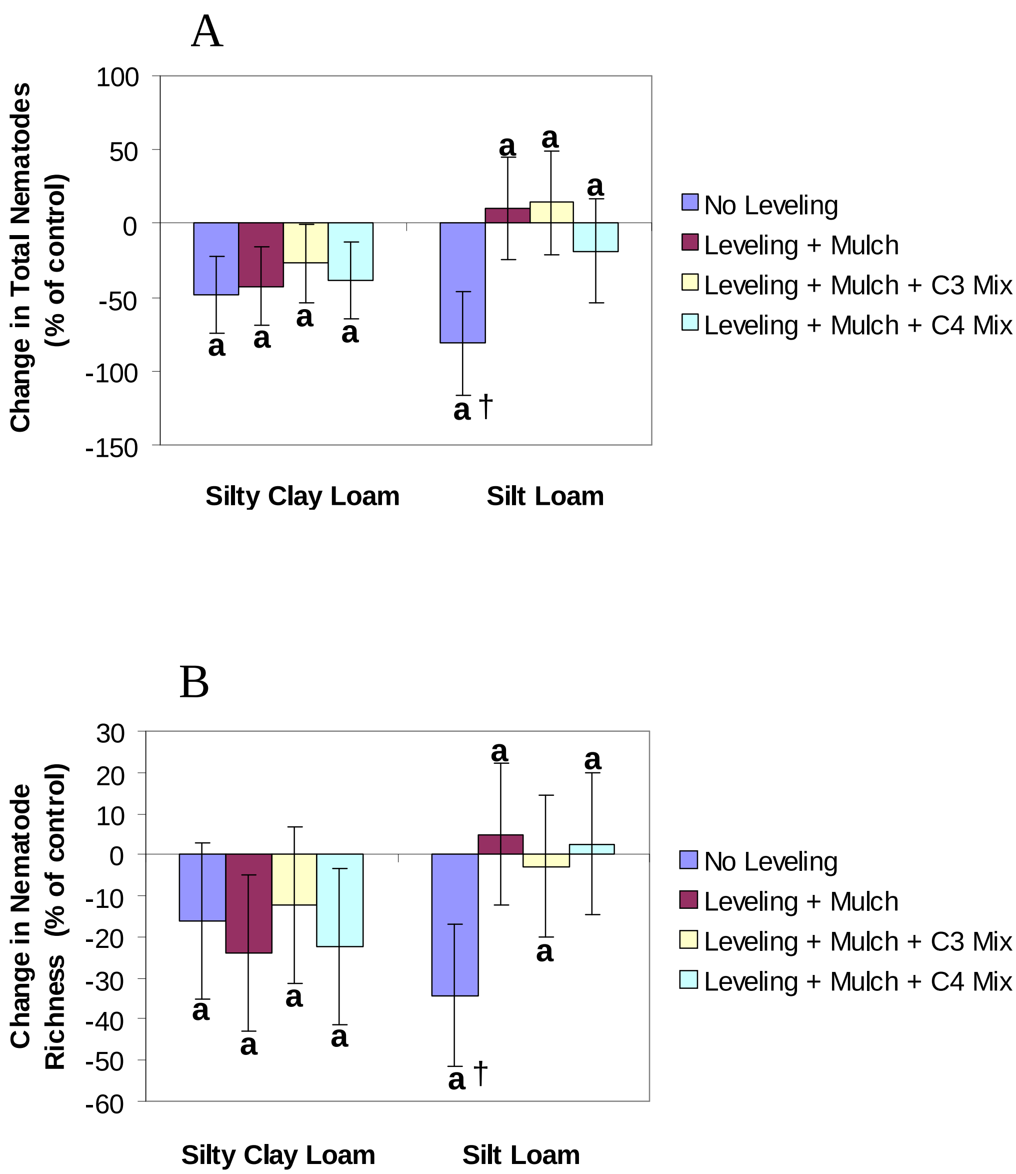


Figure 4.7. Effect of LRAM procedures on disturbance response for (A) nematode abundance and (B) family richness following 10 passes with a wheeled Light Medium Tactical Vehicle (LMTV) during wet soil conditions in (A) silty clay loam and (B) silt loam soils. Data are means ± standard error. † indicates a significant difference from the control at $p \leq 0.10$. Treatments within soil type with the same letter are not significantly different at $p \leq 0.05$. Nematode abundance averaged 0.95 and 1.28 million m^{-2} for controls in silty clay loam soil and silt loam soil, respectively. Species richness averaged 15 and 12 for controls in silty clay loam soil and silt loam soil, respectively.

