WINTER RYE COVER CROPPING TO IMPROVE WATER QUALITY IN CORN-BASED CROPPING SYSTEMS

A THESIS
SUBMITTED TO THE FACULTY OF
THE UNIVERSITY OF MINNESOTA

BY

ADAM PAUL HERGES

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

MASTER OF SCIENCE

DR. PAUL PORTER AND DR. JOHN BAKER, CO-ADVISORS

March 2013

Acknowledgements

I have the utmost respect and appreciation for Dr. Erik Krueger, Dr. John Baker, Dr. Paul Porter, and Dr. Gary Feyereisen for their generous support, advice, and assistance in implementing experimental design and layout for these studies. Dr. Erik Krueger was influential in all aspects of this work. His dedication and advice on my graduate program is greatly appreciated. In addition, I would like to thank Todd Schumacher for completion of all field work collections, laboratory analyses, and his friendship.

Special gratitude goes to the farmers involved in this project, Rob Miller and Bob Walkes. Their cooperation allowed the project to be on-farm and emphasized that agricultural research is achievable in this setting. Our ability to work together on implementing and designing field work days with their scheduled operations was crucial to our success.

I would also like to thank Bill Breiter, Melissa Wilson, Elizabeth Petesch, Patrick Knudson, and Mark Zumwinkle for their assistance in rainfall simulations, data collection, and construction of edge of field collection sites. Without their help, these simulation days would have never been completed. A special appreciation goes to Mark Zumwinkle for his knowledge of rainfall simulations, design and construction of edge of field sites, and his guidance over the past six years. Without his direction, I may have never been involved in agriculture or this project.

I would also like to thank my committee members Dr. Deborah Allan and Dr. Don Wyse for their support and guidance in my research projects.

The financial support from the Minnesota Department of Agriculture through the Clean Water Legacy Act funded this research. I am deeply grateful for its contribution. In addition, I would like to thank the sponsors of the Gandrud Fellowship for their financial support in the fall 2011.

Finally, I would like to thank my friends and family for their loving support throughout my life and academic career; specifically John Herges, Diane Botzek, Mary Herges, Annie Hagen, and Erik Leonhart.

Dedication

This thesis is dedicated to my loving mother, Diane.

May the gentle ocean breeze
Flow through your hair,
May the sands
Wash upon your feet,
As the sun shines to warm your face
While breaking new light,
As you wait for your son
To join you in eternal brightness

I'm honored and forever grateful to call you my mother.

Abstract

Winter rye (*Secale cereale* L.) cover cropping as a best management practice aimed at improving surface water quality by providing more ground cover, retaining nutrients, and preventing movement of surface water that carries nitrogen, phosphorus, and sediment to rivers, lakes, and streams. These four studies evaluated winter rye effects on surface water quality using different seeding methods in a variety of cropping systems. The first study (chapter 1) evaluated surface water quality under a one hour simulated rainfall event using different seeding methods of establishing winter rye following soybean (*Glycine max L.*) in fall and spring. Aerial, airflow, and broadcast seeding methods provided optimal winter rye ground cover to reduce surface runoff, NO_3-N, NH_4-N, phosphorus, and sediment compared to fallow. The second study (chapter 2) evaluated surface water quality under a one hour simulated rainfall event using different management practices of winter rye following corn (*Zea mays L.*) stover removal for silage in spring of 2010 and 2011. Standing and harvested rye treatments reduced surface runoff, NO_3-N, NH_4-N, phosphorus, and sediment compared to fallow, with standing rye being superior to harvested rye. Harvesting the rye for forage or bedding still provided exceptional environmental benefits for improving water quality compared to fallow. The last two studies (chapters 3 and 4) monitored and evaluated surface runoff in a paired watershed design. The longitudinal limitations of these studies provided insufficient results to conclude if winter rye was effective at reducing surface runoff and improving water quality at the field edge. Overall, simulated rainfall studies showed that winter rye was effective at reducing surface runoff and improving water quality, but the results of field scale studies were less clear.

Table of Contents

Chapter 1 – Effect of Winter Rye Seeding Methods on Surface Runoff under a Simulated Rainfall Event

Chapter 2 – Effect of Management of Winter Rye on Surface Runoff under a Simulated Rainfall Event

Chapter 3 – Effect of Removed Corn Stover on Surface Runoff in a Paired Watershed

Chapter 4 - Effect of Winter Rye following Corn Silage on Surface Runoff in a Paired Watershed

List of Tables

List of Figures

Introduction

With the emergence of biofuel production that may increase the demand of corn stover and increased precipitation frequency and intensity that may promote soil erosion in the absence of ground cover, maintenance of soil quality and health has become challenging in corn-based cropping systems. Cellulosic biofuel production may increase demand for biomass, specifically corn residue, because it is readily available and harvesting technologies are well established. Maintaining residue to reduce soil erosion risks while harvesting corn stover has been a focal point in a number of studies, dating back to the work of Lindstrom et al. (1979), who concluded that the amount of corn residue to prevent soil erosion risks should be site specific in the U.S. Corn Belt. More recently, Thomas et al. (2011) found that removal of corn stover at rates of 38, 52.5, and 70% increase annual soil erosion. Continued research in this area will enhance our ability to maintain soil conservation practices and our ability to harvest corn stover once second generation (cellulosic) biofuel production becomes viable.

Climate change has also been a major focus within the scientific community in recent decades. Increases in atmospheric carbon dioxide and other greenhouse gases have resulted in rising mean global surface temperatures, which have been coupled with an increase in mean atmospheric water vapor (Frei et al. 1998). This has coincided with a higher frequency and intensity of storm events throughout the contiguous U.S. A century ago, the most extreme storms contributed only 1% of total annual rainfall. Now extreme storms contribute 20% of total rainfall in the continental U.S. while total precipitation has only increased by 7% over the past century (Rosenzweig et al. 2000). Heavy and intense rainfall can be devastating to cropland because of induced soil erosion, nutrient loss, and flooding. The rainfall erosion index component of the Universal soil-loss equation quantifies the effects of rainfall events on soil loss. Rainfall erosion potential is greatly affected by rainfall intensity and less by amount of rainfall produced (Wischmeier, 1959). Since extreme storm events are occurring more frequently and with higher intensity, it is necessary to provide some mitigation management tools to prevent excessive losses of sediment and nutrients from cropland.

In addition to soil quality declines associated with loss of topsoil, offsite nutrient transport also threatens surface water quality. Nutrients are lost in surface runoff in both dissolved and particulate form. Nitrogen fractions lost in surface runoff include NH_4+ and NO_3- (Ruiz Diaz et al. 2010, Pauer and Auer 2000). Excessive nitrate concentrations in coastal waters lead to algal blooms that cause hypoxia and damage coastal ecosystems (David et al. 2010, Rabalais et al. 2001). Phosphorus (P) is a major contributing factor to eutrophication of fresh waters. In agricultural landscapes, manure and chemical fertilizers are major contributors to phosphorus buildup in the soil (Hart et al. 2004). Once phosphorus reaches excessive levels in the soil, the excess P can be a source for non-point pollution when water erosion occurs (Hart et al. 2004, Sims et al. 1998). Phosphorus lost in surface runoff can be quantified and reported as total dissolved phosphorus, total phosphorus, PO_4-, and particulate phosphorus (He, et al. 2006). In addition, sediment, when deposited in rivers and lakes through surface runoff, can change the dynamics of water flow and ecosystems within freshwater areas. Once sediment settles in rivers or lakes in large amounts, navigation can be affected, necessitating costly removal. Thus, a key component of climate change mitigation will involve actions to avoid these negative consequences of intense precipitation. Winter cover crops provide one potential tool.

Due to its resilience to cold, winter rye cover cropping is a suitable practice during dormant periods in corn-soybean cropping systems of the Upper Midwest. Winter rye is winter hardy, suppresses weeds, provides cover to minimize soil erosion and offsite transport of nutrients in surface runoff, and reduces nitrate leaching to ground water (Krueger et al. 2011). Winter rye can also increase nitrogen use efficiency. The mechanism is twofold: winter rye helps to reduce soil erosion, thus keeping the organic matter in the top soil; it also scavenges nitrate that would otherwise be lost through the system via leaching (Hively et al. 2009). A meta-analysis found a 70% average reduction in nitrate leaching when cover crops were used (Tonitto et al. 2006). Staver and Brinsfield found that winter rye reduced nitrogen loads by 80% in subsurface groundwater and in deeper aquifers under corn rotations (1998). In another study in Canada, winter rye cover crops reduced nitrate concentrations in groundwater by 70% (Ball Coelho et al. 2005). However, the uptake of nitrogen by winter rye is dependent upon both early establishment of winter rye in the fall and robust spring biomass accumulation (Hively et al. 2009, Feyereisen et al. 2006).

Our research included four studies to evaluate winter rye effect on surface runoff following soybeans, corn silage, and corn for grain. Two studies (chapters 1 and 2) were small plot studies that utilized a rainfall simulator to simulate a 6.34 cm hr-1 storm event over a 60 minute period. The other two studies (chapters 3 and 4) were field-scale studies involving paired watersheds. One study (chapter 4) evaluated surface runoff in a corn silage system where one watershed used conventional practices, and the other watershed was drilled with winter rye. In the corn stover management experiment (chapter 3), conventional no-till practices were used in one watershed and in the other watershed corn stover was baled and removed.

References

Ball Coelho BR, Roy RC, and Bruin AJ. 2005. Long-term Effects of Late-Summer Overseeding of Winter Rye on Corn Grain Yield and Nitrogen Balance. Canadian Journal of Plant Science 85: 543-554.

David MB, Drinkwater LE, and McIsaac GF. 2010. Sources of Nitrate Yields in the Mississippi River Basin. Journal of Environmental Quality 39: 1657-1667.

Feyereisen GW, Wilson BN, Sands GR, Strock JS, and Porter PM. 2006. Potential for a Rye Cover Crop to Reduce Nitrate Loss in Southwestern Minnesota. Agronomy Journal 98: 1416-1426.

Frei C, Schar C, Luthi D, and Davies HC. 1998. Heavy Precipitation Processes in a Warmer Climate. Geophysical Research Letters Vol. 25: 9, P. 1431, 1998 doi:10.1029/98GL51099

Hart MR, Quin BF, and Nguyen ML. 2004. Phosphorus Runoff from Agricultural Land and Direct Fertilizer Effects: A Review. Journal of Environmental Quality 33:1954-1972.

He ZL, Zhang MK, Stoffella PJ, Yang XE, and Banks DJ. 2006. Phosphorus Concentrations and Loads in Runoff Water under Crop Production. Soil Science 70:1807-1816.

Hively WD, Lang M, McCarty GW, Keppler J, Sadeghi A, and McConnell LL. 2009. Using Satellite Remote Sensing to Estimate Winter Cover Crop Nutrient Uptake Efficiency. Journal of Soil and Water Conservation, 64(5): 303-313.

Krueger E, Ochsner TE, Porter PM, and Baker JM. 2011. Winter Rye Cover Crop Management Influences on Soil Water, Soil Nitrate, and Corn Development. Agronomy Journal 103: 316–323.

Lindstrom MJ, Skidmore EL, Gupta SC, and Onstad CA. 1979. Soil conservation limitations on removal of crop residues for energy production. Journal of Environmental Quality 8:533–537.

Pauer JJ, and Auer MT. 2000. Nitrification in the water column and sediment of a hypereutrophic lake and adjoining river system. Water Research 34:1247–1254.

Rabalais N, Eugene Turner R, and Wiseman WJ. 2001. Hypoxia in the Gulf of Mexico. Journal of Environmental Quality 30:320–329.

Rosenzweig C, Iglesias A, Yang XB, Epstein PR, and Chivian E. 2000. Climate Change and U.S. Agriculture: The Impacts of Warming and Extreme Weather Events on productivity, Plant Diseases, and Pests. Center for Health and the Global Environment. IPCC report. Boston, MA.

Ruiz Diaz DA, Sawyer JE, Barker DW, and Mallarino AP. 2010. Runoff Nitrogen Loss with Simulated Rainfall Immediately Following Poultry Manure Application for Corn Production. Soil Science 74:221-230.

Sims JT, Simard RR, and Joern BC. 1998. Phosphorus loss in agricultural drainage: Historical perspective and current research. Journal of Environmental Quality 27:277–293.

Thomas MA, Engel BA, and Chaubey I. 2011. Multiple Corn Stover Removal Rates for Cellulosic Biofuels and Long-term Water Quality Impacts. Journal of Soil and Water Conservation 66(6): 431-444.

Tonitto C, David MB, and Drinkwater LE. 2006. Replacing Bare Fallows with Cover Crops in Fertilizer-Intensive Cropping Systems: A Meta-Analysis of Crop Yield and N Dynamics. Agriculture, Ecosystems and Environment 112: 58-72.

Wischmeier WH. 1959. A Rainfall Erosion Index for a Universal Soil-Loss Equation. Soil Science 23(3): 246-249.

Chapter 1 - Effect of Winter Rye Seeding Methods on Surface Runoff under a Simulated Rainfall Event

Chapter Summary

The potential for soil erosion following soybeans is higher than after corn for grain harvest in agricultural landscapes. Winter rye cover crops can provide plant cover to mitigate soil losses and can be established more easily following soybeans than corn for grain in the Upper Mississippi River Basin. The objective of this study was to evaluate winter rye seeding methods and their potential to minimize the adverse effects of high rainfall rates on surface runoff, sediment, and nutrient transport from agricultural landscapes following soybean harvest. A simulated rainfall event of 6.34 cm hr^{-1} for 60 minutes was applied to rye and fallow treatments in fall 2010 and spring 2011 at the University of Minnesota Experimental Research Station in Rosemount, MN. Treatments were rye seeded by broadcast spreader, by airflow spreader, aerially by helicopter, and winter fallow (no rye). Rye biomass accumulation in spring was greatest with broadcast, followed by aerial, then airflow. There was 74, 78, and 83% ground cover in the spring for aerial, airflow, and broadcast treatments, respectively, compared to fallow, which had 49% ground cover. Winter fallow produced the highest volumes of surface runoff, nutrient concentrations, and sediment losses in both the fall and spring compared to winter rye treatments. Compared with winter fallow, total surface runoff was reduced by 78, 96, and 63% in the fall in aerial, airflow, and broadcast treatments, respectively, and by 100, 96, and 97% in aerial, airflow, and broadcast treatments, respectively, in the spring. NO_3-N losses in surface runoff in the fall were reduced by an average of 80% across rye seeding treatments. NO_3-N losses in surface runoff in the spring were reduced by 100, 96, and 97% with aerial, airflow, and broadcast treatments, respectively, compared with winter fallow. NH_4-N losses were reduced in the fall by 72, 53, and 53% in aerial, airflow, and broadcast seedings, respectively, and in the spring by 100, 100, and 99% in aerial, airflow, and broadcast seedings compared to winter fallow, respectively.

Total phosphorus losses were reduced in the fall by 86, 99, and 83% in aerial, airflow, and broadcast seedings, respectively, and in the spring by 100, 98, and 98% in aerial, airflow, and broadcast seedings, respectively, compared to fallow. Sediment losses were reduced in the fall by 78, 91, and 67% in aerial, airflow, and broadcast seedings, respectively, and in the spring by 100, 97, and 98% in aerial, airflow, and broadcast seedings, respectively, compared to fallow. We conclude that seeding winter rye into soybeans can reduce soil erosion and nutrient runoff in both fall and spring, with the greatest environmental benefits of additional cover occurring in the spring.

Introduction

Corn and soybean acreage in Minnesota was estimated at 15 million acres per year from 2007 to 2012 (USDA National Agricultural Statistics Service). These two crops comprise about half the total farmed acres in Minnesota. Current production practices with corn and soybean result in NO_3-N leaching into rivers, streams, and lakes through overland flow and subsurface drainage. Winter cover crops can provide NO_3-N retention through uptake of nitrogen during fallow periods. A meta-analysis found a 70% average reduction in NO_3-N leaching using cover crops (Tonitto et al. 2006). Staver and Brinsfield found that winter rye reduced nitrogen loads by 80% in subsurface groundwater and in deeper aquifers under corn rotations (1998).

Soil erosion during the dormant period is another concern with corn-soybean crop rotations, especially following soybean. Soil erosion can increase by 35% after soybeans compared to corn because of lower residue production and faster decomposition of soybean residue (Laflen and Moldenhauer 1979). Winter cover crops can provide the necessary erosion control after soybean harvest. A study by Kessavalou and Walters (1997) showed that ground cover increased by 30% when winter rye was planted after soybeans compared to just fallow. The increase in ground cover minimized soil erosion before a corn canopy (corn-soybean rotation) could be established in early summer the following year.

Winter cover crops are sometimes difficult to establish after row crops in the Upper Midwest because of the short growing season. The early soybean harvest in Minnesota increases the time available for establishing cover crops when compared with the later corn grain harvest. Soybean harvest in Minnesota usually occurs in late September and October during normal growing conditions, whereas harvesting corn for grain continues into November (USDA 1997). Winter cover crops, especially winter rye, can be planted into a standing soybean crop in late August to mid-September in Minnesota, when soybeans are showing 10% or more leaf yellowing or leaf drop. This provides adequate solar radiation for fall establishment of winter rye.

Winter rye can be seeded into soybean using several different methods. These include aerial application from a helicopter, broadcast seeding from a tractor, and airflow seeding from a tractor. Timing of planting, seeding rates, method of seeding, and soil moisture play crucial roles in the success of establishing winter rye into soybean in late August or September.

We hypothesized that a winter rye cover crop seeded into standing soybeans can reduce non-point source pollution through surface runoff and minimize soil erosion by adding additional surface cover along with soybean residue. The objective of this study was to evaluate winter rye seeding methods and their potential to minimize the negative effects of high rainfall rates on surface runoff, sediment and nutrient transport from agricultural landscapes by providing increased ground cover during fall and spring following soybean harvest.