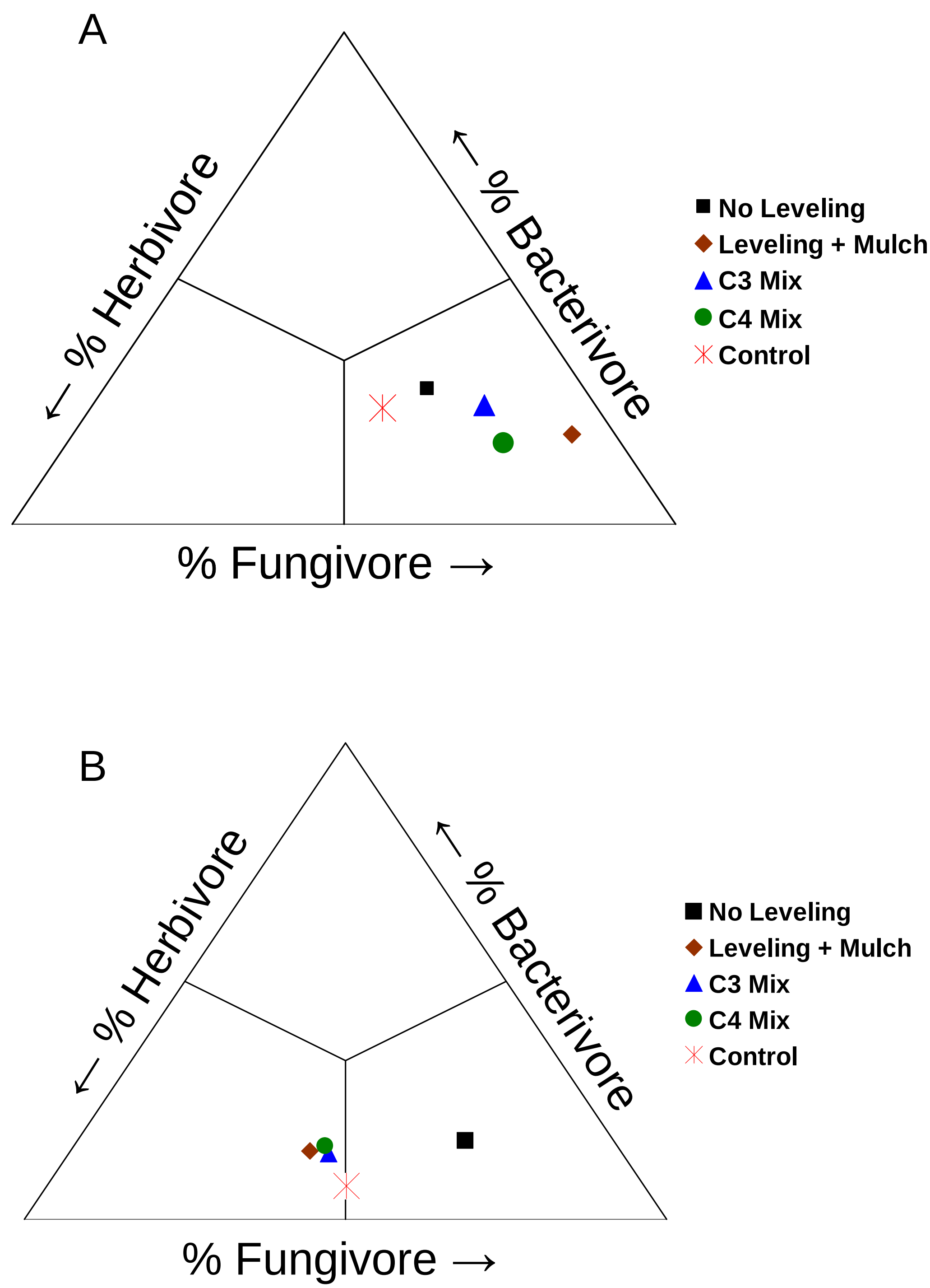


Figure 4.8. Effect of LRAM procedures on nematode enrichment profiles in (A) silty clay loam and (B) silt loam soil following 10 passes with a wheeled Light Medium Tactical Vehicle (LMTV) during wet soil conditions.

Table 4.1. Plant species identified from LRAM plots 6 months following disturbance with a wheeled Light Medium Tactical Vehicle (LMTV) during wet soil conditions in silty clay loam and silt loam soils.

Treatment				
Control	No Remediation	Leveling and Mulching	Leveling, Mulching, C_3	Leveling, Muching, C_4
		Silty Clay Loam		
Achillea millefolium	*Agropyron smithii*	*Agropyron smithii*	*Andropogon gerardii*	*Andropogon gerardii*
Ambrosia spp.	*Ambrosia* spp.	*Andropogon gerardii*	*Bromus* spp.	*Ambrosia* spp.
Aster ericoides	*Artemisia ludoviciana*	*Aster ericoides*	*Desmanthus illinoensis*	*Aristida oligantha*
Bromus spp.	*Bromus* spp.	*Bouteloua curtipendula*	*Panicum virgatum*	*Aster ericoides*
Carex spp.	*Carex spp.*	*Bromus* spp.	*Solidago* spp.	*Bouteloua curtipendula*
Cassia chamaecrista	*Euphorbia spp.*	*Cassia chamaecrista*		*Bromus* spp.
Koeleria macrantha	*Panicum dichotomilflorum*	*Chloris verticillata*		*Dichanthelium oligosar*
Lespedeza cuneata	*Panicum virgatum*	*Convolvulus arvensis*		*Kuhnia eupatorioides*
Schizachyrium scoparium	*Schizachyrium scoparium*	*Croton texensis*		*Panicum virgatum*
Sorghastrum nutans	*Sorghastrum nutans*	*Dichanthelium oligosanthes*		*Setaria viridis*
Sporobolus asper	*Sporobolus asper*	*Lespedeza stipulacea*		*Schizachyrium scopari*
		Panicum virgatum		*Sorghastrum nutans*
		Schizachyrium scoparium		*Sporobolus asper*
		Solidago spp.		
		Sorghastrum nutans		
		Silt Loam		
Andropogon gerardii	*Andropogon gerardii*	*Andropogon gerardii*	*Andropogon gerardii*	*Andropogon gerardii*
Bouteloua curtipendula	*Antennaria neglecta*	*Aster ericoides*	*Antennaria neglecta*	*Artemisia ludoviciana*
Bromus spp.	*Artemisia ludoviciana*	*Bouteloua curtipendula*	*Artemisia ludoviciana*	*Aster ericoides*
Carex spp.	*Aster ericoides*	*Bromus* spp.	*Aster ericoides*	*Bouteloua curtipendula*
Dichanthelium oligosanthes	*Bromus* spp.	*Carex spp.*	*Bromus* spp.	*Bromus* spp.
Kuhnia eupatorioides	*Carex spp.*	*Melilotus officinalis*	*Carex spp.*	*Carex spp.*
Schizachyrium scoparium	*Ruellia humilis*	*Panicum dichotomilflorum*	*Dichanthelium oligosanthes*	*Panicum dichotomilflor*
Solidago spp.	*Schizachyrium scoparium*	*Schizachyrium scoparium*	*Panicum dichotomilflorum*	*Ruellia humilis*
Sorghastrum nutans	*Sporobolus asper*	*Solidago* spp.	*Ruellia humilis*	*Schizachyrium scopari*
		Sporobolus asper	*Schizachyrium scoparium*	*Setaria viridis*
		Veronia baldwinii	*Solidago* spp.	*Solidago* spp.
			Sorghastrum nutans	*Sorghastrum nutans*
			Sporobolus asper	*Sporobolus asper*
			Sporobolus cryptandrus	*Tridens flavus*

Appendix A - Treatment Means and Standard Errors

Table A.1. Treatment absolute means and standard errors for grass biomass (g m^{-2}) in silty clay loam and silt loam soils, 2005 – 2007.

	2005	2006		2007	
Treatment	Unburned	Burned	Unburned	Burned	Unburned
			Silty Clay Loam		
Dry 10 laps Cu	1.0 ± 0.8	53.9 ± 34.4	64.8 ± 35.3	31.6 ± 13.8	60.2 ± 26.0
Dry 10 laps St	37.4 ± 8.3	156.1 ± 26.7	117.5 ± 11.8	83.0 ± 32.9	70.5 ± 29.8
Dry 5 laps Cu	47.3 ± 34.6	59.1 ± 27.6	43.7 ± 26.9	162.3 ± 42.7	39.7 ± 24.4
Dry 5 laps St	64.2 ± 21.0	67.7 ± 30.5	91.1 ± 27.8	167.0 ± 9.4	198.6 ± 12.7
Wet 10 laps Cu	16.0 ± 10.5	64.6 ± 53.9	59.4 ± 33.3	30.6 ± 9.1	11.2 ± 3.0
Wet 10 laps St	35.0 ± 21.7	132.7 ± 29.1	165.6 ± 80.7	100.8 ± 37.7	150.6 ± 68.5
Wet 5 laps Cu	26.4 ± 18.1	100.9 ± 23.4	50.5 ± 19.1	170.5 ± 83.1	58.0 ± 22.3
Wet 5 laps St	36.8 ± 16.5	152.0 ± 44.3	127.4 ± 69.5	102.5 ± 52.2	170.2 ± 17.1
Control	86.2 ± 17.9	217.1 ± 40.6	85.9 ± 6.9	70.2 ± 13.2	126.9 ± 14.5
			Silt Loam		
Dry 10 laps Cu	35.7 ± 13.0	68.3 ± 32.4	150.9 ± 51.5	247.6 ± 4.4	182.0 ± 79.4
Dry 10 laps St	96.0 ± 8.2	176.2 ± 64.6	92.6 ± 21.8	265.3 ± 28.9	189.7 ± 53.5
Dry 5 laps Cu	95.6 ± 25.4	143.8 ± 90.1	180.6 ± 91.4	238.3 ± 92.8	232.6 ± 98.1
Dry 5 laps St	141.5 ± 27.4	182.8 ± 33.3	135.7 ± 38.4	330.5 ± 58.6	245.3 ± 79.5
Wet 10 laps Cu	66.1 ± 33.1	91.1 ± 53.8	197.5 ± 74.3	79.2 ± 37.7	160.7 ± 16.5
Wet 10 laps St	48.2 ± 9.1	168.4 ± 52.4	78.8 ± 13.1	246.2 ± 42.0	217.2 ± 92.9
Wet 5 laps Cu	121.7 ± 34.9	182.3 ± 33.2	177.5 ± 56.9	232.5 ± 95.5	248.8 ± 67.9
Wet 5 laps St	142.6 ± 29.1	215.6 ± 44.2	134.0 ± 12.7	210.4 ± 20.1	251.9 ± 37.5
Control	194.1 ± 26.5	272.1 ± 60.3	231.1 ± 71.4	499.7 ± 181.6	174.4 ± 55.3

Table A.2. Treatment absolute means and standard errors for forb biomass (g m^{-2}) in silty clay loam and silt loam soils, 2005 – 2007.

	2005	2006		2007	
Treatment	Unburned	Burned	Unburned	Burned	Unburned
			Silty Clay Loam		
Dry 10 laps Cu	25.8 ± 20.2	139.2 ± 74.7	49.0 ± 39.9	203.0 ± 113.8	44.3 ± 13.4
Dry 10 laps St	21.9 ± 9.0	54.9 ± 37.8	22.1 ± 8.1	151.1 ± 63.9	86.4 ± 38.0
Dry 5 laps Cu	94.9 ± 29.9	93.3 ± 19.8	44.1 ± 26.1	61.2 ± 26.7	22.5 ± 2.6
Dry 5 laps St	85.0 ± 57.5	120.0 ± 65.8	39.7 ± 21.2	109.0 ± 53.5	40.7 ± 13.7
Wet 10 laps Cu	5.1 ± 0.8	7.4 ± 3.7	173.5 ± 92.9	24.7 ± 11.0	28.7 ± 16.5
Wet 10 laps St	27.7 ± 14.2	4.9 ± 3.8	11.3 ± 5.8	20.4 ± 10.2	30.1 ± 13.7
Wet 5 laps Cu	12.0 ± 1.9	25.6 ± 14.1	34.2 ± 8.7	115.6 ± 40.2	29.4 ± 3.7
Wet 5 laps St	18.6 ± 5.9	3.5 ± 3.6	16.9 ± 5.2	52.8 ± 25.8	28.6 ± 10.2
Control	42.1 ± 20.6	50.3 ± 42.3	55.5 ± 27.6	168.7 ± 110.8	58.4 ± 36.1
			Silt Loam		
Dry 10 laps Cu	8.7 ± 7.9	141.3 ± 63.9	163.2 ± 150.3	89.5 ± 79.9	129.5 ± 72.8
Dry 10 laps St	42.7 ± 19.9	58.6 ± 10.6	89.4 ± 67.7	31.4 ± 15.8	18.8 ± 7.5
Dry 5 laps Cu	76.1 ± 56.9	61.8 ± 31.1	139.2 ± 118.7	133.4 ± 111.6	244.8 ± 123.7
Dry 5 laps St	22.8 ± 9.6	43.3 ± 15.5	43.1 ± 17.1	150.0 ± 72.7	92.5 ± 46.8
Wet 10 laps Cu	73.9 ± 25.0	71.9 ± 17.6	82.7 ± 11.6	79.6 ± 49.8	57.1 ± 14.6
Wet 10 laps St	32.4 ± 9.5	153.3 ± 71.8	84.0 ± 47.1	81.3 ± 40.6	36.3 ± 10.5
Wet 5 laps Cu	7.7 ± 3.8	64.4 ± 21.4	88.4 ± 82.4	77.0 ± 38.1	94.8 ± 44.7
Wet 5 laps St	61.6 ± 30.7	124.8 ± 65.8	31.7 ± 13.2	91.3 ± 53.2	85.2 ± 64.0
Control	35.4 ± 17.5	70.8 ± 29.4	90.8 ± 86.1	92.7 ± 82.2	137.5 ± 36.7

Table A.3. Treatment absolute means and standard errors for bulk density (g cm^{-3}) in silty clay loam and silt loam soils, 2005 – 2007.

	2005	2006		2007	
Treatment	Unburned	Burned	Unburned	Burned	Unburned
			Silty Clay Loam		
Dry 10 laps Cu	1.03 ± 0.02	1.08 ± 0.04	1.07 ± 0.04	1.10 ± 0.06	1.16 ± 0.06
Dry 10 laps St	1.02 ± 0.03	1.09 ± 0.04	1.08 ± 0.06	1.16 ± 0.03	1.18 ± 0.03
Dry 5 laps Cu	1.08 ± 0.04	1.08 ± 0.03	1.08 ± 0.03	1.13 ± 0.03	1.18 ± 0.03
Dry 5 laps St	1.13 ± 0.02	1.98 ± 0.02	1.11 ± 0.03	1.11 ± 0.04	1.23 ± 0.03
Wet 10 laps Cu	1.13 ± 0.04	1.15 ± 0.03	1.12 ± 0.01	1.26 ± 0.03	1.19 ± 0.02
Wet 10 laps St	1.13 ± 0.01	1.13 ± 0.04	1.16 ± 0.01	1.19 ± 0.02	1.24 ± 0.02
Wet 5 laps Cu	1.13 ± 0.08	1.14 ± 0.04	1.16 ± 0.04	1.17 ± 0.05	1.25 ± 0.02
Wet 5 laps St	1.12 ± 0.02	1.10 ± 0.05	1.15 ± 0.02	1.20 ± 0.02	1.19 ± 0.03
Control	1.06 ± 0.05	1.11 ± 0.04	1.14 ± 0.02	1.15 ± 0.05	1.21 ± 0.03
			Silt Loam		
Dry 10 laps Cu	1.06 ± 0.01	0.90 ± 0.05	1.09 ± 0.01	1.05 ± 0.01	1.04 ± 0.07
Dry 10 laps St	0.84 ± 0.04	0.95 ± 0.04	0.91 ± 0.02	1.00 ± 0.01	0.93 ± 0.04
Dry 5 laps Cu	0.95 ± 0.05	1.01 ± 0.02	0.97 ± 0.05	1.07 ± 0.05	1.03 ± 0.06
Dry 5 laps St	0.93 ± 0.01	0.96 ± 0.04	0.99 ± 0.04	0.97 ± 0.04	0.94 ± 0.01
Wet 10 laps Cu	1.03 ± 0.03	1.08 ± 0.03	1.05 ± 0.04	1.13 ± 0.05	1.21 ± 0.02
Wet 10 laps St	1.02 ± 0.04	0.90 ± 0.03	1.00 ± 0.09	1.04 ± 0.03	1.11 ± 0.03
Wet 5 laps Cu	1.10 ± 0.04	0.99 ± 0.03	1.03 ± 0.02	1.05 ± 0.05	1.08 ± 0.01
Wet 5 laps St	0.96 ± 0.02	0.96 ± 0.04	0.96 ± 0.01	0.98 ± 0.01	1.02 ± 0.06
Control	0.97 ± 0.04	1.00 ± 0.03	0.96 ± 0.01	1.03 ± 0.05	1.04 ± 0.06

Table A.4. Treatment absolute means and standard errors for porosity (%) in silty clay loam and silt loam soils, 2005 – 2007.