Materials and Methods

The rainfall simulation study was conducted on field I-10 at the University of Minnesota Outreach, Research and Education (UMore) Park located in Rosemount, MN (44.706^0 N, 93.067^0 W) on 2, 3, and 4 November 2010 and on 28, 29 April 2011 and 2 May 2011. In both fall and spring, simulations occurred on the same field on land with a 3% slope. The soil series was Waukegan Silt Loam (fine-silty over sandy, mixed, superactive, mesic Typic Hapludolls) and Urban Land-Waukegan Complex (fine-silty over sandy, mixed, superactive, mesic Typic Hapludolls). This study consisted of four treatments with two replications in a completely randomized design. Originally there were three replications for each treatment; however, the third replication site was an outlier and had uncharacteristic winter rye stands and soil composition compared with the other two replications. For these reasons, only two replications were analyzed. The treatments were aerial, airflow, broadcast, and winter fallow (drilled rye later in fall). The winter rye cultivar "Rymin" was seeded at rates of 112 kg ha^{-1}, 112 kg ha^{-1}, 224 kg ha^{-1}, and 89 kg ha^{-1}, respectively; in strips across a 40-acre field using a bucket spinner attached to a helicopter, a Gandy airflow spreader attached to a tractor, a bucket spreader with spinning plate attached to a tractor, and drilled in 17.78 cm rows, respectively. Dates of seeding were 9 September 2010, 14 September 2010, 14 September 2010, and 14 October 2010, respectively. The target seeding rate for all treatments was meant to be 112 kg ha^{-1}; however, calibration of controlling rate for broadcast treatments was unsuccessful. Seeding rates will be a confounding factor for determining the effect of ground cover and biomass on surface runoff. Fallow treatments were prepared by chemical termination of rye in the drilled strips using glyphosate (Roundup Ready solution at a rate of 1 kg acid equivalent ha^{-1}) soon after rye germination on 22 October 2010. The field management consisted of no-tilling practices. New fallow treatments had to be established prior to spring simulations since no-till practices were used in the larger field, making previous fallow plots unusable. Additional chemical treatment of glyphosate occurred on 21 March 2011 to create fallow treatments. All winter rye treatments were terminated using glyphosate in late-May prior to corn silage planting.

Plot sizes were 4.8 m wide by 7.6 m long, with the longer side running down the slope. Galvanized steel sheets (1.52 m long by 0.152 m wide) were pounded 0.076 m into the ground to create treatment borders. A galvanized steel catchment (1.52 m long by 0.3048 m wide) was used to capture surface runoff, which drained through a pipe on the back end of the steel catchment. The rainfall simulations were conducted in the center of each treatment, leaving 0.9 m on each side of the treatments for access to the rainfall simulator. A Norton Ladder type Purdue Rainfall Simulator constructed by

Advanced Design and Machine (Clarks Hill, IN) was used to apply simulated rainfall. The simulator used a pressurized nozzle with an oscillating boom. Because time constraints prevented completion of all simulations in one day, simulations were spread over three days (2, 3, 4 November 2010 and 28, 29 April 2011 and 2 May 2011). UMore Park well water was hauled in tanks and used to perform the surface runoff experiment. Water was pumped from the reservoir to the simulator using a Honda 5000 generator (Honda Power Equipment, Alpharetta, GA) and septic water pump (Goulds Pumps, Seneca Falls, NY). Water was transferred to a polyvinyl chloride (PVC) manifold that transferred the water to three inlets on top of the rainfall simulator. The three inlets allowed the water to flow through six floodjet 3/8K SS45 nozzles (Spraying Systems Co. Wheaton, IL) that evenly dispersed the simulated rainfall to the different treatments.

Winter Rye Biomass Determination

Winter rye biomass was collected on 4 November 2010 and 2 May 2011 after rainfall simulations were conducted. Winter rye biomass yield was determined by harvesting an area of 0.25 m^3 three times for each rye treatment in a randomly selected location adjacent to each treatment plot. Samples were dried at 65°C for 72 h and dry matter was calculated. A subsample was ground, passed through a 1 mm sieve, and analyzed for total N (TKN), neutral detergent fiber, and phosphorus by wet analysis by Stearns DHIA Laboratories, Sauk Centre, MN.

Water Samples

Water samples were collected in 1 L polypropylene bottles (Teledyne ISCO Inc., Lincoln, NE) every 10 minutes after initial surface runoff occurred in each simulation. Between samples, all water was collected to determine total surface runoff volume from the treatment. The water samples were immediately placed in a cooler with ice. Samples were filtered using a 0.2 μ filter with a non-surgical syringe (120 ml was filtered from each bottle) (VWR International, Chicago, IL). Filtered samples were analyzed for NO_3-

N, NH_4-N, and dissolved reactive phosphorus (DRP) using a Quikchem 8500 Lachat Ion analyzer (Hach Company, Loveland, CO). Other filtered samples were analyzed for total dissolved phosphorus (TDP) (University of Minnesota Soil Testing Laboratory) using rapid flow analyzer (RFA) method with Alpkem RFA 300 (RFA, 1986 and Astoria-Pacific, Clackamas, OR). Unfiltered samples were analyzed for total suspended solids (TSS), sediment carbon, sediment nitrogen, and total phosphorus (TP). TSS was determined with ESS Method 340.2 (U.S. Environmental Protection Agency). TP analysis was performed by the University of Minnesota Soil Testing Laboratory using RFA method with Alpkem RFA 300 (RFA, 1986 and Astoria-Pacific, Clackamas, OR). Sediment carbon and sediment nitrogen were determined using Elementar Vario EL combustion analyzer (Elementar Americas, Inc., Mt. Laurel, NJ).

Soil Samples

On 4 November 2010 and 2 May 2011, soil samples were collected from the simulation treatments plots to a depth of 90 cm using a Giddings probe (5.08 cm diameter) mounted on a truck. One core was collected at the upslope, mid slope, and downslope positions of each treatment, for a total of three cores per treatment. These cores were subsampled by depth in the following increments: 0-15, 15-30, 30-60 and 60-90 cm, and composited by depth for each plot. Soil samples were subsampled (approximately 200 g per sample) for physical analysis and were dried at 105°C to determine gravimetric water content and bulk density. The bulk of the soil sample was dried at 37°C, ground through a <0.5 mm sieve, and analyzed for soil NO_3-N, NH_4-N, and Mehlich-III P using a Quikchem 8500 Lachat Ion analyzer (Hach Company, Loveland, CO). Additional soil sampling to a depth of 0-15 cm was used to calculate antecedent soil moisture conditions at the time of rainfall simulations. There was no difference in antecedent moisture between treatments, with gravimetric water content averaging 0.20 for fall and 0.22 for spring.

Ground Cover

Ground cover data were collected on 2 November 2010 and 28 April 2011. At the time of simulations, three digital photographs were taken of each treatment using a camera mounted on a stand facing downward at a height of 1.2 m. The photographs were analyzed using USDA Sample-Point Measurement Software 1.48 (Booth, 2006). This software allows for a 100-point grid to be placed over each photograph. Average ground cover was determined by visual observation at each point.

Calibration of Rainfall Simulator

The Rainfall Simulator was calibrated on 19 May 2010. A control setting for field simulations was chosen to represent a roughly 5 cm hr^{-1} storm event, corresponding to a rain event with a 10-year return frequency in Rochester, MN. For these calibrations, 40 uniform jars were arranged between the simulator nozzles and under the simulator nozzles within one treatment. Rain intensity was determined from the volume of water collected in each jar and the duration of the event. Average rainfall rate using the jar method was 6.34 cm hr^{-1} for both calibrations. Ten rain gauges were used in every treatment during rainfall simulations for comparison to the calibration used at the field. Average rain gauge measurement for 2010 was 5.60 cm and 5.85 cm for 2011.

Statistical Analysis

Data in the study were subjected to a two-way ANOVA (Rweb version 2.20.1., R core Team, 2009) and statistical significance was evaluated at the $p \leq 0.05$. In fall, winter rye seeding method had no treatment effect on runoff volume, winter rye biomass, ground cover, soil nutrient concentrations (except for ammonium which differed across depths), nutrient losses, and sediment. In spring, the effect of treatment was significant for runoff volume, NO_3-N losses, NH_4-N losses, sediment losses, and ground cover. There was no treatment effect in soil nutrient concentrations in spring. Interaction of biomass and ground cover had an effect on runoff for spring but not in fall. Runoff had significant effect on NO_3-N losses, phosphorus losses and on sediment. Least significant difference (LSD) testing was used to observe differences between treatments. A LSD test confidence interval of 0.05 was used throughout the analysis.

Results and Discussion

Rye Biomass, Ground Cover, Soil Composition

Ground cover provided by soybean residue decreased from fall to spring for all treatments because of residue decomposition (Table 1-1). By the spring, rye significantly increased ground cover compared with winter fallow for all treatments. Ground cover is important for preventing wind and water erosion in agricultural landscapes following soybean harvest in the Upper Mississippi River Basin because of rapid decomposition of soybean residue during the dormant period (Ghidey and Alberts 1998).

Winter rye biomass accumulation was greater in spring than in fall. Between fall and spring, winter rye biomass increased by 83, 43, and 73% for aerial, airflow, and broadcast treatments, respectively (Table 1-1). Differences in biomass accumulation may be due to differences in seeding methods and seeding rates. Broadcast rye treatment had double the seeding rate than aerial and airflow treatments. In airflow seeding, it is essential to have higher airflows to control uniformity in seed distribution; however, higher air flows can cause seed blowouts at the open end of the seeder and lead to decreased uniformity across the field. Controlling uniformity in seeding winter rye is essential to having successful seed distribution across the field.

Winter rye had an average of 1.7% and 2.4% TKN for fall and spring, respectively. The average phosphorus in winter rye plant tissue was 0.17% and 0.25% for fall and spring, respectively. Nitrogen accumulation for rye treatments in the fall were 11 kg ha^{-1}, 12 kg ha^{-1}, and 19 kg ha^{-1}, for aerial, airflow, and broadcast, respectively. In the spring, nitrogen accumulation for rye treatments were 92 kg ha^{-1}, 35 kg ha^{-1}, and 89 kg ha^{-1}, for aerial, airflow, and broadcast, respectively. Neutral detergent fiber (NDF) of rye was 44% in fall, and 42% in spring. NDF is the measurement of cellulose, hemicellulose, lignin, and cutin in forage which provides fiber for ruminant animals. Alfalfa has a typical NDF value of 43-51% and mixed grass forage has a typical NDF of 60% (National Research Council 2001, Miller and Hoover 1998).

Soil NO_3-N, NH_4-N and Mehlich-III P did not vary by treatment for either fall or spring (Fig 1-1). NO_3-N concentrations decreased from fall to spring in all treatments. Fallow treatments were initially drilled winter rye that had chemical termination prior to simulations. Fall preparation of fallow treatments had winter rye terminated after germination; however, spring termination of drilled winter rye for fallow treatment preparation occurred after snowmelt where winter rye plants had substantial growth. The presence of the rye is the reason for uptake of NO_3-N in the fallow treatments in the spring. For aerial and airflow treatments soil NO_3-N decreased from fall to spring but broadcast treatments did not change. This implies that at least some winter rye treatments did scavenge NO_3-N between fall and spring for some treatments. NH_4-N concentrations in fall differed among depths. NH_4-N concentrations were greater in the 0 to 30 cm depth than the 30 to 90 cm depth.

Total Surface Runoff

Winter rye treatments had 98% less runoff in spring compared to fallow (Table 1-2). Not surprising, no differences were observed in fall surface runoff because there was minimal rye growth in rye treatments. In spring, fallow had the greatest amount of runoff. The presence of winter rye and increased ground cover in winter rye treatments were the major contributing factors to decrease in runoff compared to fallow for spring simulations.

NO_3-N, NH_4-N, and Phosphorus loss in Surface Runoff

In spring, winter rye treatments reduced NO_3-N and NH_4-N losses in surface runoff compared to fallow. In fall, no differences were found in reductions of NO_3-N and NH_4-N losses in surface runoff compared to fallow (Table 1-3). In the spring NO_3-N losses were reduced by 98% for rye treatments compared to fallow (Table 1-3). NH_4-N losses followed a similar pattern to NO_3-N losses for the spring. In spring, NH_4-N losses were reduced by 100%, in rye treatments compared to fallow.

Water was the driving force behind increases in NO_3-N and NH_4-N losses, with greater amounts of runoff resulting in higher losses of NO_3-N and NH_4-N. Concentrations of NO_3-N in runoff for all treatments ranged from 4.84 mg L^{-1} to 7.66 mg L^{-1} in fall. In spring, NO_3-N concentrations ranged from 6.11 mg L^{-1} to 8.96 mg L^{-1}. These concentrations are below the EPA water quality standard of 10 mg L^{-1} in drinking water and for toxicity levels to aquatic species (EPA 2012). This standard of 10 mg L^{-1} of nitrate in drinking water was established to prevent human infant deaths caused by blue-baby syndrome. Blue-baby syndrome is an environmentally-caused health disorder in which the blood is unable to carry enough oxygen to vital tissues and organs (Knobeloch et al. 2000).

Phosphorus losses followed a similar trend as nitrogen losses for the four treatments. In the fall there was no difference in losses for any of the P fractions measured (Table 1-4). Differences were observed in spring loss of P, with fallow having the highest loss of P for several measured P fractions, and no differences existed between the rye seeding treatments (Table 1-4). Reduction in TP for spring was 100, 98, and 98% for aerial, airflow, and broadcast rye treatments, respectively, compared to fallow. Broadcast, aerial, and airflow rye treatments were similar in TP loss. The majority of P losses for all treatments were in the form of particulate phosphorus (PP) for both fall and spring where PP was 50 to 78% of total P lost in surface runoff (Table 1-4). This is not surprising, since many soils in their natural state are low in dissolved phosphorus and the majority of P lost in surface runoff occurs in the form of PP (Hart et al. 2004). Catchment studies conducted in New Zealand found that PP contributed 62 to 91% of total phosphorus fractions (Gillingham and Thorrold 2000). Phosphorus losses were impacted by increased runoff. Concentrations of TP in runoff for all treatments ranged from 0.13 mg L^{-1} to 0.22 mg L^{-1} in fall. In spring TP concentrations ranged from 0.15 mg L^{-1} to 0.22 mg L^{-1}. Phosphorus is the limiting nutrient for organisms in freshwater ecosystems, and in excess concentrations it can cause eutrophication. Eutrophication accelerates when 0.025 mg L^{-1} is added to lakes and rivers (EPA 2012). The maximum recommended concentration of phosphorus in rivers is 0.1 mg L^{-1} and in lakes is 0.05 mg L^{-1} (EPA 2012). The phosphorus in the runoff from the rainfall simulations is higher than the maximum recommendation for waterways; however, these concentrations came from the upland area of a field and were not directly running off into rivers or lakes. Phosphorus losses decrease with increased distance between field and waterways. Phosphorus losses can also decrease with additional buffer strips that would prevent sediment bound P or particulate phosphorus from reaching rivers or lakes (Dougherty et al. 2004).

Sediment Loss

In both fall and spring no differences were seen in sediment losses between aerial, airflow, and broadcast rye treatments compared to fallow (Table 1-5). Fallow appeared to have the highest loads of sediment in fall and spring compared to rye treatments (Table 1-5). Soil loss on agricultural landscapes increases with greater surface runoff since sediment movement is caused by overland flow of water in this study and not by wind erosion, which is another factor causing translocation of top soil in agricultural landscapes. Greater loss of sediment in surface runoff, as expected, attributes to a greater loss of total nitrogen and total carbon. In spring, differences were seen in total nitrogen and total carbon with fallow having greater loads then rye treatments (Table 1-5). Sediment losses were higher in fallow treatments for both fall and spring and the majority of phosphorus loss was in the form of sediment bound phosphorus or particulate phosphorus (Table 1-4).

Conclusions

The potential for soil erosion following soybean is higher than following corn for grain harvest in agricultural landscapes. A winter rye cover crop can provide plant cover to mitigate soil losses and can be established more easily following soybean than corn for grain in the Upper Mississippi River Basin. The objective of this study was to evaluate winter rye seeding methods and their potential to minimize the effects of high rainfall rates on surface runoff, sediment, and nutrient transport from agricultural landscapes by providing more ground cover during the fall and spring fallow periods following soybean harvest. Regardless of seeding method, the addition of winter rye following soybean reduced surface runoff compared with winter fallow. With reduced runoff, nutrient and sediment losses were also reduced with the presence of rye when compared with winter fallow. Aerial seeded rye reduced NO_3-N, NH_4-N, and TP by 81, 72, and 86% in fall compared to fallow, respectively, and had greater reductions in spring with 100% in all water quality parameters. Airflow seeded rye reduced NO_3-N, NH_4-N, and TP by 96, 53, and 99% in fall compared to fallow, respectively, and had reductions in spring of 96, 100, and 98%, respectively. Broadcast seeded rye reduced NO_3-N, NH_4-N, and TP by 64, 53, and 83% in fall compared to fallow, respectively, and in spring had reductions of 97, 99, and 98%, respectively. Soybean residue after harvest provided enough ground cover to minimize surface runoff in fall for all treatments. After rapid decomposition of soybean residue, spring surface runoff was 95% greater than fall runoff in fallow, which is a concern for water quality and a reason to seed winter rye for protection from soil erosion during spring rainfall events.

Establishing uniform stands of winter rye can be challenging depending on seeding method, date of planting, seeding rate, and environmental conditions that support winter rye germination and growth. Selecting the proper seeding method and rate can be costly to farmers who want to use this practice to provide environmental benefits. Broadcast had double the seeding rate of aerial and did not provide more environmental benefits with the higher seeding rate. This is a concern for farmers who do not need to spend more money for establishing a cover crop when they can receive equal environmental benefits using the lower seeding rate.

References

Dougherty WJ, Fleming NK, Cox JW, and Chittleborough DJ. 2004. Phosphorus Transfer in Surface Runoff from intensive Pasture Systems at Various Scales: A Review. Journal of Environmental Quality 33: 1973-1988.

EPA. 2012. Water Quality Criteria. United States Environmental Protection Agency. http://water.epa.gov/scitech/swguidance/standards/crit.cfm

Ghidey F and Alberts EE. 1998. Runoff and Soil Losses as Affected by Corn and Soybean Tillage Systems. Journal of Soil and Water Conservation, 53(1): 64-70.

Gillingham AG and Thorrold BS. 2000. A Review of New Zealnd Research Measuring Phosphorus in Runoff from Pasture. Journal of Environmental Quality 29: 88-96.

Hart MR, Quin BF, and Nguyen ML. 2004. Phosphorus Runoff from Agricultural Land and Direct Fertilizer Effects: A Review. Journal of Environmental Quality 33:1954-1972.

Knobeloch L, Salna B, Hogan A, Postle J, and Anderson H. 2000. Blue Babies and Nitrate-Contaminated Well Water. Environmental Health Perspectives July 108(7): 675-678.

Lachat Instruments. 2000a. Nitrate/nitrite, nitrite in surface water, wastewater. Quikchem Method no. 10-107-04-1-A. Lachat Instruments, Milwaukee, WI.

Lachat Instruments. 2000b. Ortho phosphate in waters. Quikchem Method no. 10-115-01-1-A. Lachat Instruments, Milwaukee, WI.