	2005	2006		2007	
Treatment	Unburned	Burned	Unburned	Burned	Unburned
			Silty Clay Loam		
Dry 10 laps Cu	61.1 ± 0.9	59.4 ± 1.3	59.8 ± 1.3	58.5 ± 2.3	56.1 ± 2.4
Dry 10 laps St	61.6 ± 1.2	58.9 ± 1.6	59.1 ± 2.5	56.1 ± 1.2	55.4 ± 1.3
Dry 5 laps Cu	59.4 ± 1.4	59.4 ± 1.3	59.4 ± 1.2	57.3 ± 1.0	55.6 ± 1.0
Dry 5 laps St	57.3 ± 0.9	63.2 ± 0.9	58.2 ± 1.2	58.2 ± 1.5	53.6 ± 1.2
Wet 10 laps Cu	57.5 ± 1.4	56.5 ± 1.2	57.6 ± 0.2	52.6 ± 1.3	55.0 ± 0.9
Wet 10 laps St	57.5 ± 0.5	57.3 ± 1.6	56.3 ± 0.3	55.2 ± 0.7	53.4 ± 0.8
Wet 5 laps Cu	57.4 ± 2.9	57.1 ± 1.7	56.1 ± 1.3	55.7 ± 2.0	52.7 ± 0.6
Wet 5 laps St	57.7 ± 0.6	58.5 ± 1.7	56.5 ± 0.9	54.6 ± 0.8	55.1 ± 1.3
Control	59.9 ± 1.9	58.2 ± 1.6	57.1 ± 0.9	56.6 ± 2.0	54.2 ± 1.1
			Silt Loam		
Dry 10 laps Cu	60.1 ± 0.2	66.0 ± 1.8	58.8 ± 0.2	60.2 ± 0.5	60.8 ± 2.8
Dry 10 laps St	68.3 ± 1.5	64.3 ± 1.6	65.6 ± 0.9	62.3 ± 0.4	64.9 ± 1.7
Dry 5 laps Cu	64.2 ± 1.7	61.8 ± 0.8	63.3 ± 1.8	59.6 ± 1.7	61.0 ± 2.4
Dry 5 laps St	64.8 ± 0.4	63.7 ± 1.5	62.8 ± 1.5	63.3 ± 1.5	64.5 ± 0.3
Wet 10 laps Cu	61.2 ± 1.2	59.4 ± 1.1	60.4 ± 1.6	57.5 ± 1.7	54.5 ± 0.8
Wet 10 laps St	61.4 ± 1.5	66.1 ± 1.1	62.1 ± 3.5	60.9 ± 1.1	58.3 ± 1.0
Wet 5 laps Cu	58.6 ± 1.4	62.7 ± 1.3	61.2 ± 0.8	60.2 ± 1.9	59.1 ± 0.4
Wet 5 laps St	63.9 ± 0.6	63.6 ± 1.6	63.6 ± 0.4	63.0 ± 0.4	61.5 ± 2.4
Control	63.2 ± 1.6	62.3 ± 1.3	63.8 ± 0.5	61.2 ± 2.1	60.9 ± 2.2

Table A.5. Treatment absolute means and standard errors for water content (%) in silty clay loam and silt loam soils, 2005 – 2007.

	2005	2006		2007	
Treatment	Unburned	Burned	Unburned	Burned	Unburned
			Silty Clay Loam		
Dry 10 laps Cu	30.4 ± 0.8	29.4 ± 3.3	28.4 ± 1.5	31.6 ± 0.3	28.8 ± 1.0
Dry 10 laps St	30.4 ± 0.6	24.0 ± 1.0	29.7 ± 1.4	29.9 ± 1.0	29.4 ± 1.5
Dry 5 laps Cu	29.7 ± 2.3	25.9 ± 0.6	26.9 ± 3.6	30.0 ± 0.2	30.7 ± 1.3
Dry 5 laps St	31.9 ± 1.3	27.6 ± 1.0	31.3 ± 2.1	30.5 ± 1.5	29.0 ± 1.0
Wet 10 laps Cu	25.8 ± 2.0	23.7 ± 3.3	24.5 ± 0.6	26.4 ± 2.5	30.7 ± 2.2
Wet 10 laps St	27.6 ± 1.9	24.3 ± 2.6	27.3 ± 0.7	28.9 ± 1.9	29.1 ± 0.8
Wet 5 laps Cu	28.6 ± 1.4	23.1 ± 2.2	25.7 ± 2.7	31.5 ± 0.7	26.0 ± 0.3
Wet 5 laps St	31.0 ± 1.7	25.4 ± 2.3	30.5 ± 1.5	28.1 ± 1.9	30.4 ± 0.1
Control	30.7 ± 1.2	25.0 ± 1.1	31.4 ± 0.7	29.8 ± 0.4	21.6 ± 9.0
			Silt Loam		
Dry 10 laps Cu	31.0 ± 1.1	27.2 ± 1.6	28.7 ± 1.0	31.5 ± 0.9	29.4 ± 1.4
Dry 10 laps St	37.8 ± 1.3	25.1 ± 1.0	33.8 ± 1.3	33.0 ± 2.4	36.7 ± 0.8
Dry 5 laps Cu	35.6 ± 0.7	21.7 ± 2.9	24.5 ± 0.9	30.8 ± 0.9	32.2 ± 0.5
Dry 5 laps St	36.3 ± 1.9	22.6 ± 3.3	31.3 ± 1.0	33.9 ± 2.1	33.6 ± 1.3
Wet 10 laps Cu	28.1 ± 1.0	22.7 ± 1.5	25.9 ± 1.0	27.9 ± 1.6	28.6 ± 0.8
Wet 10 laps St	30.4 ± 1.8	24.2 ± 1.8	25.5 ± 2.9	29.8 ± 2.7	28.1 ± 1.1
Wet 5 laps Cu	30.7 ± 0.7	23.3 ± 1.4	33.3 ± 2.9	30.4 ± 1.9	29.9 ± 0.9
Wet 5 laps St	33.2 ± 1.4	19.7 ± 0.6	31.8 ± 2.0	31.0 ± 1.0	32.7 ± 0.8
Control	34.0 ± 1.0	21.4 ± 1.5	32.9 ± 0.8	29.8 ± 0.5	35.5 ± 2.8

Table A.6. Treatment absolute means and standard errors for soil P (mg kg^{-1}) in silty clay loam and silt loam soils, 2006 – 2007.

	2006		2007	
Treatment	Burned	Unburned	Burned	Unburned
		Silty Clay Loam		
Dry 10 laps Cu	4.3 ± 0.7	7.3 ± 2.3	4.3 ± 0.3	6.0 ± 1.0
Dry 10 laps St	6.7 ± 0.9	5.7 ± 0.7	7.7 ± 1.5	5.3 ± 0.3
Dry 5 laps Cu	4.0 ± 1.0	5.7 ± 0.9	5.3 ± 0.9	5.7 ± 1.2
Dry 5 laps St	7.3 ± 1.9	3.7 ± 0.7	5.7 ± 0.9	7.7 ± 2.3
Wet 10 laps Cu	3.3 ± 0.3	3.7 ± 0.7	4.0 ± 0.6	5.7 ± 2.2
Wet 10 laps St	6.0 ± 1.5	5.3 ± 0.9	5.7 ± 1.7	5.3 ± 1.5
Wet 5 laps Cu	5.5 ± 0.5	4.0 ± 0.6	4.0 ± 0.0	4.7 ± 0.7
Wet 5 laps St	6.3 ± 0.7	4.7 ± 0.3	4.3 ± 0.3	5.0 ± 0.6
Control	4.7 ± 0.9	4.7 ± 0.9	5.7 ± 1.8	3.7 ± 0.9
		Silt Loam		
Dry 10 laps Cu	11.7 ± 1.3	7.3 ± 1.3	8.0 ± 1.5	5.7 ± 1.2
Dry 10 laps St	9.7 ± 0.3	17.7 ± 4.7	8.7 ± 0.9	14.7 ± 2.8
Dry 5 laps Cu	8.7 ± 1.8	18.3 ± 8.4	9.7 ± 3.3	11.7 ± 3.2
Dry 5 laps St	10.3 ± 1.2	11.0 ± 2.5	9.3 ± 2.2	8.0 ± 0.6
Wet 10 laps Cu	10.7 ± 2.2	10.0 ± 2.1	9.7 ± 0.7	6.3 ± 1.2
Wet 10 laps St	19.0 ± 9.5	11.7 ± 0.9	14.7 ± 5.2	9.0 ± 2.6
Wet 5 laps Cu	10.3 ± 1.5	7.0 ± 1.5	12.0 ± 3.2	7.3 ± 1.5
Wet 5 laps St	10.0 ± 1.7	16.0 ± 3.5	7.3 ± 2.3	9.7 ± 1.7
Control	14.0 ± 1.5	11.7 ± 2.3	10.3 ± 0.3	20.7 ± 9.9

Table A.7. Treatment absolute means and standard errors for soil K (mg kg^{-1}) in silty clay loam and silt loam soils, 2006 – 2007.

	2006		2007	
Treatment	Burned	Unburned	Burned	Unburned
		Silty Clay Loam		
Dry 10 laps Cu	313 ± 14	373 ± 47	306 ± 21	319 ± 23
Dry 10 laps St	377 ± 4	371 ± 18	379 ± 21	361 ± 5
Dry 5 laps Cu	294 ± 19	311 ± 16	272 ± 35	312 ± 13
Dry 5 laps St	351 ± 44	349 ± 10	326 ± 23	340 ± 56
Wet 10 laps Cu	218 ± 34	251 ± 11	246 ± 25	281 ± 26
Wet 10 laps St	315 ± 20	321 ± 27	294 ± 1	307 ± 13
Wet 5 laps Cu	287 ± 26	288 ± 14	252 ± 15	238 ± 7
Wet 5 laps St	318 ± 36	343 ± 23	295 ± 18	307 ± 10
Control	316 ± 9	333 ± 27	312 ± 37	306 ± 54
		Silt Loam		
Dry 10 laps Cu	348 ± 26	230 ± 33	262 ± 27	217 ± 10
Dry 10 laps St	298 ± 36	391 ± 47	313 ± 8	406 ± 18
Dry 5 laps Cu	262 ± 25	361 ± 68	270 ± 59	336 ± 66
Dry 5 laps St	309 ± 34	364 ± 33	302 ± 21	322 ± 19
Wet 10 laps Cu	267 ± 45	252 ± 64	277 ± 29	194 ± 40
Wet 10 laps St	342 ± 88	243 ± 15	326 ± 41	266 ± 23
Wet 5 laps Cu	285 ± 40	214 ± 20	252 ± 50	247 ± 14
Wet 5 laps St	288 ± 6	334 ± 40	243 ± 29	320 ± 22
Control	278 ± 7	316 ± 10	248 ± 4	410 ± 87

Table A.8. Treatment absolute means and standard errors for soil Ca (mg kg^{-1}) in silty clay loam and silt loam soils, 2006 – 2007.

	2006		2007	
Treatment	Burned	Unburned	Burned	Unburned
		Silty Clay Loam		
Dry 10 laps Cu	3546 ± 159	3316 ± 268	3332 ± 121	3039 ± 449
Dry 10 laps St	3071 ± 259	3036 ± 319	3136 ± 353	2986 ± 357
Dry 5 laps Cu	2999 ± 408	2945 ± 300	3123 ± 597	2884 ± 359
Dry 5 laps St	3079 ± 474	3047 ± 323	2600 ± 312	3215 ± 432
Wet 10 laps Cu	2808 ± 351	3215 ± 158	2630 ± 371	2763 ± 69
Wet 10 laps St	3015 ± 221	3185 ± 314	2770 ± 231	2836 ± 139
Wet 5 laps Cu	2898 ± 255	2763 ± 263	2587 ± 358	2487 ± 186
Wet 5 laps St	2827 ± 280	2798 ± 262	2646 ± 291	2691 ± 170
Control	2926 ± 305	3062 ± 378	2687 ± 300	2808 ± 482
		Silt Loam		
Dry 10 laps Cu	2723 ± 189	2400 ± 70	2569 ± 76	2333 ± 105
Dry 10 laps St	2719 ± 96	2905 ± 132	2688 ± 36	3031 ± 182
Dry 5 laps Cu	2519 ± 127	2898 ± 195	2464 ± 152	2659 ± 214
Dry 5 laps St	2708 ± 30	2880 ± 97	2599 ± 87	2626 ± 15
Wet 10 laps Cu	2604 ± 168	2431 ± 168	2438 ± 126	2354 ± 40
Wet 10 laps St	2931 ± 328	2502 ± 71	2820 ± 260	2598 ± 52
Wet 5 laps Cu	2666 ± 65	2369 ± 59	2520 ± 88	2487 ± 63
Wet 5 laps St	2852 ± 135	2859 ± 135	2686 ± 172	2510 ± 84
Control	2884 ± 87	2723 ± 128	2641 ± 163	2663 ± 100

Table A.9. Treatment absolute means and standard errors for total C (g kg^{-1}) in silty clay loam and silt loam soils, 2006 – 2007.