Laflen JM and Moldenhauer WC. 1979. Soil and water losses from corn–soybean rotations. Soil Science 43:1213–1215.

Miller TK and Hoover WH. 1998. Nutrient Analyses of Feedstuff Including Carbohydrates. Animal Science Report No. 1. West Virginia University, Morgantown.

Mueller DK. and Helsel DR. 1999. "Nutrients in the Nation's Waters--Too Much of a Good Thing?" U.S. Geological Survey Circular 1136. National Water-Quality Assessment Program. http://water.usgs.gov/nawqa/circ-1136.html.

National Research Council. 2001. Nutrient Requirements of Dairy Cattle (7th rev. ed.) Natl. Acad. Sci., Washington, DC.

R Core Team. 2009. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. Vienna, Austria. ISBN 3-900051-07-0. http://www.R-project.org.

RFA Methodolgy. 1986. Astoria-Pacific International PO Box 830, Clackamas, OR 97015.

Staver KW and Brinsfield RB. 1998. Using Cereal Grain Winter Cover Crops to Reduce Groundwater Nitrate Contamination in the Mid-Atlantic Coastal Plain. Journal of Soil and Water Conservation 53 (3): 230-240.

Tonitto C, David MB, and Drinkwater LE. 2006. Replacing Bare Fallows with Cover Crops in Fertilizer-Intensive Cropping Systems: A Meta-Analysis of Crop Yield and N Dynamics. Agriculture, Ecosystems and Environment 112: 58-72.

USDA. 1997. Usual Planting and Harvesting Dates for U.S. Field Crops. National Agricultural Statistics Service. Agricultural Handbook 628. December.

Table 1-1. Rye dry matter and ground cover near Rosemount, MN in the fall of 2010 and spring of 2011.

	Dry Matter		**Ground Cover**	
	Fall	Spring[†]	Fall	Spring[†]
Treatment	- - - - - kg ha^{-1} - - - -		- - - - - - % - - - - - -	
Aerial	570	3348b	87	74b
Airflow	750	1316c	97	78ab
Broadcast	1295	4798a	96	83a
Fallow	0	0d	93	49c
LSD (0.05)	NS[‡]	86	NS[‡]	8
P value	0.30	0.03	0.15	0.04

† For a given sampling date, values followed by the same letter are not statistically different at $p \leq 0.05$

‡ NS = not significant

Table 1-2. Total surface runoff from simulated rainfall events near Rosemount, MN in the fall of 2010 and spring of 2011.

	Fall	**Spring**[†]
Treatment	- - - - - - - - - - - - mm	- - - - - - - - - - - -
Aerial	0.11	0.00b
Airflow	0.02	0.47b
Broadcast	0.19	0.31b
Fallow	0.51	10.56a
LSD (0.05)	NS[‡]	4.37
P value	0.35	0.03

† For a given sampling date, values followed by the same letter are not statistically different at $p \leq 0.05$

‡ NS = not significant

Table 1-3. NO_3-N and NH_4-N losses in surface runoff from simulated rainfall near Rosemount, MN in the fall of 2010 and spring of 2011.

	NO_3-N		NH_4-N	
	Fall	Spring†	Fall	Spring†
Treatment	- - - - - - - - - - - - - - - -	mg	- - - - - - - - - - - - - - - -	
Aerial	5.54	0.00b	0.09	0.00b
Airflow	1.15	24.25b	0.15	0.00b
Broadcast	10.78	16.70b	0.15	0.09b
Fallow	29.77	607.94a	0.32	26.44a
LSD (0.05)	NS‡	29.26	NS‡	5.59
P value	0.40	0.01	0.38	0.01

† For a given sampling date, values followed by the same letter are not statistically different at $p \leq 0.05$

‡ NS = not significant

Table 1-4. Phosphorus losses in surface runoff from simulated rainfall near Rosemount, MN in the fall of 2010 and spring of 2011.

	TP		**PP**		**TDP**		**DIP**		**DOP**	
	Fall	Spring†	Fall	Spring†	Fall	Spring	Fall	Spring	Fall	Spring
Treatment	- - - - - - - - - - - - - - - - - - -					mg - - - - - - - - - - - - - - - - - - -				
Aerial	0.33	0.00b	0.24	0.00b	0.09	0.00b	0.00	0.00	0.09	0.00
Airflow	0.02	2.00b	0.01	1.20b	0.01	0.80b	0.00	0.05	0.01	0.75
Broadcast	0.41	1.35b	0.32	1.04b	0.09	0.31b	0.01	0.01	0.08	0.30
Fallow	2.43	87.94a	1.85	64.43a	0.58	23.51a	0.01	0.51	0.57	23.00
LSD (0.05)	NS‡	13.61	NS‡	11.03	NS‡	7.97	NS‡	NS‡	NS‡	NS‡
P value	0.41	0.05	0.41	0.04	0.43	0.10	0.62	0.32	0.45	0.11

† For a given sampling date, values followed by the same letter are not statistically different at $p \leq 0.05$

‡ NS = not significant

Table 1-5. Sediment, total nitrogen and total carbon loads in surface runoff from simulated rainfall near Rosemount, MN in the fall of 2010 and spring of 2011.

Treatment	TSS		Total N		Total C	
	Fall	Spring	Fall	Spring[†]	Fall	Spring[†]
	- - - - - - - - - - - - - - - - - - - kg ha^{-1} - - - - - - - - - - - - - - - - - - -					
Aerial	7.05	0.00	0.05	0.00b	0.42	0.00b
Airflow	2.98	3.21	0.02	0.02b	0.15	0.21b
Broadcast	10.66	1.94	0.07	0.01b	0.61	0.11b
Fallow	32.64	115.77	0.20	0.36a	1.77	4.38a
LSD (0.05)	NS[‡]	NS[‡]	NS[‡]	0.25	NS[‡]	2.87
P value	0.32	0.10	0.39	0.03	0.41	0.04

† For a given sampling date, values followed by the same letter are not statistically different at $p \leq 0.05$

‡ NS = not significant

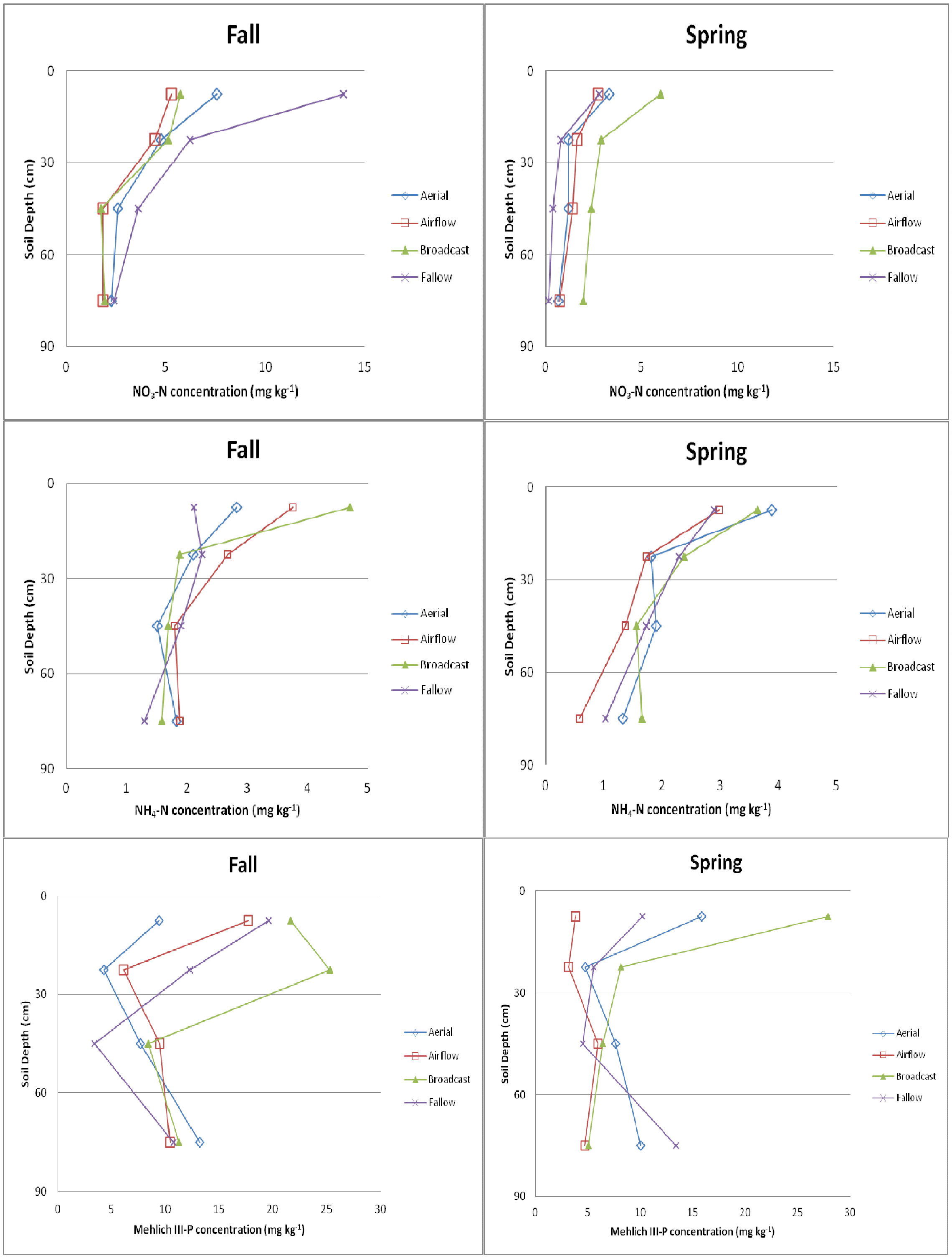


Figure 1-1. Soil nutrient concentrations of treatments near Rosemount, MN in the fall of 2010 and spring of 2011. Soil cores were analyzed for NO_3-N, NH_4-N, and Mehlich III-P. Concentrations are reflected in the figure at the average point between sample increments. No differences were observed in fall or spring for soil concentrations of NO_3-N, NH_4-N, and Mehlich III-P.

Chapter 2 - Effect of Management of Winter Rye on Surface Runoff under a Simulated Rainfall Event

Chapter Summary

Higher intensities and frequencies of rainfall events in the Upper Midwest, a predicted and observed manifestation of climate change, have the potential to cause significant damage to agricultural landscapes through soil erosion and transport of nutrients to waterways. The objective of this study was to evaluate the potential of a winter rye cover crop to minimize these effects by providing ground cover during the fall and spring dormant periods. A simulated rainfall event of 6.34 cm hr^{-1} for 60 minutes was applied to standing winter rye, harvested winter rye, and fallow treatments with four replications in spring 2010 and spring 2011 on a farm near Lewiston, MN. The fallow treatment produced the highest volume of surface runoff, nutrient, and sediment loads compared to winter rye treatments. Total surface runoff was reduced in 2010 by 99% for standing and harvested rye treatments compared to fallow. In 2011, total surface runoff was reduced by 67 and 19% for standing and harvested rye treatments, respectively, compared to fallow. Nutrient and sediment loads follow similar trends to total surface runoff for each year. In 2010 and 2011, NO_3-N losses were reduced by 99% and 68% for standing rye and 99% and 19% for harvested rye compared to fallow, respectively. NH_4-N losses were reduced by 96% and 80% in 2010 and 2011 for standing rye and 96% and 50% for harvested rye compared to fallow. Dissolved phosphorus losses were reduced by 99% and 75% in 2010 and 2011 for standing rye compared to fallow. Dissolved phosphorus losses were reduced by 98% in 2010 for harvested rye compared to fallow but increased by 1% in 2011. Sediment load was reduced by 99% and 92% in 2010 and 2011 for standing rye and 99% and 68% for harvested rye compared to fallow. We conclude that regardless of how winter rye is managed in the spring it still provides the ability to prevent surface runoff, soil erosion, and offsite nutrient transport relative to fallow in the Upper Midwest.

Introduction

Climate change has been a major focus within the scientific community in recent decades. Increases in atmospheric carbon dioxide and other greenhouse gases have resulted in rising mean global surface temperatures, which have been coupled with an increase in mean atmospheric water vapor (Frei et al. 1998). This has coincided with a higher frequency and intensity of storm events throughout the contiguous U.S. A century ago, the most extreme storms contributed only 1% of total annual rainfall. Now extreme storms contribute 20% of total rainfall in the continental U.S. while total precipitation has only increased by 7% over the past century (Rosenzweig et al. 2000). Heavy and intense rainfall can be devastating to cropland because of induced soil erosion, nutrient loss, and flooding. The rainfall erosion index component of the Universal soil-loss equation tries to quantify the effects of rainfall events on soil loss. Rainfall erosion potential is greatly affected by rainfall intensity and less by the amount of rainfall produced (Wischmeier 1959). Since extreme storm events are occurring more frequently and with higher intensity, it is necessary to provide some mitigation management tools to prevent excessive losses of sediment and nutrients from cropland.

In addition to soil quality declines associated with loss of topsoil, offsite nutrient transport also threatens surface water quality. Nutrients are lost in surface runoff in both dissolved and particulate form. Nitrogen fractions lost in surface runoff include NH_4-N and NO_3-N (Ruiz Diaz et al. 2010, Pauer and Auer 2000). Excessive NO_3-N concentrations in coastal waters lead to algal blooms that cause hypoxia and damage coastal ecosystems (David et al. 2010, Rabalais et al. 2001). Phosphorus (P) is a major contributing factor to eutrophication of fresh waters. In agricultural landscapes, manure and chemical fertilizers are major contributors to phosphorus buildup in the soil (Hart et al. 2004). Once phosphorus reaches excessive levels in the soil, the excess P can be a source for non-point pollution when water erosion occurs (Hart et al. 2004, Sims et al. 1998). P lost in surface runoff can be quantified and reported as total dissolved phosphorus, total phosphorus, PO_4^-, and particulate phosphorus (He et al. 2006). Sediment, when deposited in rivers and lakes through surface runoff can change the dynamics of water flow and ecosystems within those freshwater areas. Once sediment settles in rivers or lakes in large amounts, it can affect navigation, necessitating costly removal. Thus, a key component of climate change mitigation will involve actions to avoid these negative consequences of intense precipitation. Winter cover crops provide one potential tool.

Due to its cold tolerance, winter rye is an appropriate cover crop following corn (*Zea mays* L.) silage in the Upper Midwest (Krueger et al. 2012). Winter rye can also increase nitrogen use efficiency. The mechanism is twofold: winter rye helps to reduce soil erosion, thus keeping the organic matter in the top soil, and it also scavenges nitrate that would otherwise be lost through leaching (Hively et al. 2009). A meta-analysis found a 70% average reduction in nitrate leaching when cover crops were used (Tonitto et al. 2006). Staver and Brinsfield found that winter rye reduced nitrogen loads by 80% in subsurface groundwater and in deeper aquifers under corn rotations (1998). In another study, winter rye cover crops reduced nitrate concentrations in Canadian groundwater by 70% (Ball Coelho et al. 2005). However, the uptake of nitrogen by winter rye is dependent upon both early establishment of winter rye in the fall and robust spring biomass accumulation (Hively et al. 2009, Feyereisen et al. 2006).

We hypothesized that the use of a winter rye cover crop planted after corn silage harvest can reduce non-point source pollution through surface runoff compared to conventional corn silage management. The objective of this study was to evaluate the potential of a winter rye cover crop to minimize the effects of high rainfall rates on surface runoff, sediment, and nutrient transport from agricultural landscapes by providing cover during the fall and spring dormant periods. Since many farmers prefer to harvest winter rye for forage, we evaluated the effect of rye with and without rye biomass removal.

Methods and Materials

The study was conducted on a farm located near Lewiston, MN (43.969^0 N, 91.776^0 W) in 2010 and 2011. Each year, rainfall simulations occurred on different adjacent fields on a Seaton silt loam (Fine-silty, mixed, superactive, mesic Typic Hapludalfs) with a 3% slope. This study consisted of three treatments with four replications in a completely randomized design. The treatments were situated on the upland portion of the field where there was a straight downward slope of 3 % across an area that would fit all of the 12 randomized plots. Treatments were winter fallow after corn silage, standing winter rye, and harvested winter rye. Winter rye was cut at 10.2 cm above ground using a scythe and removed from the field for harvested rye treatments on 17 May 2010 and 2011. Winter rye cultivar "Rymin" was seeded over the entire experimental area on 28 September 2009 and 15 October 2010 at a rate of 101 kg ha^{-1} following corn stover removal for silage using a grain drill with 17.8 cm row spacing. The fallow treatment was prepared by chemical termination of rye using glyphosate (at a rate of 1 kg acid equivalent ha^{-1}) soon after rye germination on 15 October 2009 and 20 October 2010. For spring 2011 rainfall simulations, the fallow treatment required an additional application of glyphosate on 30 March.

Rainfall simulation plots were 4.8 m wide by 7.6 m long, with the longer side running down the slope. Galvanized steel sheets (1.52 m long by 0.152 m wide) were pounded 0.076 m into the ground to create treatment borders. A galvanized steel catchment (1.52 m long by 0.305 m wide) was used to capture surface runoff. The rainfall simulations were conducted in the center of the treatment, leaving 0.9 m on each side of the treatments for access to the rainfall simulator. A Norton Ladder type Purdue Rainfall Simulator constructed by Advanced Design and Machine (Clarks Hill, Indiana) was used, employing pressurized nozzle-type simulator with an oscillating boom. Because time constraints prevented completion of all simulations in one day, two simulations for each treatment were preformed per day (18 and 19 May 2010, 18 and 19 May 2011). City of Lewiston treated water was hauled in tanks and used for the surface runoff experiment. Water was pumped from the reservoir to the simulator using a Honda 5000 generator (Honda Power Equipment, Alpharetta, GA) and septic water pump (Goulds Pumps, Seneca Falls, NY). From the pump, water was transferred to a Polyvinyl chloride (PVC) manifold that then transferred the water to the three inlets on top of the rainfall simulator. The three inlets allowed the water to flow through six floodjet 3/8K

SS45 nozzles (Spraying Systems Co. Wheaton, IL) that evenly dispersed the simulated rainfall to the different treatments.

Calibration of Rainfall Simulator

The Rainfall Simulator was calibrated on 19 May 2010 and 19 May 2011 after rainfall simulations were completed. A control setting was chosen for field simulations that approximately represented a 5 cm hr^{-1} storm event, corresponding to a rain event with a 10 year return frequency for Rochester, MN. For these calibrations, 40 uniform jars were arranged between and under nozzles within each plot. Rain intensity was determined from the volume of water collected in each jar and the duration of the event. The average rainfall rate using the jar method was determined to be 6.34 cm hr^{-1} for both calibrations. Ten rain gauges were used in each plot during rainfall simulations for comparison to the calibration used at the field. The actual average rain gauge measurement for 2010 was 6.09 cm and 5.95 cm for 2011.

Winter Rye Biomass Determination

Winter rye biomass was collected on 17 May 2010 and 17 May 2011 prior to rainfall simulations. Harvested rye treatments were established by cutting the rye with a scythe on 17 May 2010 and 2011 to a height of 10.2 cm above ground and removing the clipped biomass. Biomass yield was determined by harvesting an area of 0.53 m^3 twice in each plot. Samples were dried at 65°C for 72 h prior to weighing. A subsample was ground, passed through a 1 mm sieve, and analyzed for total N (TKN), neutral detergent fiber and phosphorus by wet analysis by Stearns DHIA Laboratories, Sauk Centre, MN.

Water Samples

Water samples were collected in 1 L polypropylene bottles (Teledyne ISCO Inc., Lincoln, NE) every 10 minutes after initial surface runoff occurred in each rainfall simulation. Between samples, the water was collected to determine total surface runoff volume from the rainfall simulation. Water samples were immediately placed on ice in a cooler and subsequently filtered using a 0.2 μ filter (VWR International, Chicago, IL) with a non-surgical syringe (120 mL was filtered from each bottle). Filtered samples were analyzed for NO_3-N, NH_4-N, and dissolved reactive Phosphorus using a Quikchem 8500 Lachat Ion analyzer (Hach Company, Loveland, CO). Total dissolved phosphorus was determined for filtered samples (University of Minnesota Soil Testing Laboratory) using RFA method with Alpkem RFA 300 (RFA, 1986 and Astoria-Pacific, Clackamas, OR). Unfiltered samples were analyzed for Total Suspended Solids (TSS), Sediment Carbon, Sediment Nitrogen, and Total Phosphorus (TP). TSS was determined with ESS Method 340.2 (Environmental Protection Agency, US). TP analysis was performed by the University of Minnesota Soil Testing Labortory using RFA method with Alpkem RFA 300 (RFA, 1986 and Astoria-Pacific, Clackamas, OR). Sediment carbon and sediment nitrogen were determined using Elementar Vario EL combustion analyzer (Elementar Americas, Inc., Mt. Laurel, NJ).

Soil Samples

On 18 and 19 May 2010, soil samples were collected from all plots to a depth of 90 cm using a rotary hammer equipped with a 23 mm diameter probe. One core was collected at the upslope, mid slope, and downslope positions of each plot for a total of 3 cores per plot. Cores were subsampled by depth in the following increments: 0-15, 15-30, 30-60 and 60-90 cm, and composited by depth for each treatment. Soil samples were sub-sampled (approximately 200 grams per sample) for physical analysis and were dried at 105^0C to determine gravimetric water content and bulk density. The bulk soil sample was dried at 37^0C, ground through a <0.5 mm sieve, and analyzed for soil NO_3-N, NH_4-N, and Mehlich III P using a Quikchem 8500 Lachat Ion analyzer (Hach Company, Loveland, CO). Additional soil sampling to a depth of 0-15 cm was used to calculate antecedent soil moisture conditions at the time of rainfall simulations. Antecedent gravimetric soil moisture for depth of 0-15 cm was 0.25, 0.28, and 0.25 for standing rye, harvested rye, and fallow, respectively, for 2010. For 2011, antecedent gravimetric soil moisture was 0.22, 0.24, and 0.24 for standing rye, harvested rye, and fallow, respectively. There was no difference between treatments and years for antecedent soil moisture. On 17 May 2011, soil samples were collected adjacent to each simulation plots to a depth of 90 cm using a Giddings probe mounted on a truck (5.08 cm diameter). The same sampling protocol and analysis were followed as in 2010.

Ground Cover

Photographs for ground cover determination were collected on 17 May 2010 and 17 May 2011. At the time of simulations, three digital photographs were taken in each plot using a camera mounted on a stand facing downward at a height of 1.2 m. The photographs were analyzed using USDA Sample-Point Measurement Software 1.48 (Booth, 2006). This software allows for an overlay of a 100-point grid to be placed over each photograph. Ground cover was determined by visual observation at each point on the 100-point grid overlay.

Statistical Analysis

Data in the study were subjected to a two-way ANOVA (Rweb version 2.20.1., R core Team, 2009) and statistical significance was evaluated at the $p \leq 0.05$. In 2010, treatment effects were observed in runoff volume, winter rye biomass, ground cover, NO_3-N, NH_4-N, dissolved inorganic phosphorus, total phosphorus, total dissolved phosphorus, dissolved organic phosphorus, total suspended solids, sediment total nitrogen, sediment total carbon, and soil NO_3-N. In 2011, treatment effects were found in runoff, winter rye biomass, ground cover, NO_3-N, NH_4-N, dissolved inorganic phosphorus, total dissolved phosphorus, total suspended solids, sediment total nitrogen, and sediment total carbon. All other measurements not mentioned did not have any differences. Least significant difference (LSD) testing was used to observe differences between treatments. A LSD test confidence interval of 0.05 was used throughout the analysis.

Results and Discussion

Rye Biomass, Ground Cover, Soil Composition

Differences between treatments were observed in both 2010 and 2011 for ground cover and winter rye biomass. Rye biomass in the standing rye treatments was greater in 2010 than 2011 because planting occurred earlier in fall 2009 than in fall 2010 (Table 2-1). Winter rye had an average of 2% TKN and 0.25% phosphorus. Nitrogen accumulation for winter rye in 2010 was 122 kg ha^{-1} and 101 kg ha^{-1}, for standing rye and harvested rye, respectively. Nitrogen accumulation for winter rye in 2011 was 110 kg ha^{-1} and 108 kg ha^{-1}, for standing rye and harvested rye, respectively. Neutral detergent fiber (NDF) of rye was 46% in 2010, and 47% in 2011. NDF is the measurement of cellulose, hemicellulose, lignin, and cutin in forage which provides fiber for ruminant animals. Alfalfa has a typical NDF value of 43-51% and mixed grass forage has a typical NDF of 60% (National Research Council 2001, Miller and Hoover 1998). Winter rye provides similar fibrosity and energy value to alfalfa and mixed grass forages which is critical for producers to understand when adding winter rye to feed mixtures.

Standing rye and harvested rye had a 423 % and 398% increase in ground cover compared to fallow treatments in 2010, respectively. In 2011 standing rye and harvested rye had 497% and 400% greater ground cover than fallow, respectively (Table 2-1). In the spring, the harvested rye ground cover percentage was greater than in a similar Minnesota study where harvested winter rye provided “at least 30% ground cover” before corn planting in the spring (Krueger et al. 2012). Not surprisingly, there was a positive correlation between winter rye biomass and ground cover percentages (Table 2-1). Rye biomass and ground cover aid in the prevention of soil erosion in agricultural landscapes. Both standing biomass and ground cover act as buffers to the impact of rain drops that hit the soil surface and can also impede surface water that moves laterally over land surfaces.

Surface water that moves laterally over soil surfaces can accumulate and form concentrated flows or channels that sometimes cause gullies (Reicosky and Forcella, 1998).

In 2010, soil NO_3-N concentrations were reduced by 64% and 61% after standing rye and harvested rye compared to fallow treatments (Fig. 2-1). Winter rye did not impact soil NH_4-N or Mehlich-III P for either 2010 or 2011. This suggests that the winter rye effectively scavenged excess soil NO_3-N during the spring. However, in 2011 there was no difference in NO_3-N among treatments, possibly resulting from later rye planting and incomplete rye termination in 2010. Reduction in NO_3-N by winter rye can vary across soil types and rotations. On a research station in western Minnesota, winter rye reduced soil nitrate by 43 to 47% on silt loam soil following corn (Krueger et al. 2011). In Nebraska, winter rye reduced NO3-N by 18 to 33% following soybean on a silty clay loam soil (Kessavalou and Walters, 1999). Concerns of available soil N following termination of winter rye is a main factor affecting a subsequent corn crop. Side-dressing nitrogen is a potential solution to providing adequate soil N in early development of subsequent crop (Kuo and Jellum, 2002).

Total Surface Runoff

The standing rye and harvested rye treatments for both years produced less surface runoff when compared to the fallow treatment (Table 2-2). The reduction in runoff volume with rye compared with fallow was greater in 2010, primarily due to greater ground cover and total rye biomass than in spring 2011 (Table 2-1). In 2010, runoff was reduced by 99% for both standing rye and harvested rye compared to fallow. In 2011, runoff was reduced by 67% and 19% for standing rye and harvested rye, respectively, compared to fallow (Table 2-2). The difference in total volume of surface runoff between years was likely more attributable to differences in biomass and ground cover than to differences in antecedent rainfall. Rainfall was similar each year for the six week period before rainfall simulations, with precipitation totaling 15.2 and 14.5 cm in 2010 and 2011, respectively. Rye biomass and ground cover were lower in 2011 than

2010. These results are consistent with previous reports of increasing runoff and erosion associated with decreases in ground cover and canopy cover (Nearing et al. 2005).

NO_3-N, NH_4-N, and P loss in Surface Runoff

In both years, NO_3-N and NH_4-N losses from fallow treatments were substantially greater than from standing rye and harvested rye treatments (Table 2-3). NO_3-N was reduced by 99% for both standing rye and harvested rye compared to fallow in 2010. In 2011, NO_3-N was reduced by 68% and 19% for standing rye and harvested rye, respectively, compared to fallow (Table 2-3). Differences were found in both years for NO_3-N between treatments with standing rye having a higher reduction of NO_3-N than harvested rye when both treatments were compared to fallow. NH_4-N was reduced in both years by rye treatments compared to fallow which had the highest loss of NH_4-N. In 2010, NH_4-N was reduced by 97% and 96% for standing rye and harvested rye, respectively, compared to fallow. In 2011, reductions in NH_4-N were 80% and 50% for standing rye and harvested rye, respectively, compared to fallow (Table 2-3). Similar to NO_3-N losses in 2011, standing rye provided the greatest reduction for in NH_4-N than harvested rye. In 2010 no differences were found in NH_4-N losses between rye treatments however, both had greater reductions in NH_4-N losses than fallow (Table 2-3). The 2011 simulations had higher nutrient losses than 2010 because there was more runoff in every treatment compared to 2010. Concentrations of NO_3-N in runoff for all treatments ranged from 1.05 mg L^{-1} to 7.58 mg L^{-1} in 2010. In 2011, NO_3-N concentrations ranged from 5.10 mg L^{-1} to 5.65 mg L^{-1}. These concentrations are below the EPA water quality standard of 10 mg L^{-1} in drinking water (EPA 2012). This standard of 10 mg L^{-1} in drinking water was established to prevent human infant deaths caused by blue-baby syndrome. Blue-baby syndrome is an environmentally-caused health disorder in which the blood is unable to carry enough oxygen to vital tissues and organs (Knobeloch et al. 2000).

Phosphorus losses followed similar pattern as NO_3-N and NH_4-N losses, with standing rye having the lowest phosphorus loss, followed by harvested rye and fallow having the highest losses of phosphorus. In 2010, total phosphorus (TP) and total dissolved phosphorus (TDP) was reduced by 99% in both standing rye and harvested rye compared to fallow. In 2011, no differences were found in TP for standing rye, harvested rye, and fallow (Table 2-4). TDP was reduced by 67% in standing rye compared to fallow in 2011. Dissolved phosphorus losses were reduced by 99% and 75% in 2010 and 2011 for standing rye compared to fallow. Dissolved phosphorus losses were reduced by 98% in 2010 for harvested rye compared to fallow but increased by 1% in 2011 (Table 2-4). Harvested rye had higher TDP and dissolved inorganic phosphorus (DIP or dissolved reactive phosphorus or Ortho-P) than fallow in 2011, suggesting that there was P loss from the winter rye tissue on the surface (Hart et al. 2004) (Table 2-4). Concentrations of TP in runoff for all treatments ranged from 0 mg L^{-1} to 1.22 mg L^{-1} in 2010. In 2011, TP concentrations ranged from 0.20 mg L^{-1} to 7.06 mg L^{-1}. Phosphorus is the limiting nutrient for organisms in freshwater ecosystems, and in excess concentrations it can cause eutrophication. Eutrophication accelerates when 0.025 mg L^{-1} is added to lakes and rivers (EPA). The maximum concentration of phosphorus in rivers is 0.1 mg L^{-1} and in lakes is 0.05 mg L^{-1} (EPA). The phosphorus in the runoff from the rainfall simulations is higher than the maximum recommendation for waterways; however, these concentrations came from the upland area of a field and were not directly running off into rivers or lakes. Phosphorus losses decrease with increased distance between field and waterways. Phosphorus losses can also decrease with additional buffer strips that would prevent sediment bound P or particulate phosphorus from reaching rivers or lakes (Dougherty et al. 2004).

Sediment Loss

Sediment loads in winter rye treatments was greater in 2011 than 2010 due to the higher runoff totals in all treatments; however, fallow had greater sediment loss in 2010 than 2011. Sediment loss from fallow treatments in both years was greater than standing rye and harvested rye treatments. In 2010, sediment loss was reduced by 99% in both standing rye and harvested rye compared to fallow. In 2011, sediment was reduced by

92% and 68% in standing rye and harvested rye, respectively, compared to fallow (Table 2-5). Total nitrogen (N) and Total carbon (C) show the same trend as sediment across the treatments, where fallow treatments had higher sediment, total N, and total C loads compared to winter rye treatments. As expected, greater surface runoff produced higher loads of sediment (Table 2-5).

Conclusions

Winter rye, both standing and clipped, reduced runoff in both years. In 2010, runoff was reduced by 99% for both standing rye and harvested rye compared to fallow. In 2011, runoff was reduced by 67% and 19% for standing rye and harvested rye, respectively, compared to fallow. As a consequence, nutrient and sediment loads were also reduced compared to the fallow treatments. In 2010, winter rye treatments reduced NO_3-N, TP, and sediment by 99% compared to fallow. In 2011, standing rye reduced NO_3-N and sediment by 68% and 92% compared to fallow. Harvested rye treatments under performed in 2011 compared to 2010. In 2011, harvested rye reduced NO_3-N and sediment by 19% and 68% compared to fallow. When winter rye is managed in the spring, in this case, clipped and harvested for forage, the left over stubble still provided adequate cover to prevent surface runoff, sediment, and nutrient losses compared to fallow in 2010 and 2011. With increasing precipitation projected for the future, providing some plant cover or residue cover will be a key component in preserving soil quality and soil health of our agricultural lands. We conclude that a winter rye cover crop on the landscape during the dormant seasons can aid in reducing runoff into rivers, lakes, or streams. Of course, many other factors affect the transport of water across an agricultural field, e.g. – soil hydraulic conductivity, water holding capacity, topography, and tillage practices.

References

Ball Coelho BR, Roy RC, and Bruin AJ. 2005. Long-term Effects of Late-Summer Overseeding of Winter Rye on Corn Grain Yield and Nitrogen Balance. Canadian Journal of Plant Science 85: 543-554.

Booth DT, Cox SE, and Berryman RD. 2006. Point sampling digital imagery using ‘SamplePoint’. Environmental Monitoring and Assessment 123, 97–108. doi:10.1007/s10661-005-9164-7.

Dougherty WJ, Fleming NK, Cox JW, and Chittleborough DJ. 2004. Phosphorus Transfer in Surface Runoff from intensive Pasture Systems at Various Scales: A Review. Journal of Environmental Quality 33: 1973-1988.

Feyereisen GW, Wilson BN, Sands GR, Strock JS, and Porter PM. 2006. Potential for a Rye Cover Crop to Reduce Nitrate Loss in Southwestern Minnesota. Agronomy Journal 98: 1416-1426.

Frei C, Schar C, Luthi D, and Davies HC. 1998. Heavy Precipitation Processes in a Warmer Climate. Geophysical Research Letters Vol. 25: 9, P. 1431, 1998 doi:10.1029/98GL51099

He ZL, Zhang MK, Stoffella PJ, Yang XE, and Banks DJ. 2006. Phosphorus Concentrations and Loads in Runoff Water under Crop Production. Soil Science 70:1807-1816.

Hively WD, Lang M, McCarty GW, Keppler J, Sadeghi A, and McConnell LL. 2009. Using Satellite Remote Sensing to Estimate Winter Cover Crop Nutrient Uptake Efficiency. Journal of Soil and Water Conservation, 64(5): 303-313.

Kessavalou A and Walters D. 1999. Winter Rye Cover Crop Following Soybean Under Conservation Tillage: Residual Soil Nitrate. Agronomy Journal 91:643–649.

Krueger E, Ochsner TE, Porter PM, and Baker JM. 2011. Winter Rye Cover Crop Management Influences on Soil Water, Soil Nitrate, and Corn Development. Agronomy Journal 103: 316–323.

Krueger E, Ochsner TE, Baker JM, Porter PM, and Reicosky DC. 2012. Rye-Corn Silage Double-Cropping Reduces Corn Yield but Improves Environmental Impact. Agronomy Journal 104:888-896.

Kuo S and Jellum E. 2002. Influence of Winter Cover Crop and Residue Management on Soil Nitrogen Availability and Corn. Agronomy Journal 94:501–508.

Lachat Instruments. 2000a. Nitrate/nitrite, nitrite in surface water, wastewater. Quikchem Method no. 10-107-04-1-A. Lachat Instruments, Milwaukee, WI.

Lachat Instruments. 2000b. Ortho phosphate in waters. Quikchem Method no. 10-115-01-1-A. Lachat Instruments, Milwaukee, WI.

Miller TK and Hoover WH. 1998. Nutrient Analyses of Feedstuff Including Carbohydrates. Animal Science Report No. 1. West Virginia University, Morgantown.

National Research Council. 2001. Nutrient Requirements of Dairy Cattle (7th rev. ed.) Natl. Acad. Sci., Washington, DC.

Nearing MA, Jetten V, Baffaut C, Cerdan O, Couturier A, Hernandez M, Bissonnais TL, Nichols MH, Nunes JP, Renschler CS, Souchere V, and Van Oost K. 2005. Modeling response of soil erosion and runoff to changes in precipitation and cover. Catena 61: 131-154.

Pauer JJ, and Auer MT. 2000. Nitrification in the water column and sediment of a hypereutrophic lake and adjoining river system. Water Research 34:1247–1254.

R Core Team. 2009. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. Vienna, Austria. ISBN 3-900051-07-0. http://www.R-project.org.