	2005	2006		2007	
Treatment	Unburned	Burned	Unburned	Burned	Unburned
			Silty Clay Loam		
Dry 10 laps Cu	1.85 ± 0.21	1.76 ± 0.09	2.36 ± 0.47	1.66 ± 0.12	1.66 ± 0.09
Dry 10 laps St	2.46 ± 0.15	2.40 ± 0.07	2.35 ± 0.12	2.21 ± 0.20	2.22 ± 0.18
Dry 5 laps Cu	1.85 ± 0.16	1.74 ± 0.05	1.83 ± 0.02	1.65 ± 0.12	1.78 ± 0.13
Dry 5 laps St	2.43 ± 0.05	2.36 ± 0.23	2.32 ± 0.16	2.01 ± 0.09	2.40 ± 0.38
Wet 10 laps Cu	1.48 ± 0.09	1.35 ± 0.02	1.31 ± 0.10	1.37 ± 0.03	1.39 ± 0.08
Wet 10 laps St	2.02 ± 0.16	1.81 ± 0.18	1.70 ± 0.17	1.57 ± 0.02	1.61 ± 0.18
Wet 5 laps Cu	1.79 ± 0.05	1.76 ± 0.10	1.73 ± 0.12	1.56 ± 0.17	1.40 ± 0.08
Wet 5 laps St	1.94 ± 0.12	2.04 ± 0.14	1.84 ± 0.06	1.76 ± 0.14	1.86 ± 0.22
Control	2.25 ± 0.03	1.93 ± 0.20	2.06 ± 0.19	1.90 ± 0.17	1.82 ± 0.11
			Silt Loam		
Dry 10 laps Cu	2.97 ± 0.22	3.04 ± 0.08	2.51 ± 0.09	2.80 ± 0.09	2.54 ± 0.05
Dry 10 laps St	3.67 ± 0.25	2.89 ± 0.23	3.43 ± 0.21	3.34 ± 0.03	3.81 ± 0.10
Dry 5 laps Cu	3.41 ± 0.22	2.84 ± 0.16	3.08 ± 0.18	2.75 ± 0.17	2.86 ± 0.08
Dry 5 laps St	3.85 ± 0.32	3.11 ± 0.17	3.29 ± 0.07	3.10 ± 0.28	3.13 ± 0.10
Wet 10 laps Cu	2.79 ± 0.06	2.62 ± 0.21	2.49 ± 0.19	2.37 ± 0.04	2.14 ± 0.12
Wet 10 laps St	2.99 ± 0.17	3.31 ± 0.48	2.78 ± 0.21	3.60 ± 0.29	2.86 ± 0.28
Wet 5 laps Cu	2.70 ± 0.15	3.07 ± 0.25	2.56 ± 0.16	2.80 ± 0.27	2.87 ± 0.12
Wet 5 laps St	3.34 ± 0.09	2.92 ± 0.17	3.32 ± 0.16	2.67 ± 0.09	3.07 ± 0.22
Control	3.42 ± 0.22	3.13 ± 0.21	3.53 ± 0.22	2.92 ± 0.32	2.93 ± 0.13

Table A.10. Treatment absolute means and standard errors for total N (g kg^{-1}) in silty clay loam and silt loam soils, 2005 – 2007.

	2005	2006		2007	
Treatment	Unburned	Burned	Unburned	Burned	Unburned
			Silty Clay Loam		
Dry 10 laps Cu	0.16 ± 0.02	0.17 ± 0.01	0.20 ± 0.04	0.14 ± 0.01	0.14 ± 0.01
Dry 10 laps St	0.20 ± 0.01	0.20 ± 0.01	0.20 ± 0.01	0.18 ± 0.02	0.18 ± 0.02
Dry 5 laps Cu	0.16 ± 0.01	0.16 ± 0.00	0.16 ± 0.00	0.14 ± 0.01	0.15 ± 0.01
Dry 5 laps St	0.19 ± 0.00	0.20 ± 0.03	0.19 ± 0.01	0.16 ± 0.00	0.19 ± 0.03
Wet 10 laps Cu	0.13 ± 0.01	0.13 ± 0.01	0.13 ± 0.01	0.11 ± 0.00	0.12 ± 0.01
Wet 10 laps St	0.17 ± 0.01	0.17 ± 0.01	0.16 ± 0.01	0.13 ± 0.00	0.13 ± 0.01
Wet 5 laps Cu	0.16 ± 0.01	0.17 ± 0.01	0.16 ± 0.01	0.13 ± 0.02	0.12 ± 0.01
Wet 5 laps St	0.17 ± 0.01	0.18 ± 0.01	0.16 ± 0.00	0.14 ± 0.01	0.15 ± 0.02
Control	0.19 ± 0.01	0.18 ± 0.01	0.18 ± 0.01	0.15 ± 0.01	0.14 ± 0.01
			Silt Loam		
Dry 10 laps Cu	0.25 ± 0.02	0.26 ± 0.01	0.22 ± 0.01	0.23 ± 0.01	0.20 ± 0.01
Dry 10 laps St	0.30 ± 0.02	0.24 ± 0.02	0.28 ± 0.01	0.26 ± 0.00	0.29 ± 0.00
Dry 5 laps Cu	0.29 ± 0.02	0.24 ± 0.01	0.26 ± 0.02	0.22 ± 0.01	0.23 ± 0.01
Dry 5 laps St	0.32 ± 0.02	0.26 ± 0.01	0.28 ± 0.00	0.24 ± 0.02	0.25 ± 0.01
Wet 10 laps Cu	0.24 ± 0.01	0.23 ± 0.02	0.22 ± 0.01	0.20 ± 0.00	0.18 ± 0.01
Wet 10 laps St	0.26 ± 0.02	0.29 ± 0.04	0.24 ± 0.02	0.29 ± 0.03	0.23 ± 0.02
Wet 5 laps Cu	0.23 ± 0.01	0.26 ± 0.02	0.22 ± 0.01	0.22 ± 0.02	0.23 ± 0.01
Wet 5 laps St	0.28 ± 0.01	0.26 ± 0.02	0.28 ± 0.01	0.22 ± 0.01	0.24 ± 0.01
Control	0.28 ± 0.02	0.25 ± 0.02	0.29 ± 0.02	0.24 ± 0.03	0.24 ± 0.01

Table A.11. Treatment absolute means and standard errors for soil microbial C (μg g^{-1}) in silty clay loam and silt loam soils, 2005 – 2007.