Rabalais N, Eugene Turner R, and Wiseman WJ. 2001. Hypoxia in the Gulf of Mexico. Journal of Environmental Quality 30:320–329.

RFA Methodolgy. 1986. Astoria-Pacific International PO Box 830, Clackamas, OR 97015.

Rosenzweig C, Iglesias A, Yang XB, Epstein PR, and Chivian E. 2000. Climate Change and U.S. Agriculture: The Impacts of Warming and Extreme Weather Events on productivity, Plant Diseases, and Pests. Center for Health and the Global Environment. IPCC report. Boston, MA.

Ruiz Diaz DA, Sawyer JE, Barker DW, and Mallarino AP. 2010. Runoff Nitrogen Loss with Simulated Rainfall Immediately Following Poultry Manure Application for Corn Production. Soil Science 74:221-230.

Sims JT, Simard RR, and Joern BC. 1998. Phosphorus loss in agricultural drainage: Historical perspective and current research. Journal of Environmental Quality 27:277–293.

Staver KW and Brinsfield RB. 1998. Using Cereal Grain Winter Cover Crops to Reduce Groundwater Nitrate Contamination in the Mid-Atlantic Coastal Plain. Journal of Soil and Water Conservation 53 (3): 230-240.

Tonitto C, David MB, and Drinkwater LE. 2006. Replacing Bare Fallows with Cover Crops in Fertilizer-Intensive Cropping Systems: A Meta-Analysis of Crop Yield and N Dynamics. Agriculture, Ecosystems and Environment 112: 58-72.

Wischmeier WH. 1959. A Rainfall Erosion Index for a Universal Soil-Loss Equation. Soil Science 23(3): 246-249.

Table 2-1. Rye dry matter and ground cover near Lewiston, MN in spring of 2010 and 2011.

	Dry Matter†		Ground Cover†	
	2010	2011	2010	2011
Treatment	- - - - - kg ha^{-1} - - - - -		- - - - - % - - - - -	
Standing Rye	5872a	4096a	95.8a	85.5a
Harvested Rye	1434b	1205b	91.3b	71.6b
Fallow	0c	0c	18.3c	14.3c
LSD (0.05)	44.4	51.7	2.71	3.21
P value	<0.0000	0.001	<0.0000	<0.0000

† For a given sampling date, values followed by the same letter are not statistically different at $p \leq 0.05$

Table 2-2. Total surface runoff after 1 hr of simulated rainfall near Lewiston, MN in spring of 2010 and 2011.

	Runoff†	
	2010	2011
Treatment	- - - - - - - - mm - - - - - - -	
Standing Rye	0.06b	5.13c
Harvested Rye	0.03b	12.62b
Fallow	11.36a	15.55a
LSD (0.05)	1.56	2.52
P value	<0.0000	0.0006

† For a given sampling date, values followed by the same letter are not statistically different at $p \leq 0.05$

Table 2-3. NO_3-N and NH_4-N losses in surface runoff after 1 hr of simulated rainfall near Lewiston, MN in spring of 2010 and 2011.

	NO_3-N†		**NH_4-N**†	
	2010	2011	2010	2011
Treatment	- - - - - mg - - - - -		- - - - - mg - - - - -	
Standing Rye	1.91b	228.59c	0.76b	12.45c
Harvested Rye	1.06b	574.89b	1.03b	30.87b
Fallow	514.02a	710.01a	23.81a	62.32a
LSD (0.05)	9.89	16.74	2.84	6.23
P value	<0.0000	0.0004	<0.0000	0.0037

† For a given sampling date, values followed by the same letter are not statistically different at $p \leq 0.05$

Table 2-4. Phosphorus losses in surface runoff after 1 hr of simulated rainfall near Lewiston, MN in spring of 2010 and 2011.

	TP		TDP		DIP		DOP	
	2010†	2011	2010†	2011†	2010†	2011†	2010†	2011
Treatment	- - - - - - - - - - - - - - - mg - - - - - - - - - - - - - - -							
Standing Rye	0.07b	23.53	0.21b	31.14b	0.12b	17.55b	0.09b	13.59
Harvested Rye	0.16b	76.66	0.196b	96.25a	0.12b	72.42a	0.08b	28.83
Fallow	43.23a	104.36	53.61a	94.44a	49.09a	71.26a	4.52a	23.19
LSD (0.05)	5.62	NS‡	4.12	6.56	4.29	5.23	1.89	NS‡
P value	0.001	0.103	<0.000	0.001	<0.000	<0.000	0.002	0.285

† For a given sampling date, values followed by the same letter are not statistically different at $p \leq 0.05$

‡ NS = not significant

Table 2-5. Sediment, total nitrogen, and total carbon loads in surface runoff after 1 hr of simulated rainfall near Lewiston, MN in spring of 2010 and 2011.

	TSS†		**Total N Loss**†		**Total C loss**†	
	2010	2011	2010	2011	2010	2011
Treatment	- - - - - - - - - - - - - - - - - - kg ha^{-1} - - - - - - - - - - - - - - - - - -					
Standing Rye	3.97b	51.60c	0.05b	1.23c	0.34b	10.88c
Harvested Rye	1.25b	220.15b	0.004b	5.43b	0.03b	44.08b
Fallow	1359.16a	683.85a	37.07a	16.77a	312.64a	142.52a
LSD (0.05)	23.30	13.38	4.28	2.08	12	5.86
P value	<0.0000	<0.0000	0.0002	<0.0000	0.0001	<0.0000

† For a given sampling date, values followed by the same letter are not statistically different at $p \leq 0.05$

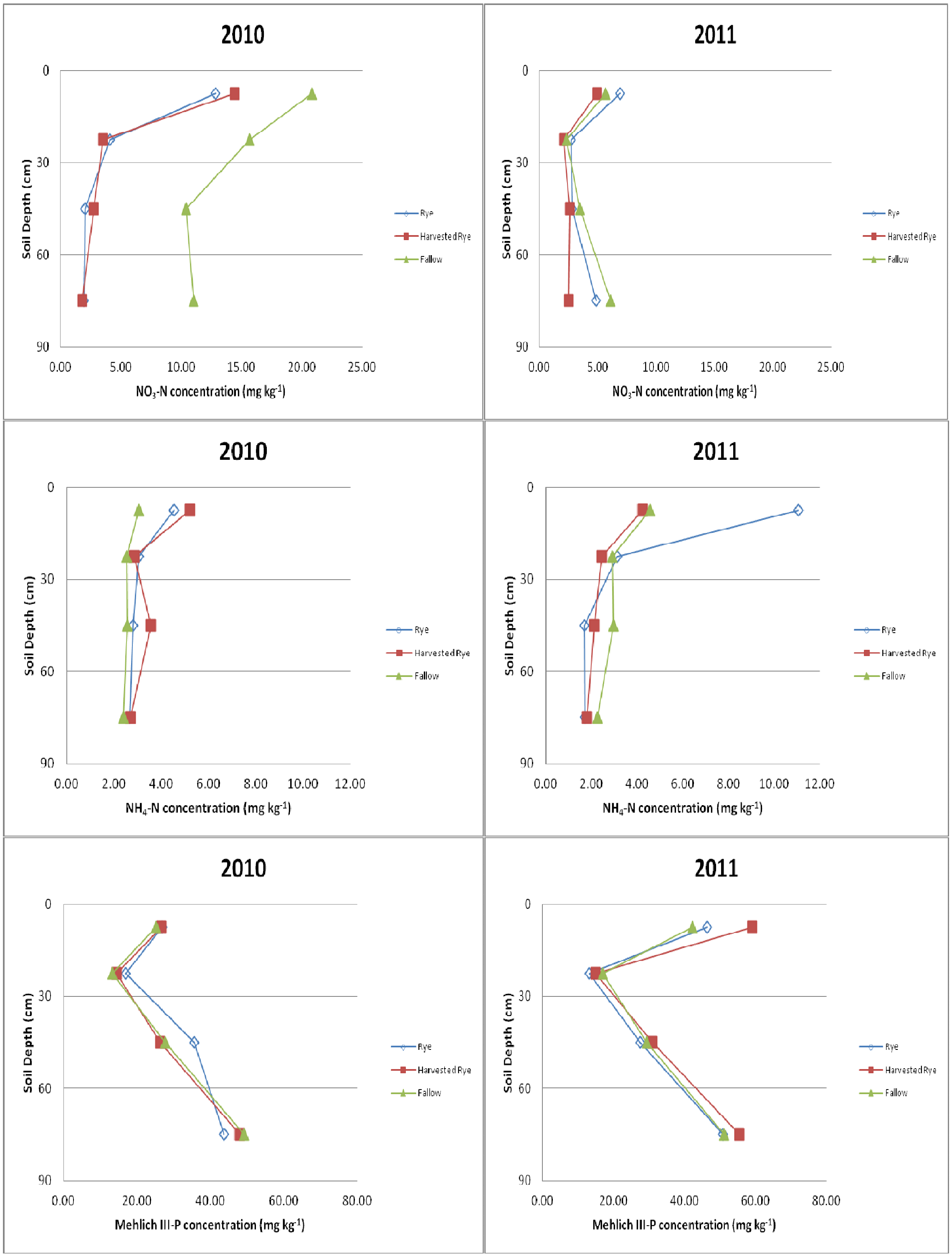


Figure 2-1. Soil NO_3-N, NH_4-N, and Mehlich III-P concentrations after winter fallow, harvest rye, and standing rye for 2010 and 2011 near Lewiston Minnesota. Concentrations are reflected in the figure at the average point between sample increments. Differences were observed in soil NO_3-N for 2010 but not for 2011. No differences were observed in soil NH_4-N and Mehlich III-P for either 2010 or 2011.

Chapter 3 - Effect of Removed Corn Stover on Surface Runoff in a Paired Watershed

Chapter Summary

Removal of corn stover for 2nd generation biofuel production, animal bedding, or feed can have detrimental impacts on water quality because of increased potential for offsite nutrient and sediment transport. Surface water runoff from a no-till corn grain-soybean rotation (control) and in a no-till corn grain-soybean rotation with corn stover removal (treatment) was monitored using H-flumes with ISCO portable samplers and bubbler flow meters from 2010 to 2012 on a farm near Plainview, MN. Baseline comparisons in 2010 showed that the control watershed (because of its larger size) had more surface runoff than the treatment watershed, but both had similar soil characteristics. Experimental year data (2011) showed that removal of corn stover increased surface runoff by 30% compared to conventional no-till practices. Water quality parameters in surface runoff (NO_3-N, NH_4-N, phosphorus and sediment) were not evaluated in 2011 due to sampler malfunction during runoff events (the major event for 2011 was spring snowmelt). Indications from 2010 surface runoff sample collections showed that NO_3-N, NH_4-N, phosphorus and sediment would have increased in 2011 because of increased volume of surface runoff. Removal of corn stover may increase soil erosion risks associated with no-till conventional practices and may negatively impact water quality.

Introduction

There are 2.4 million cattle in Minnesota, and they have a unique effect on corn-based cropping systems because they consume both corn grain and stover (NASS, 2012). Baling of corn stover after grain harvest reduces crop residue remaining and can have adverse effects on soil quality and health. Corn stover is a viable biofuel feedstock for 2nd generation (cellulosic) biofuel production that could reduce fossil fuel consumption and CO_2 emissions (Blanco-Canqui et al. 2006). Technologies for harvesting corn stover are well advanced, and as cellulosic biofuel demand increases, demand for corn stover is also expected to increase. This may have adverse effects on soil quality and health with increased risk of soil erosion on corn-based agricultural land. Corn residues left after harvest are vital to environmental protection of water resources for most of the U.S. Corn Belt. If removed for biofuel production, the lack of residues on the soil surface could increase soil erosion and offsite transport of nutrients into rivers, streams, and lakes. Removal of corn residue at excessive rates can influence changes at the soil surface, particularly crusting and surface sealing (Blanco-Canqui et al. 2006). Crust layers are thin compared to other soil layers but are dense and have low permeability, which affects soil infiltration and increase surface runoff (USDA-NRCS, 1996). Corn residue also minimizes raindrop impact that causes dispersion of surface aggregates. Several studies evaluated different rates of corn stover removal and its impact on maintaining residue requirements to reduce soil erosion risks. Thomas et al. found that removal of corn stover at rates of 38, 52.5, and 70% all increased annual soil erosion (2011). However, the amount of corn stover removed without increasing soil erosion risks should be site specific in the US Corn Belt (Lindstrom et al. 1979).

Initially, the objective of this study was to evaluate removal of corn stover with addition of winter rye to minimize soil erosion risks associated with removing corn residue on the soil surface. Rye aerially seeded into standing corn grain in September of 2010 was not successfully established. In order to maintain field sites for an experiment, the new objective of the study was to evaluate the impact of removing corn stover on water quality in a paired watershed design. Two adjacent watersheds equipped with edge-of-field surface runoff monitoring equipment were used to compare runoff volume, nutrient load, and sediment load of conventional residue management practices and removal of corn stover.

Methods and Materials

The study was conducted on a farm located near Plainview, MN (44.187^0 N, 92.183^0 W) in 2009 to 2012. Two adjacent watersheds on Downs-Hersey Complex with 2 to 12% slope (Fine-silty, mixed, superactive, mesic Mollic Hapludalfs) were chosen for edge-of-field surface runoff monitoring. This study consisted of two treatments in a paired watershed experimental design. One watershed was used as the control where cropping rotation was corn, corn, and soybean. The treatment watershed was corn, corn followed by removal of corn stover, and soybean. The first year was a baseline year, and the second year treatment (removing corn stover) was applied on 30 October 2010 following harvest of corn grain. Wing-walls were constructed using methods outlined by the United States Geological Survey and the University of Wisconsin-Madison (Stuntebeck, 2008). Construction began on 11 November 2009 and ended on 13 November 2009. Watersheds were trenched to 61 cm depth for plywood wall installation, and each wall measured 45 m when completed. After wall installation and backfilling, the wall was reinforced with 1.8 m T-posts spaced 2-5 m apart. Each watershed had sufficient elevation change on the downstream side of the flumes to prevent ponding which drained into an adjacent pasture. An electric fence was installed to prevent the cattle in the pasture from damaging the equipment in both watersheds. Platforms for the ISCO shelter and rebar support for the flumes were also installed in both watersheds. One H-flume (Plasti-Fab Inc., Tualatin, OR), 0.91 m in height, coupled with an ISCO 3700 portable sampler and 4230 bubbler flow meter (Teledyne ISCO Inc., Lincoln, NE) was used at each watershed in accordance with USGS recommendations (Stuntebeck, 2008). Equipment enclosures, flumes, ISCO portable samplers, and bubbler flow meters were installed in January 2010. Flow monitoring was initiated on 5 February 2010.

Corn Stover and Yield Measurements

Corn for grain was harvested on 5 October 2010. Determination of corn grain yield was completed by hand harvesting corn cobs from corn plants in a 3 m length of a 76 cm spaced row at 14 locations in each watershed. A mechanical sheller was used to thresh the grain from the cobs. Subsamples for each location were dried for 3 days at 70^{o}C. Kernels were weighed and yield was determined.

Corn stover was hand harvested in an area of 0.09 m^2 from 10 locations in the treatment watershed on 26 October 2010. Subsamples from each location were weighed and dried for 3 days at 70^{o}C to determine moisture content at time of sampling. Dry mass was then determined. Field removal of corn stover occurred on 30 October 2010.

The treatment watershed was initially to be winter rye with removal of corn stover. Problems arose with the aerial seeding of winter rye in fall 2010. Aerial seeding of winter rye occurred on 2 September 2010 at a rate of 112 kg ha^{-1}. Winter rye seed was observed on the soil surface four days after the aerial application. However, there was no observed winter rye germination in the treatment watershed a week after the initial observation. We suspect that predation, a storm on 23 September 2010, and pilot error were key factors complicating the establishment of winter rye in the treatment watershed. Because of the unsuccessful winter rye seeding, this location resulted in a stover management experiment studying the effect of corn stover residue on runoff quantity and quality.

Soybean plants were collected on 6 October 2011, three days prior to field harvest. Soybean plants were hand harvested in 3 m rows (76 cm row spacing) at seven locations in each watershed. A mechanical sheller was used to thresh the beans from the pods. Subsamples for each location were dried for three days at 70°C to determine moisture content. Beans were weighed and yield was determined.

Water Samples

The automated field sites were programmed to sample on a volume basis with one sample collected for every 29.08 m^3 of surface runoff during snowmelt or rainfall events. In spring 2010, snowmelt runoff exceeded preliminary estimates and sample volume basis was changed from 29.08 to 339.6 m^3 in order to handle peak flow rates. Three samples are composited per 1 L polypropylene bottle (Teledyne ISCO Inc., Lincoln, NE). The sample collection at 29.08 m^3 in the treatment watershed was chosen so that during a runoff event, there would be sufficient sampler capacity to capture the entire event based on a predicted average water height of 0.15 m and a flow rate of 0.017 m^3s^{-1}. Water samples were immediately placed on ice in a cooler within 24 hrs and subsequently filtered using a 0.2 μ filter (VWR International, Chicago, IL) with a non-surgical syringe (120 mL was filtered from each bottle). Filtered samples were analyzed for NO_3-N, NH_4-N, and dissolved reactive Phosphorus using a Quikchem 8500 Lachat Ion analyzer (Hach Company, Loveland, CO). Total dissolved phosphorus was determined for filtered samples (University of Minnesota Soil Testing Laboratory) using rapid flow analyzer (RFA) method with Alpkem RFA 300 (RFA, 1986 and Astoria-Pacific, Clackamas, OR). Unfiltered samples were analyzed for Total Suspended Solids (TSS), Sediment Carbon, Sediment Nitrogen, and Total Phosphorus (TP). TSS was determined with ESS Method 340.2 (Environmental Protection Agency, US). TP analysis was performed by the University of Minnesota Soil Testing Laboratory using RFA method with Alpkem RFA 300 (RFA, 1986 and Astoria-Pacific, Clackamas, OR). Sediment carbon and sediment nitrogen were determined using Elementar Vario EL combustion analyzer (Elementar Americas, Inc., Mt. Laurel, NJ).

Soil Samples

Soil samples were collected on 19 November 2009, 3 May 2010, 30 October 2010, 20 May 2011, and 11 October 2011. Sixteen sample locations were chosen in a grid pattern for each watershed to capture slope characteristics (summit, back slope, and foot slope). Prior to each sampling date, locations were found using research grade global positioning system (GPS) mapping equipment. Two soil cores were collected at each sample location to a depth of 90 cm using a truck mounted Giddings probe (3.8 cm diameter). Cores were subsampled by depth in the following increments: 0-15 cm, 15-30 cm, 30-60 cm, and 60-90 cm and composited at each location. Soil samples were sub-sampled for physical analysis and were dried at 105°C to determine gravimetric water content and bulk density. There was no statistical difference between gravimetric water content and bulk density for the watersheds. The remaining sample was dried at 37°C, ground through a <0.5 mm sieve, and analyzed for soil NO_3-N, NH_4-N, and Mehlich III P using a Quikchem 8500 Lachat Ion analyzer (Hach Company, Loveland, CO). The same sampling protocol and analysis were followed for each year of study.

Ground Cover

Photographs for ground cover determination were collected on 19 November 2009, 3 May 2010, 30 October 2010, 20 May 2011, and 11 October 2011. Ten digital photographs were taken in each watershed using a camera mounted on a stand facing downward at a height of 1.2 m. The photographs were analyzed using USDA Sample-Point Measurement Software 1.48 (Booth, 2006). This software allows for an overlay of a 100 point grid to be placed over each photograph. Average ground cover was determined by visual observation at each point.

Paired Watershed Design Comparisons

The control and treatment watersheds were adjacent to one another and had the same shape with east/west aspects but differed in size. The treatment watershed was 1.2 ha and the control was 4.2 ha. Watershed boundaries and area were found using research grade global positioning system (GPS) mapping equipment. Both watersheds exhibited same flow pattern in slope characteristics, but the distance from upper portion of watershed to equipment used to monitor surface runoff was different. The distance surface runoff traveled from the upper boundary to the flume in the treatment watershed was 85 m. The distance in the control watershed was 190 m.

Management of Watersheds

Farm management of both watersheds was similar throughout the study. Both watersheds received application of anhydrous ammonia, seedbed preparation, and crop planting in the spring. The control watershed contained a grass waterway and the farmer was unwilling to remove it because the potential for soil erosion would increase. As a compromise, the grass waterway was trimmed continuously to keep an average 10 cm height. Corn harvest occurred on 6 November 2009 and 29 October 2010. Soybean harvest occurred on 10 October 2011. Corn (roundup ready variety) planting occurred on 28 April 2010 and soybeans (roundup ready variety) were planted on 1 June 2011. However, the farmer did not plant soybeans in the entire control watershed as planned. After we discussed the planting of soybeans in both watersheds, he decided a week before planting to plant corn and alfalfa in about 50% (right down the middle) of the control watershed, with soybeans taking up the rest of the field without prior consulting. His justification was economics, since corn prices outweighed soybean prices. The treatment watershed was planted entirely with soybeans. The change in cropping rotation shows the difficulty of on-farm research.

Authenticity of Data

Freezing of the sampling line, ice buildup in the flume, and malfunction of sampler were the three main challenges to this study when surface runoff was observed. Determination of runoff start and end times were confirmed based on flow rates, time of runoff, and air temperatures at time of runoff for fall and spring runoff events. Manual correction of data then occurred during times of incorrect runoff measurements (Stuntebeck, 2008). The majority of the incorrect runoff flows were when ice buildup occurred in the flume during the night. Sampler malfunction occurred mostly during spring snowmelt events. Freezing night temperatures would cause the ice buildup in the flume and provided incorrect flow measurements. These incorrect flow measurements would trigger the sampler to take a water sample when water was not flowing

Some of the snowmelt that may have occurred during the technician's absence compromised the collection of runoff samples because ice buildup in the flume caused the sampler to use up all available collection bottles. These occurrences were not frequent but based on overall total volume of runoff from each watershed; we determined that more samples could have been collected. The control watershed had 48 samples collected and the treatment watershed had eight samples. Based on total runoff from both watersheds, 84 and 39 samples should have been collected from control and treatment watersheds, respectively. The missing samples for the control watershed occurred in the spring of 2011 when there was 31805 m^3 of runoff which should have triggered runoff collection for 31 samples. In addition, 17 samples should have been collected in summer 2011 and spring snowmelt of 2012. There were 31 samples not collected in the treatment watershed and they were missing from spring snowmelt 2011 and spring snowmelt 2012. There was 57% and 21% sample-volume coverage for control and treatment watersheds, respectively. Discovery and Pioneer farms in Wisconsin that are operated by United States Geological Survey (USGS) had 90% annual sample-volume coverage during a 6 year period from 12 edge-of-field sites (Stuntebeck, 2008).

Results and Discussion

Ground Cover, Crop Yield, Stover Removal, and Soil Composition

Ground cover percentages were similar during baseline year of fall 2009 to spring 2010 (Table 3-1). As assumed, ground cover percentages were different for the experimental year in fall 2010 to spring 2011 because removal of corn stover occurred. Fall 2011 ground cover was similar between watersheds because soybean residue remained in each. Field removal of corn stover occurred on 30 October 2010. The average dry mass of stover removed was 0.35 kg ha^{-1}. Soybean yields were not affected by removal of corn stover (Table 3-2). Long term impacts of corn stover removal may exist but the results after one year do not. Implications of long term removal may include increased risk of soil erosion and disruption in soil organic carbon dynamics that would influence future crop yields (Blanco-Canqui, 2010).

Soil NO_3-N concentrations were similar between watersheds throughout the study (Figure 3-1). This was an expected result since removing corn stover in the fall does not have direct impact on soil NO_3-N. NH_4-N concentrations in the soil fluctuate frequently during the year because it is subject to many transformations in the soil system. Nitrogen transformation of ammonium includes nitrification, immobilization, and volatilization. These transformations or fluctuations of ammonium are evident in the soil of the control and treatment watersheds (Figure 3-2). Anhydrous ammonia was applied in spring 2010 prior to soil sampling. Concentrations of ammonium increased between fall 2009 and spring 2010 because of this application of fertilizer (Figure 3-2). Anhydrous ammonia was not applied in fall 2010 or spring 2011 prior to soybean planting.

Soil Mehlich III-P concentrations were similar between fall and spring from 2009 to 2011 (Figure 3-3). This was an expected result since removing corn stover should not have a direct impact on bio-available soil phosphorus.

Total Water Volume

Differences in total surface runoff between watersheds were observed in 10 out of 25 months. These 10 months included the 4 major surface runoff events that had sample collections (see runoff losses below). In 2010, the control had 70% more surface runoff than the treatment. In 2011, the control had 43% more surface runoff than the treatment. With the removal of the corn stover, surface runoff increased by 30%.

Major differences in surface runoff were observed in snowmelt events of 2010, 2011, and 2012. In the snowmelt event of 2010, runoff from the control and treatment watersheds began 6 March 2010 and ended 14 March 2010, respectively (Figure 3-4). The surface runoff rate in the control watershed exceeded preliminary estimates, and the ISCO sampler was reset to a reduced sample collection rate one sample of 339.6 m^{-3} for the peak of the spring snow melt. The sample collection interval in the treatment watershed was one sample 29.06 m^{-3} of surface runoff. The control watershed had a greater volume of runoff than the treatment watershed (Figure 3-5). The control watershed had a maximum rate of surface runoff of 0.343 $m^3\ s^{-1}$. This flow rate corresponds to a head of 0.616 m. The treatment watershed had a maximum flow rate of 0.007 $m^3\ s^{-1}$ which corresponds to a head of 0.098 m (Figure 3-4).

Summer rainfall events in 2010 produced little or no runoff from either the control or treatment watersheds. The lack of runoff from these watersheds may have been due to high corn stover residue still present on the soil surface. The cooperator uses a no-till system, which is a best management practice for water quality.

Fall 2010 rainfall events also produced little to no runoff from either the control or treatment watersheds. The major storm event on 23 September 2010 had a total rainfall of 19.05 cm. However, this rainfall event produced little to no runoff in both watersheds. Total runoff in the control was 106 m^3 and the treatment was 84 m^3. The lack of runoff from these watersheds was probably due to high corn stover residue still present on the soil surface.

Spring 2011 snowmelt produced a greater surface runoff than spring of 2010 due to more snow. The control watershed had 1814 $m^3\ ha^{-1}$ of runoff in 2010 and 7573 $m^3\ ha^{-1}$ in 2011. The treatment had 439 $m^3\ ha^{-1}$ in 2010 and 944 $m^3\ ha^{-1}$ in 2011. There were three snowmelt periods on 16 February, 11 March, and 20 March 2011 (Figure 3-4). The greatest snowmelt runoff occurred on 11 March 2011.

The summer and fall 2011 rainfall events did not produce sufficient amount of rainfall for runoff to occur. The winter conditions of 2011 to 2012 were mild with below normal snow and above normal temperatures. As a result, little snowmelt from the control and treatment watersheds occurred. Runoff flow rates from both watersheds had low flow starting on 12 March 2012, but the snowmelt did not produce enough runoff flow to initiate a sample collection. Both watersheds had less than 15 $m^3\ ha^{-1}$ of runoff in snowmelt of 2012. Most of the snowmelt infiltrated the soils in both watersheds.

NO_3-N, NH_4-N, and Phosphorus loss in Surface Runoff

Only 2 out of the 4 runoff events had sample collection in both watersheds. Comparison can only be made in those two events (Table 3-3) because sampler malfunction occurred during the other two events. Both watersheds had low NO_3-N and NH_4-N loads in snowmelt event of 2010. This was expected since no treatment had yet been imposed. A September 2010 storm had sampling occur in both watersheds. The control watershed had 87% more NO_3-N and 86% more NH_4-N loads than the treatment watershed; however, the loads were the lowest observed in the study (Table 3-3). Runoff volumes between watersheds were comparable to each other. The control had 25 m^3 ha^{-1} and the treatment was 70 m^3 ha^{-1} for the September 23rd storm. Concentrations in the samples were also lower than other events (Figure 3-6).

None of the samples collected from the watersheds exceeded the EPA water quality standard of 10 mg L^{-1} in drinking water. This standard of 10 mg L in drinking water was established to prevent human infant deaths caused by blue-baby syndrome. Blue-baby syndrome is an environmentally-caused health disorder in which the blood is unable to carry enough oxygen to vital tissues and organs (Knobeloch et al. 2000). The highest observed NO_3-N concentration was 8.3 mg L^{-1} and was in the treatment during the 2010 snowmelt (Figure 3-6). The lowest observed NO_3-N concentration was 0.04 mg L^{-1} in the 2011 snowmelt in the control watershed. The highest NH_4-N concentration was 6.85 mg L^{-1} and occurred during the September storm in the control watershed (Figure 3-7). The lowest NH_4-N concentration was 0.0001 mg L^{-1} during the snowmelt event of 2010 in the treatment watershed (Figure 3-7). Even with lower concentrations, the control watershed had more surface runoff; thus more NO_3-N and NH_4-N was lost in surface water (Table 3-3).

The control watershed had a greater total phosphorus (TP) load than the treatment watershed in snowmelt 2010 but was equal in September 2010 storm event where samples were collected (Table 3-4). During the snowmelt of 2010, the control had 42% more TP than the treatment. Total dissolved phosphorus (TDP) was the same in both (Table 3-4). The majority of phosphorus in the control was sediment-bound phosphorus or particulate phosphorus (PP). The opposite was observed in the treatment watershed where TDP was higher than PP. It is interesting that the amount of sediment was higher in the treatment watershed than the control during this event (Table 3-5). This implies that phosphorus was at higher concentrations in the water than in the sediment.

During the rainfall runoff event in September of 2010, the control watershed had 20% more TP in surface runoff than the treatment (Table 3-4). PP and TDP were also similar between watersheds for this event.

Highest concentrations of TP were observed in the control watershed during the spring 2011 snowmelt event (Figure 3-8). This concentration was 4.8 mg L^{-1}. The lowest TP concentrations were observed in the 2010 snowmelt event in both watersheds. These concentrations ranged from 0 to 0.2 mg L^{-1}. Phosphate concentrations were generally higher during summer 2010 and spring 2011. Highest concentration of phosphate occurred on 1 July 2010 in the treatment watershed at 1.71 mg L^{-1}. In the control watershed during the spring 2011 snowmelt, the highest phosphate concentration was 1.22 mg L^{-1}. Phosphate or dissolved inorganic phosphorus (DIP) is readily available to plants as a phosphorus source. It is also readily available to algae in rivers, lakes, and streams, where in excess it can cause eutrophication. A majority of the phosphorus concentrations measured (99%) in the surface runoff in both watersheds exceeded 0.025 mg L^{-1}, the level that causes accelerated eutrophication in lakes (Figure 3-9). The maximum recommended DIP concentrations for streams and rivers are 0.1 mg L^{-1}. Only 92% of samples were over the maximum recommended concentrations for streams and rivers.

Sediment Loss

Unlike nitrogen and phosphorus loads, sediment was observed at higher rates in 1 of the 2 events for the control watershed. This was a result of higher total suspended solid (TSS) concentrations in the samples collected than in the amount of runoff. The highest TSS concentration was 23765 mg L^{-1} and was collected in the treatment watershed. The control watershed had TSS concentrations ranging from 5565 to 12765 mg L^{-1} (Figure 3-10). C/N ratios were 8 for both watersheds for the snowmelt event of 2010.

In the September 2010 storm, the control watershed had 70% more sediment load than the treatment (Table 3-5). The runoff from this storm had higher TSS concentrations than any other event that had samples collected. The TSS concentrations ranged from 61963 to 65536 mg L^{-1} in both watersheds (Figure 3-10). From what was sampled in the watersheds, 3.6 metric tons ha^{-1} of soil was lost from the control watershed and 6.6 metric tons ha^{-1} was lost from the treatment watershed in surface runoff from 2010 to 2011. Soil erosion is a major environmental concern. Soil is being lost 10 to 40 times faster than it is being replenished (Pimentel, 2006).

Conclusion

Removal of corn stover in the fall has potential to increase soil erosion. Surface runoff increased in the treatment watershed after stover was removed. The long term impacts of baling or removing corn stover could be detrimental to soil quality and health. Annual sediment and nutrient lost in surface runoff were not calculated because sample collection did not occur in 2011 in the treatment watershed. Any indications of sediment loss and nutrient loss from this watershed would have been greater in 2011 than 2010 because surface runoff was greater. Both watersheds exhibited same shape and slope, but differed in field size and distance that surface runoff traveled from the upper portion to monitoring equipment. Evaluating surface runoff in a paired watershed in an on-farm research setting presents constraints relative to University Experiment Station lands. Flexibility must be shared between the researchers and farmer involved because economic losses must be avoided. This issue arose in the last year of the study when soybeans were planted. Prior to planting soybeans, it was agreed upon that both watersheds would be planted into soybeans. One week prior to planting the cooperator decided that corn for grain would provide more profitability than soybeans. The control watershed was then planted with 50% corn for grain and alfalfa and 50% soybeans. Another major fault of the study is the duration of evaluating surface runoff in these two systems. Two years does not capture climatic variations in weather from year to year, suggesting that more years of study are necessary to control variation in weather from year to year. One major accomplishment was that we were able to have equipment in place when the 23 September storm occurred which caused the largest flooding event since 18 August 2007. A 100-year storm for this region is 15.24 cm of total rainfall over a 24-hour period.

References

Blanco-Canqui H, Lal R, Post WM, Izaurralde RC, and Owens LB. 2006. Corn Stover Impacts on Near-Surface Soil Properties of No-Till Corn in Ohio. Soil Science 70: 266-278.

Blanco-Canqui H. 2010. Energy Crops and Their Implications on Soil and Environment. Agronomy Journal 102: 403-419.

Booth DT, Cox SE, and Berryman RD. 2009. Point sampling digital imagery with 'SamplePoint'. Environmental Monitoring and Assessment 123: 97-108.

Knobeloch L, Salna B, Hogan A, Postle J, and Anderson H. 2000. Blue Babies and Nitrate-Contaminated Well Water. Environmental Health Perspectives July 108(7): 675-678.

Lachat Instruments. 2000a. Nitrate/nitrite, nitrite in surface water, wastewater. Quikchem Method no. 10-107-04-1-A. Lachat Instruments, Milwaukee, WI.

Lachat Instruments. 2000b. Ortho phosphate in waters. Quikchem Method no. 10-115-01-1-A. Lachat Instruments, Milwaukee, WI.

Lindstrom MJ, Skidmore EL, Gupta SC, and Onstad CA. 1979. Soil conservation limitations on removal of crop residues for energy production. Journal of Environmental Quality 8:533–537.

Pimentel D. 2006. Soil Erosion: A Food and Environmental Threat. Environment, Development, and Sustainability 8: 119-137.

Stuntebeck TD, Komiskey MJ, Owens DW, and Hall DW. 2008. Methods of Data Collection, Sampling Processing, and Data Analysis for Edge-of-Field, Streamgaging, Subsurface-Tile, and Meteorological Stations at Discovery Farms and Pioneer Farm in Wisconsin, 2001-7. U.S. Department of Interior and U.S. Geological Survey.

Thomas MA, Engel BA, and Chaubey I. 2011. Multiple Corn Stover Removal Rates for Cellulosic Biofuels and Long-term Water Quality Impacts. Journal of Soil and Water Conservation 66(6): 431-444.

USDA-NRCS. 1996. Soil Quality Indicators: Soil Crusts. USDA Natural Resources Conservation Service. http://soils.usda.gov/sqi/publications/files/sq_sev_1.pdf

UDSA-NASS. 2012. 2011 Minnesota State Agricultural Overview. National Agricultural Statistics Service.

Table 3-1. Ground cover in paired watersheds near Plainview, MN from 2009 to 2011.

	Year	Control	Treatment
		- - - - - %	- - - - -
Fall	2009	98	98
Spring	2010	92	82
Fall	2010	90	35
Spring	2011	87	33
Fall	2011	56	52

Table 3-2. Crop yield for corn and soybean near Plainview, MN from 2010 to 2011.

Crop	Year	Control	Treatment
		metric tons ha^{-1}	
Corn Grain	2010	9.5	11.9
Soybean	2011	3.4	3.6

Table 3-3. NO_3-N and NH_4-N loads in surface runoff from specific snowmelt or rainfall events near Plainview, MN from 2010 to 2011.

	Control		**Treatment**	
Event	**NO_3-N**	**NH_4-N**	**NO_3-N**	**NH_4-N**
	- - - - - - - - - kg ha^{-1} - - - - - - - - -			
Snowmelt 2010	1.18	0.29	1.03	0.05
Summer 2010	-[†]	-[†]	0.14	0.004
Sept 22nd, 23rd 2010	0.14	0.60	0.018	0.085
Snowmelt 2011	4.07	3.59	-[†]	-[†]

† missing data is due to sampler malfunction during events

Table 3-4. Phosphorus loads in surface runoff from specific snowmelt or rainfall events near Plainview, MN from 2010 to 2011.