	2005	2006		2007	
Treatment	Unburned	Burned	Unburned	Burned	Unburned
			Silty Clay Loam		
Dry 10 laps Cu	803 ± 95	387 ± 63	448 ± 85	396 ± 71	475 ± 49
Dry 10 laps St	1085 ± 208	486 ± 124	566 ± 103	726 ± 55	733 ± 19
Dry 5 laps Cu	987 ± 261	326 ± 157	396 ± 78	404 ± 48	505 ± 53
Dry 5 laps St	1017 ± 18	509 ± 84	452 ± 118	436 ± 26	781 ± 105
Wet 10 laps Cu	581 ± 82	260 ± 84	427 ± 65	286 ± 15	350 ± 56
Wet 10 laps St	948 ± 193	396 ± 140	462 ± 30	398 ± 68	437 ± 24
Wet 5 laps Cu	674 ± 46	280 ± 100	558 ± 128	447 ± 39	437 ± 80
Wet 5 laps St	881 ± 108	582 ± 31	423 ± 278	628 ± 24	596 ± 74
Control	1219 ± 158	317 ± 44	233 ± 16	466 ± 130	508 ± 39
			Silt Loam		
Dry 10 laps Cu	766 ± 361	424 ± 33	449 ± 27	532 ± 74	431 ± 67
Dry 10 laps St	1234 ± 173	597 ± 129	396 ± 63	566 ± 26	732 ± 78
Dry 5 laps Cu	1161 ± 80	435 ± 60	425 ± 155	503 ± 23	567 ± 158
Dry 5 laps St	1228 ± 96	486 ± 190	319 ± 5	527 ± 58	693 ± 157
Wet 10 laps Cu	647 ± 315	455 ± 91	387 ± 30	457 ± 77	401 ± 25
Wet 10 laps St	1187 ± 67	469 ± 98	595 ± 81	751 ± 63	927 ± 93
Wet 5 laps Cu	1090 ± 204	689 ± 40	241 ± 95	687 ± 60	500 ± 32
Wet 5 laps St	1222 ± 68	582 ± 107	475 ± 108	643 ± 57	493 ± 76
Control	1088 ± 69	504 ± 97	546 ± 6	691 ± 5	318 ± 39

Table A.12. Treatment absolute means and standard errors for soil microbial N (µg g^{-1}) in silty clay loam and silt loam soils, 2005 – 2007.

	2005	2006		2007	
Treatment	Unburned	Burned	Unburned	Burned	Unburned
			Silty Clay Loam		
Dry 10 laps Cu	152 ± 30	110 ± 9	163 ± 31	104 ± 19	115 ± 16
Dry 10 laps St	244 ± 46	352 ± 155	194 ± 5	167 ± 9	173 ± 23
Dry 5 laps Cu	171 ± 28	118 ± 11	118 ± 8	112 ± 5	130 ± 8
Dry 5 laps St	255 ± 18	162 ± 28	150 ± 36	141 ± 9	182 ± 42
Wet 10 laps Cu	101 ± 20	59 ± 14	80 ± 15	81 ± 6	59 ± 15
Wet 10 laps St	165 ± 36	97 ± 10	91 ± 20	81 ± 20	98 ± 13
Wet 5 laps Cu	125 ± 14	81 ± 14	82 ± 7	84 ± 8	92 ± 13
Wet 5 laps St	170 ± 15	131 ± 13	113 ± 8	115 ± 15	117 ± 8
Control	266 ± 24	135 ± 14	123 ± 12	16 ± 21	135 ± 10
			Silt Loam		
Dry 10 laps Cu	165 ± 22	147 ± 7	151 ± 5	157 ± 12	143 ± 8
Dry 10 laps St	297 ± 44	177 ± 29	215 ± 19	201 ± 1	232 ± 12
Dry 5 laps Cu	256 ± 25	153 ± 29	178 ± 19	158 ± 13	178 ± 11
Dry 5 laps St	298 ± 24	185 ± 20	184 ± 6	195 ± 20	192 ± 17
Wet 10 laps Cu	146 ± 33	128 ± 17	122 ± 5	109 ± 26	123 ± 21
Wet 10 laps St	127 ± 19	206 ± 31	172 ± 21	243 ± 30	192 ± 32
Wet 5 laps Cu	196 ± 43	215 ± 4	138 ± 16	211 ± 41	175 ± 1
Wet 5 laps St	279 ± 18	176 ± 28	151 ± 15	172 ± 5	203 ± 7
Control	266 ± 11	172 ± 23	191 ± 15	157 ± 25	149 ± 1

Table A.13. Treatment absolute means and standard errors for nematode family richness in silty clay loam and silt loam soils, 2005 – 2007.

	2005	2006		2007	
Treatment	Unburned	Burned	Unburned	Burned	Unburned
			Silty Clay Loam		
Dry 10 laps Cu	8 ± 1	12 ± 1	11 ± 2	11 ± 2	8 ± 1
Dry 10 laps St	10 ± 1	11 ± 1	15 ± 1	12 ± 0	13 ± 2
Dry 5 laps Cu	12 ± 2	12 ± 1	15 ± 1	10 ± 1	13 ± 1
Dry 5 laps St	9 ± 1	10 ± 1	13 ± 1	14 ± 2	13 ± 2
Wet 10 laps Cu	8 ± 1	11 ± 2	9 ± 1	12 ± 1	9 ± 3
Wet 10 laps St	11 ± 1	9 ± 2	12 ± 3	10 ± 1	7 ± 3
Wet 5 laps Cu	12 ± 2	14 ± 1	14 ± 3	10 ± 2	11 ± 2
Wet 5 laps St	10 ± 1	12 ± 0	13 ± 1	8 ± 2	10 ± 1
Control	11 ± 1	13 ± 1	16 ± 1	12 ± 1	12 ± 1
			Silt Loam		
Dry 10 laps Cu	14 ± 2	13 ± 1	13 ± 1	13 ± 1	13 ± 1
Dry 10 laps St	16 ± 0	14 ± 1	16 ± 1	15 ± 0	15 ± 1
Dry 5 laps Cu	15 ± 1	11 ± 0	13 ± 2	12 ± 1	11 ± 1
Dry 5 laps St	13 ± 3	12 ± 1	16 ± 1	14 ± 2	12 ± 1
Wet 10 laps Cu	10 ± 1	11 ± 0	15 ± 1	12 ± 2	10 ± 1
Wet 10 laps St	11 ± 1	12 ± 1	16 ± 0	12 ± 2	10 ± 1
Wet 5 laps Cu	14 ± 1	18 ± 1	16 ± 0	14 ± 1	11 ± 0
Wet 5 laps St	14 ± 2	15 ± 2	15 ± 2	12 ± 2	14 ± 2
Control	16 ± 1	13 ± 1	15 ± 2	13 ± 1	11 ± 1

Table A.14. Treatment absolute means and standard errors for total nematodes (M m^{-2}) in silty clay loam and silt loam soils, 2005 – 2007.