	Control				Treatment			
Event	**TP**	**PP**	**TDP**	**DIP**	**TP**	**PP**	**TDP**	**DIP**
	- - - - - - - - - - - - - kg ha^{-1} - - - - - - - - - - - - - -							
Snowmelt 2010	0.19	0.11	0.08	0.07	0.11	0.03	0.08	0.09
Summer 2010	-----	-----	-----	---†	0.022	0.002	0.02	0.04
Sept 22nd, 23rd 2010	0.05	0.01	0.04	0.1	0.04	0.01	0.03	0.03
Snowmelt 2011	2.83	0.93	1.90	1.85	-----	-----	-----	------†

† missing data is due to sampler malfunction during events

Table 3-5. Sediment, total nitrogen, and total carbon loads in surface runoff from specific events near Plainview, MN from 2010 to 2011.

	Control			Treatment		
Event	**Sediment**	**TN**	**TC**	**Sediment**	**TN**	**TC**
	- - - - - - - - - - - - - kg ha^{-1} - - - - - - - - - - - - -					
Snowmelt 2010	3588	7	57	4164	9	74
Summer 2010	-----†	-----†	-----†	629	2	20
Sept 22nd, 23rd 2010	10580	71	623	3140	15	136
Snowmelt 2011	874	4	39	-----†	-----†	-----†

† missing data is due to sampler malfunction during events

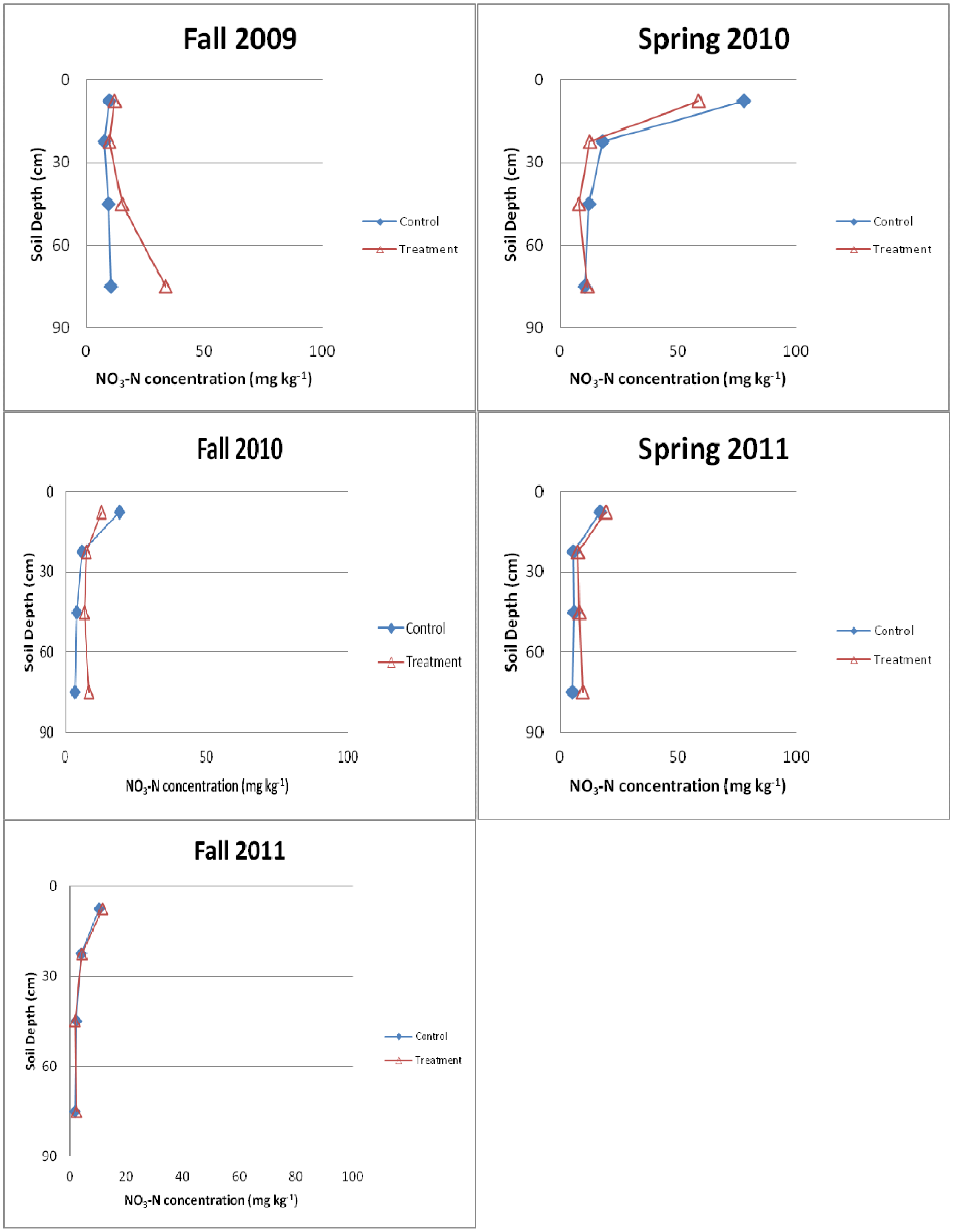
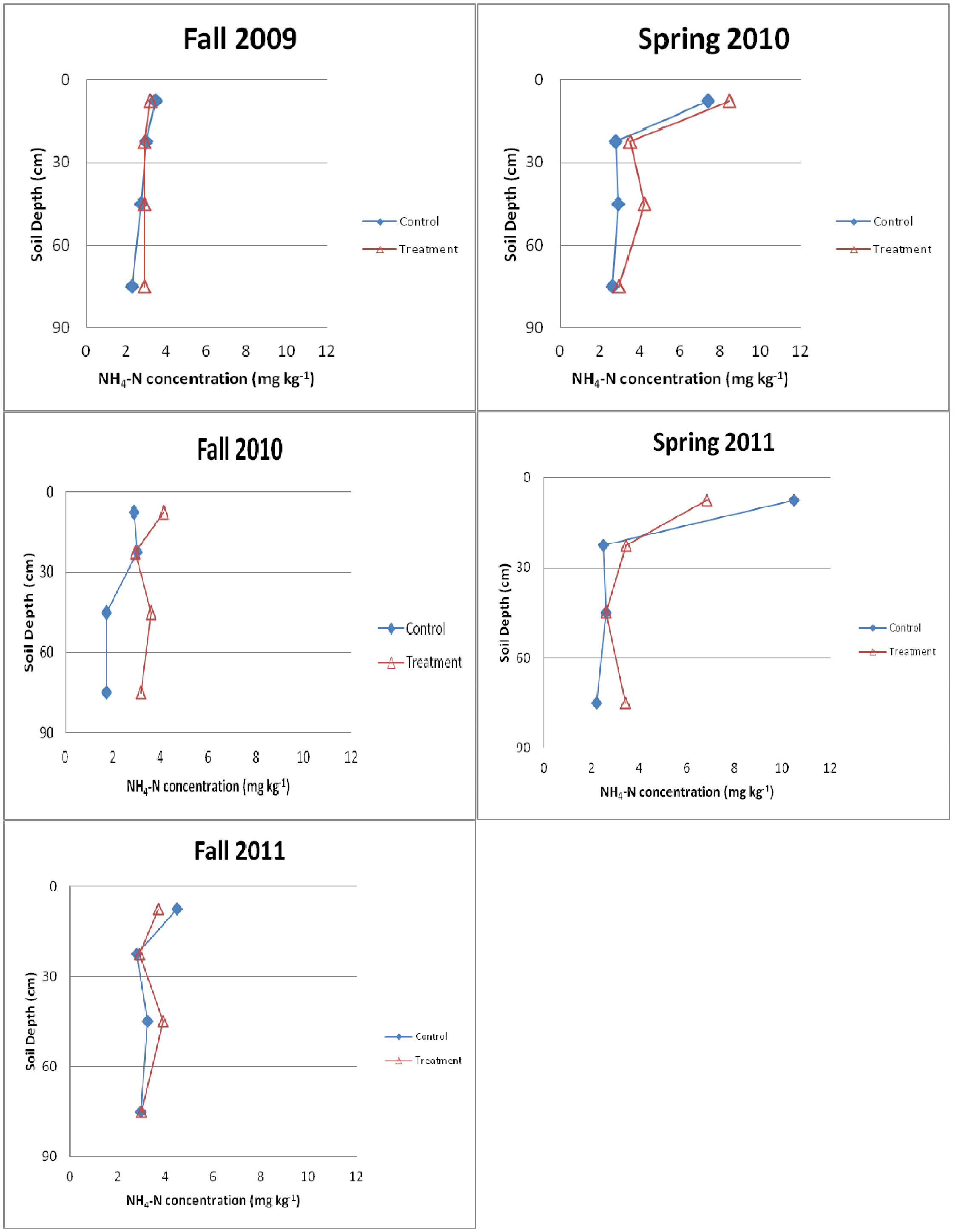


Figure 3-1. Soil NO$_3$-N concentrations near Plainview, MN for fall and spring from 2009 to 2011. Concentrations are reflected in the figure at the average point between sample increments.



Fall 2009

Spring 2010

Fall 2010

Spring 2011

Fall 2011

Figure 3-2. Soil NH_4-N concentrations near Plainview, MN for fall and spring from 2009 to 2011. Concentrations are reflected in the figure at the average point between sample increments.

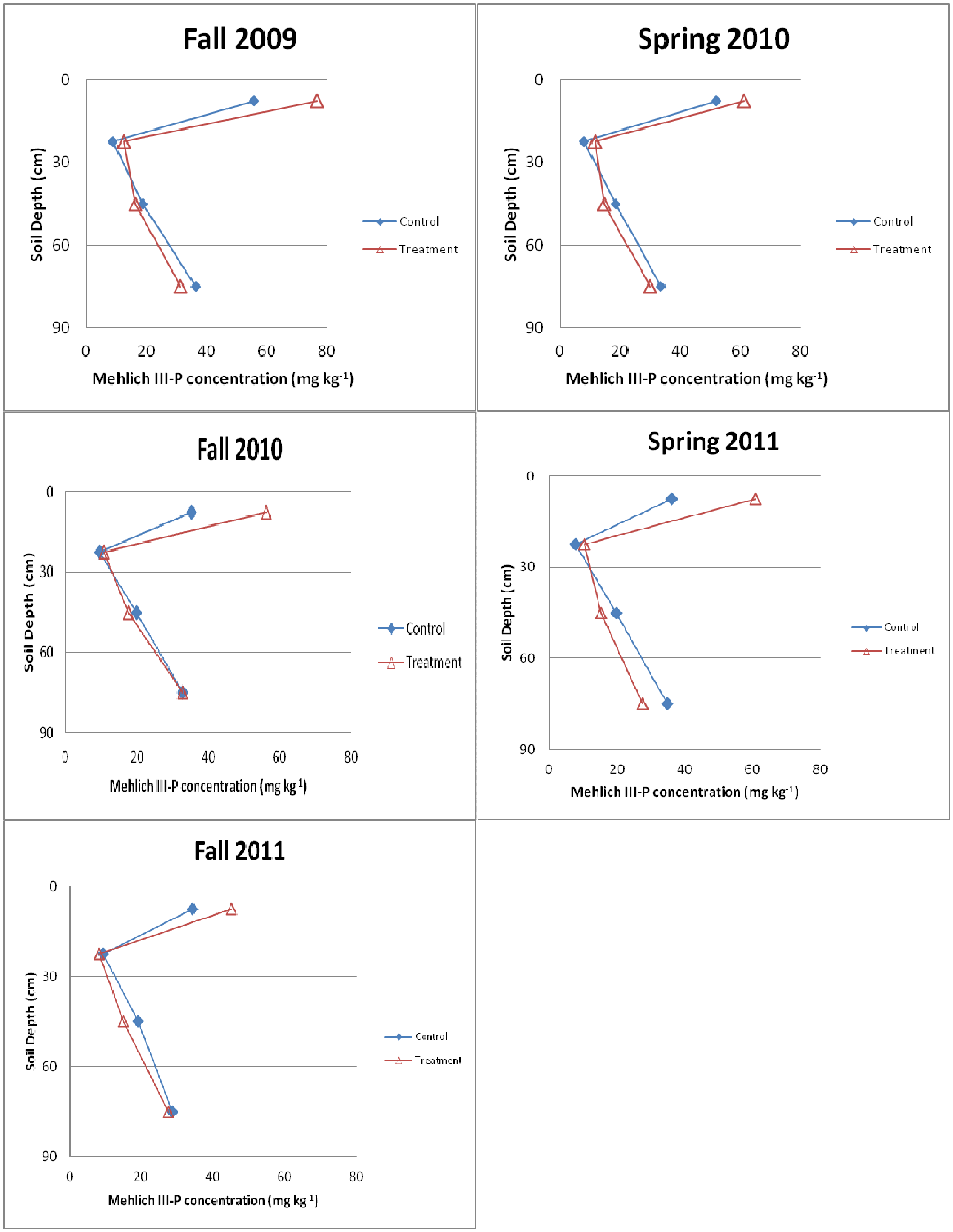


Figure 3-3. Soil Mehlich III-P concentrations near Plainview, MN for fall and spring from 2009 to 2011. Concentrations are reflected in the figure at the average point between sample increments.

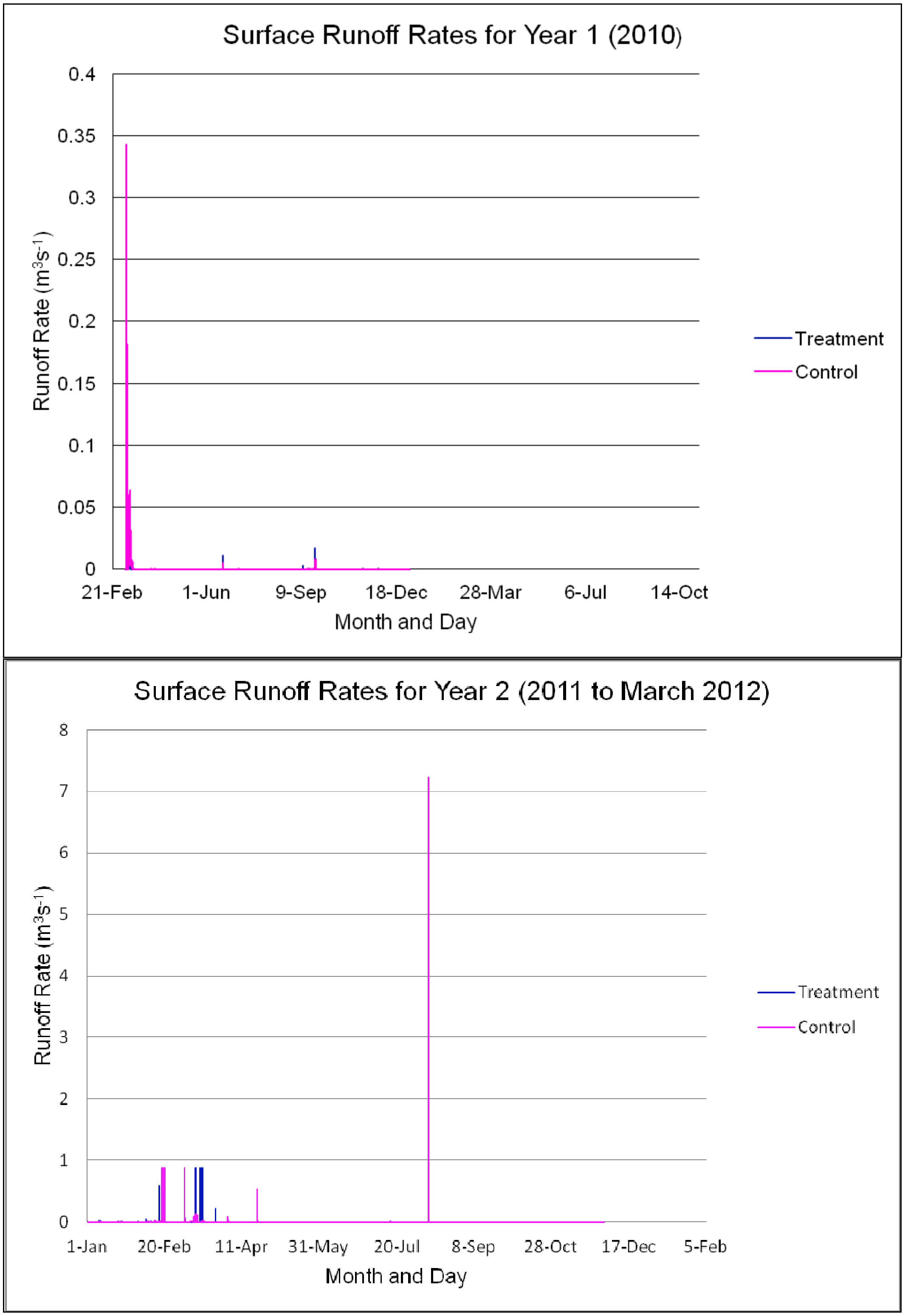


Figure 3-4. Rates of surface runoff flow for both watersheds in 2010 and 2011 near Plainview, MN.