	2005	2006		2007	
Treatment	Unburned	Burned	Unburned	Burned	Unburned
			Silty Clay Loam		
Dry 10 laps Cu	0.72 ± 0.16	0.76 ± 0.13	0.60 ± 0.23	0.36 ± 0.07	0.41 ± 0.26
Dry 10 laps St	0.94 ± 0.29	0.89 ± 0.44	1.05 ± 0.34	0.56 ± 0.22	0.39 ± 0.04
Dry 5 laps Cu	0.97 ± 0.26	0.88 ± 0.26	0.72 ± 0.21	0.32 ± 0.14	0.51 ± 0.25
Dry 5 laps St	0.88 ± 0.20	0.53 ± 0.08	0.68 ± 0.13	0.40 ± 0.17	0.49 ± 0.15
Wet 10 laps Cu	0.33 ± 0.07	0.36 ± 0.08	0.52 ± 0.11	0.25 ± 0.02	0.13 ± 0.05
Wet 10 laps St	0.77 ± 0.13	0.60 ± 0.28	0.67 ± 0.12	0.29 ± 0.01	0.14 ± 0.06
Wet 5 laps Cu	0.75 ± 0.18	1.09 ± 0.41	0.75 ± 0.21	0.26 ± 0.14	0.35 ± 0.12
Wet 5 laps St	0.87 ± 0.10	0.48 ± 0.17	1.20 ± 0.30	0.27 ± 0.11	0.30 ± 0.11
Control	1.12 ± 0.18	0.80 ± 0.11	1.14 ± 0.22	0.25 ± 0.07	0.60 ± 0.22
			Silt Loam		
Dry 10 laps Cu	1.18 ± 0.21	1.32 ± 0.04	0.73 ± 0.16	0.62 ± 0.26	0.35 ± 0.10
Dry 10 laps St	1.94 ± 0.58	1.07 ± 0.20	1.20 ± 0.23	0.58 ± 0.06	0.48 ± 0.07
Dry 5 laps Cu	1.20 ± 0.27	0.54 ± 0.08	0.80 ± 0.23	0.60 ± 0.08	0.31 ± 0.11
Dry 5 laps St	2.10 ± 0.50	0.69 ± 0.07	1.28 ± 0.18	0.57 ± 0.05	0.31 ± 0.02
Wet 10 laps Cu	0.44 ± 0.10	0.47 ± 0.05	0.66 ± 0.10	0.36 ± 0.17	0.27 ± 0.11
Wet 10 laps St	0.95 ± 0.15	0.77 ± 0.21	0.87 ± 0.08	0.56 ± 0.14	0.34 ± 0.04
Wet 5 laps Cu	1.26 ± 0.34	0.85 ± 0.05	0.90 ± 0.09	0.63 ± 0.04	0.42 ± 0.04
Wet 5 laps St	1.82 ± 0.19	0.93 ± 0.29	1.39 ± 0.26	0.54 ± 0.19	0.66 ± 0.19
Control	1.97 ± 0.65	0.85 ± 0.14	2.01 ± 0.67	0.52 ± 0.15	0.44 ± 0.05

Table A.15. Treatment absolute means and standard errors for earthworms (# m^{-2}) in silty clay loam and silt loam soils, 2005 – 2007.

	2005	2006		2007	
Treatment	Unburned	Burned	Unburned	Burned	Unburned
			Silty Clay Loam		
Dry 10 laps Cu	0 ± 0	20 ± 10	53 ± 43	20 ± 10	10 ± 10
Dry 10 laps St	20 ± 6	13 ± 9	47 ± 7	43 ± 34	30 ± 15
Dry 5 laps Cu	7 ± 3	23 ± 13	40 ± 15	10 ± 6	23 ± 19
Dry 5 laps St	17 ± 12	27 ± 13	17 ± 7	20 ± 6	13 ± 13
Wet 10 laps Cu	0 ± 0	0 ± 0	10 ± 10	13 ± 13	7 ± 3
Wet 10 laps St	0 ± 0	7 ± 3	20 ± 20	3 ± 3	3 ± 3
Wet 5 laps Cu	3 ± 3	13 ± 9	3 ± 3	0 ± 0	20 ± 15
Wet 5 laps St	3 ± 3	7 ± 3	20 ± 6	30 ± 15	27 ± 22
Control	27 ± 18	10 ± 10	30 ± 15	10 ± 6	23 ± 7
			Silt Loam		
Dry 10 laps Cu	30 ± 6	90 ± 38	67 ± 30	93 ± 35	43 ± 28
Dry 10 laps St	107 ± 53	37 ± 27	77 ± 30	37 ± 9	33 ± 9
Dry 5 laps Cu	67 ± 22	33 ± 9	77 ± 20	30 ± 17	60 ± 35
Dry 5 laps St	177 ± 52	57 ± 52	137 ± 18	20 ± 15	40 ± 26
Wet 10 laps Cu	7 ± 3	30 ± 30	27 ± 9	23 ± 23	37 ± 20
Wet 10 laps St	10 ± 10	77 ± 35	60 ± 15	47 ± 9	37 ± 18
Wet 5 laps Cu	20 ± 10	73 ± 19	73 ± 23	17 ± 9	30 ± 15
Wet 5 laps St	47 ± 18	3 ± 3	187 ± 71	23 ± 15	3 ± 3
Control	93 ± 34	67 ± 47	130 ± 26	23 ± 19	60 ± 50

Table A.16. Treatment absolute means and standard errors for macroarthropods (# m^{-2}) in silty clay loam and silt loam soils, 2005 – 2007.

	2005	2006		2007	
Treatment	Unburned	Burned	Unburned	Burned	Unburned
			Silty Clay Loam		
Dry 10 laps Cu	0 ± 0	7 ± 3	10 ± 0	23 ± 15	13 ± 9
Dry 10 laps St	17 ± 12	0 ± 0	10 ± 10	10 ± 6	23 ± 9
Dry 5 laps Cu	10 ± 6	10 ± 6	7 ± 7	13 ± 3	20 ± 20
Dry 5 laps St	7 ± 3	3 ± 3	10 ± 6	37 ± 32	27 ± 22
Wet 10 laps Cu	17 ± 17	0 ± 0	10 ± 6	20 ± 15	20 ± 6
Wet 10 laps St	0 ± 0	3 ± 3	0 ± 3	20 ± 15	33 ± 33
Wet 5 laps Cu	10 ± 6	0 ± 0	13 ± 9	13 ± 9	37 ± 15
Wet 5 laps St	0 ± 0	10 ± 6	17 ± 9	13 ± 13	13 ± 7
Control	13 ± 9	3 ± 3	17 ± 7	20 ± 15	13 ± 13
			Silt Loam		
Dry 10 laps Cu	30 ± 6	7 ± 3	3 ± 3	30 ± 20	17 ± 12
Dry 10 laps St	30 ± 6	0 ± 0	7 ± 7	37 ± 27	10 ± 10
Dry 5 laps Cu	80 ± 31	7 ± 3	0 ± 0	17 ± 7	17 ± 7
Dry 5 laps St	7 ± 7	0 ± 0	23 ± 13	10 ± 6	10 ± 6
Wet 10 laps Cu	27 ± 12	7 ± 3	10 ± 6	0 ± 0	27 ± 13
Wet 10 laps St	43 ± 18	0 ± 0	3 ± 3	23 ± 15	17 ± 7
Wet 5 laps Cu	30 ± 12	10 ± 10	3 ± 3	13 ± 3	7 ± 3
Wet 5 laps St	33 ± 28	7 ± 7	0 ± 0	47 ± 9	10 ± 6
Control	17 ± 9	3 ± 3	17 ± 7	17 ± 9	7 ± 7