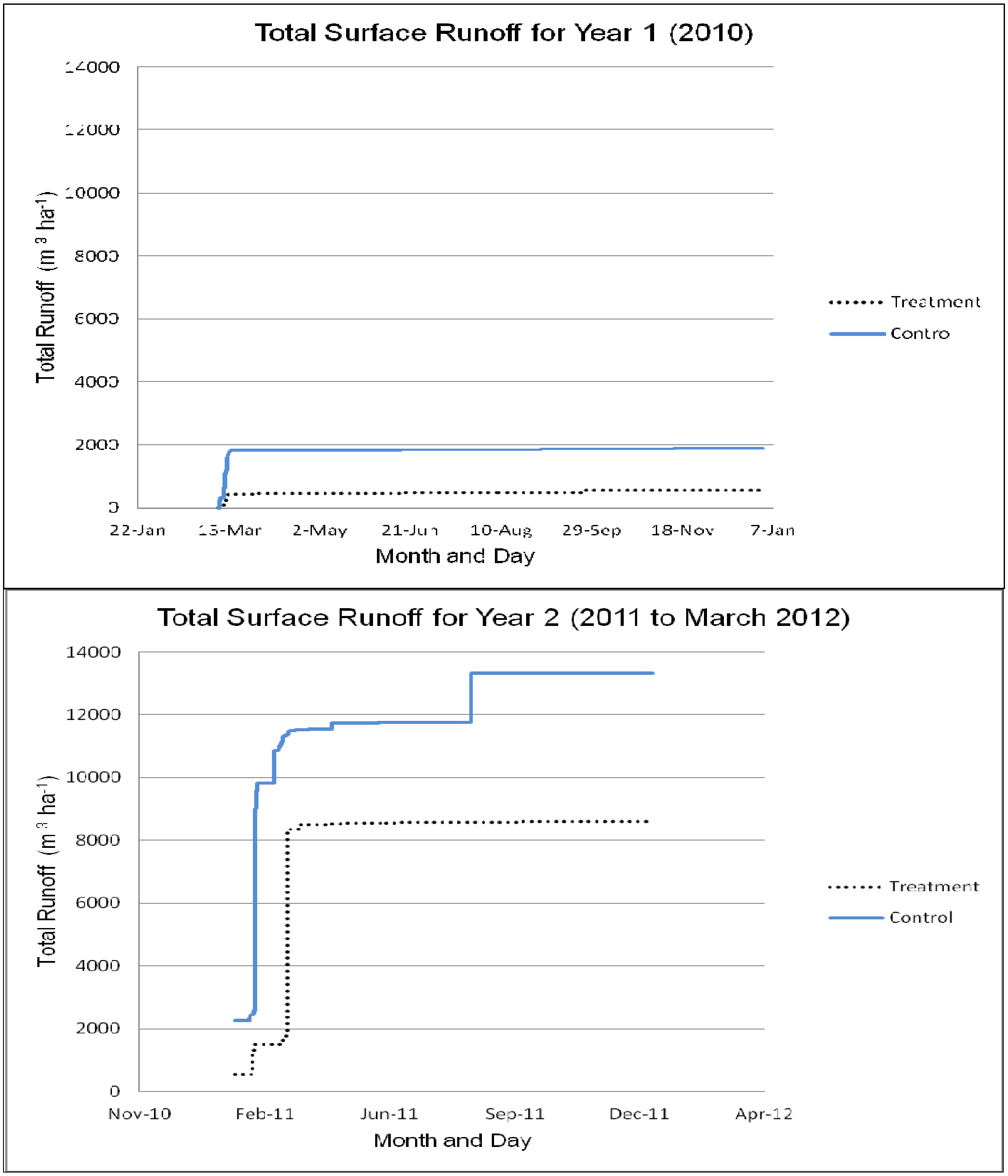


Figure 3-5. Total volume of runoff on area basis for both watersheds in 2010 and 2011 near Plainview, MN.

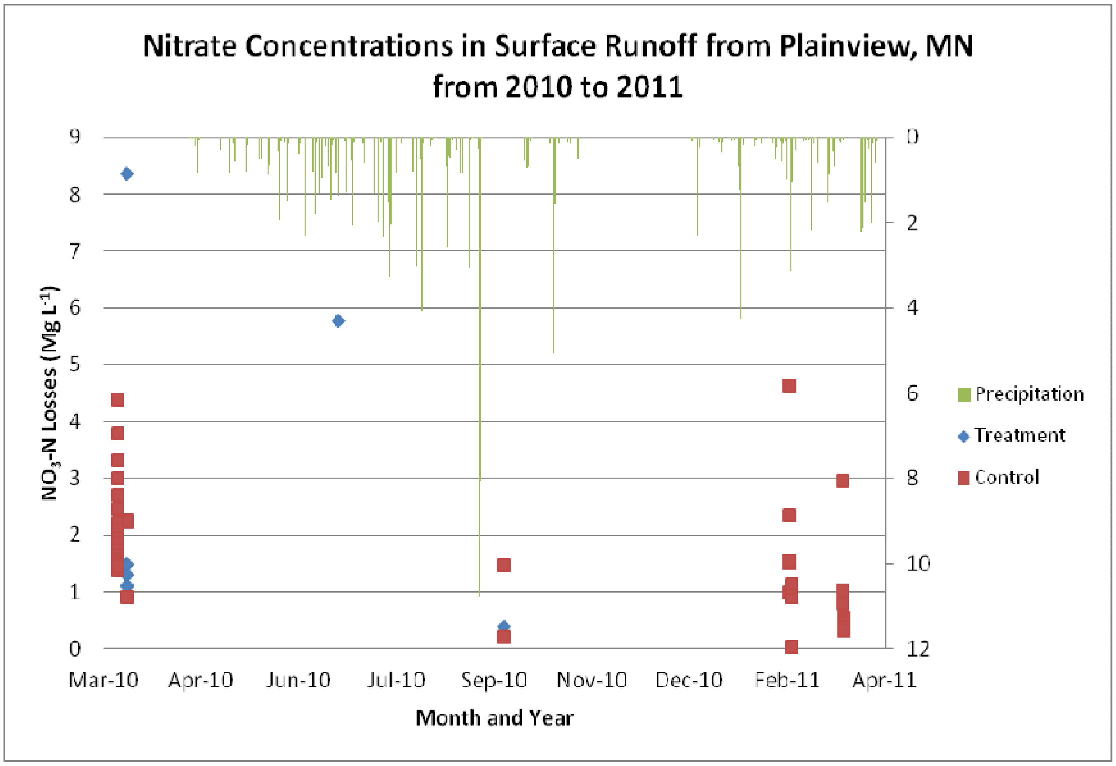


Figure 3-6. Nitrate concentrations for control and treatment watersheds near Plainview, MN from 2010 to 2011. Squares and diamonds are concentrations from samples taken during surface runoff events.

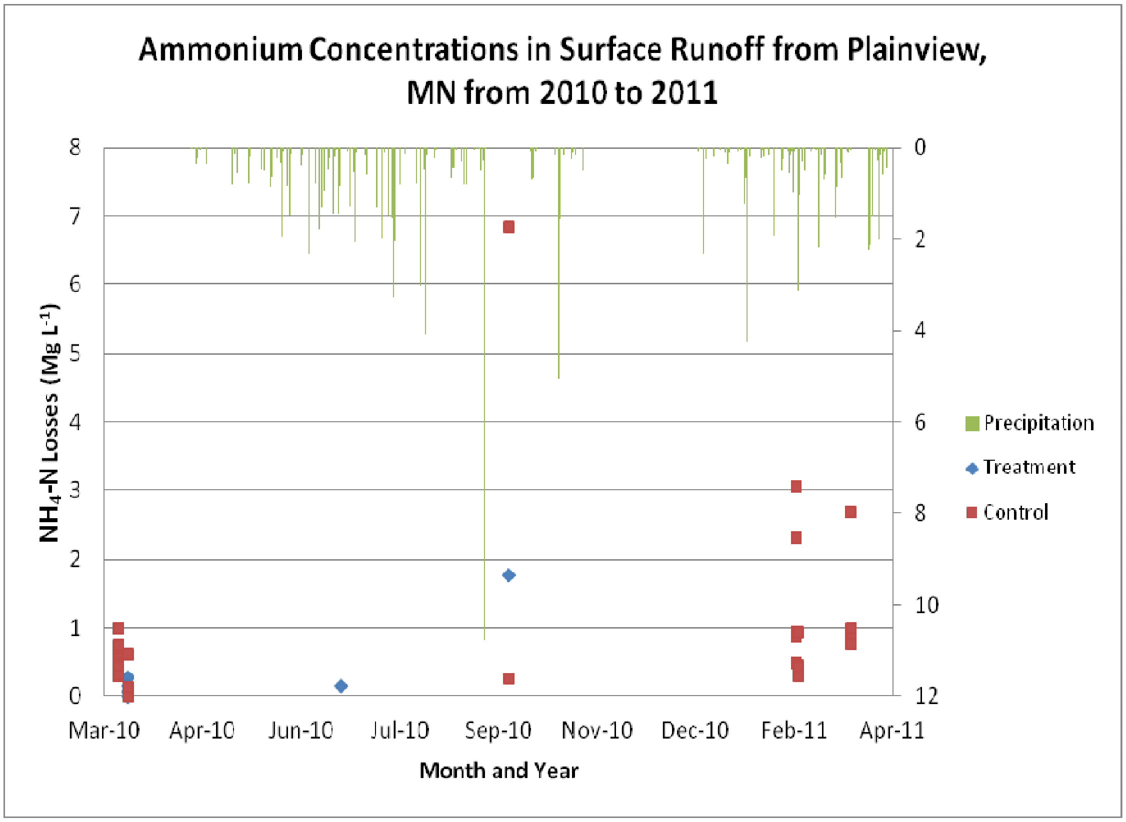


Figure 3-7. Ammonium concentrations for control and treatment watersheds near Plainview, MN from 2010 to 2011. Squares and diamonds are concentrations from samples taken during surface runoff events.

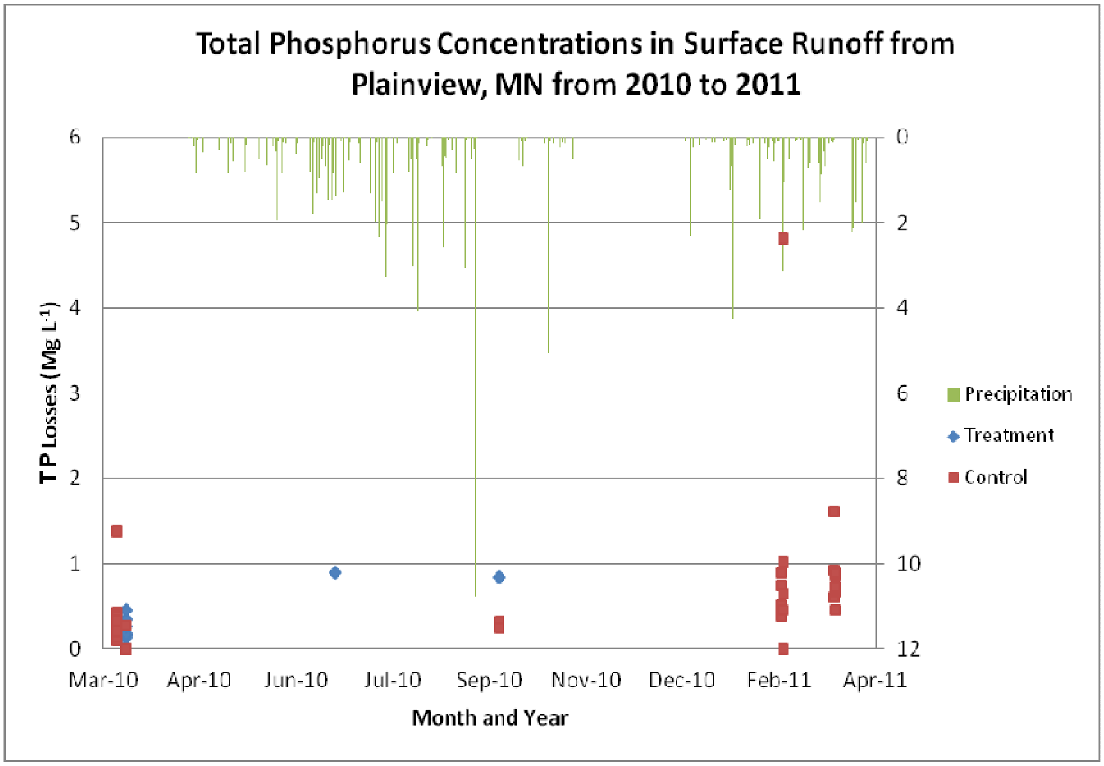


Figure 3-8. Total phosphorus concentrations for control and treatment watersheds near Plainview, MN from 2010 to 2011. Squares and diamonds are concentrations from samples taken during surface runoff events.

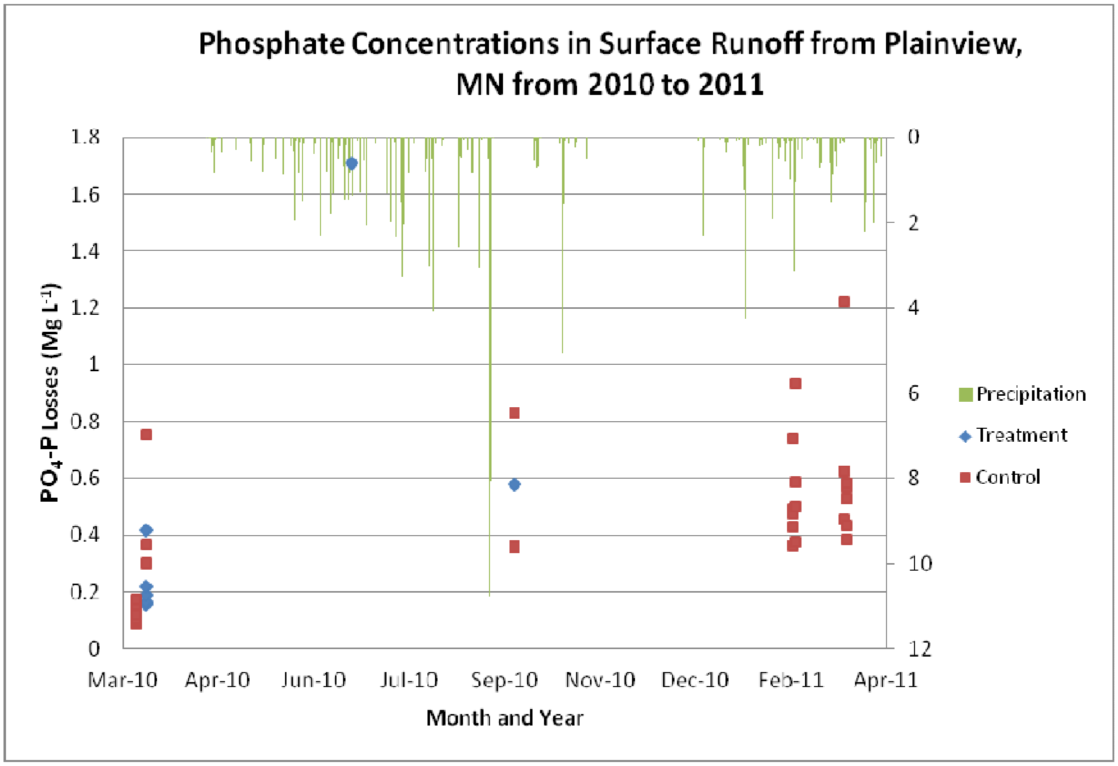


Figure 3-9. Dissolved inorganic phosphorus (phosphate) concentrations for control and treatment watersheds near Plainview, MN from 2010 to 2011. Squares and diamonds are concentrations from samples taken during surface runoff events.

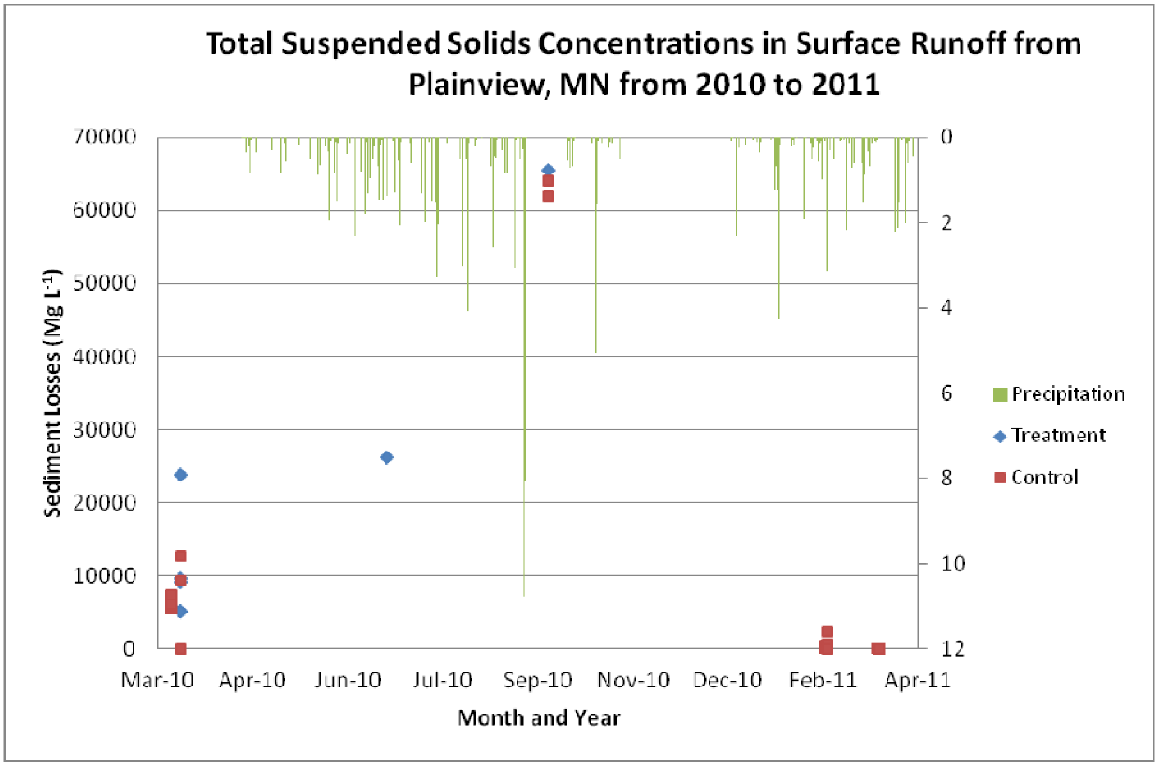


Figure 3-10. Sediment concentrations for control and treatment watersheds near Plainview, MN from 2010 to 2011. Triangles and squares are concentrations from samples taken during surface runoff events.

Chapter 4 - Effects of Winter Rye following Corn Silage on Surface Runoff in Paired Watershed

Chapter Summary

Soil conservation is paramount in a world where monoculture cropping systems are main-stream and the frequency and intensity of storm events are increasing. The objective of this study was to evaluate the potential of a winter rye cover crop to minimize soil erosion and transportation of nutrients to waterways by providing cover during the fall and spring dormant periods in a paired watershed design. H-flumes with ISCO portable samplers and bubbler flow meters were used to monitor surface water runoff from a corn silage-winter rye-soybean rotation (treatment watershed) and a conventional corn silage-soybean rotation (control watershed) from 2010 to 2012. The treatment watershed had 60% more total runoff than the control, where a majority of runoff was in spring snowmelt events. Even though winter rye scavenged 30% of nitrate during dormant periods, the treatment watershed had higher NO_3-N and NH_4-N loads than the control watershed in 2 out of the 3 events where samples were collected. This was also true in phosphorus and sediment transport. Differences in field management in fall seasons accounted for the differences in surface runoff of snowmelt events. Given the deficiencies of our data set, we were unable to determine if winter rye should still be considered a best management practice and that more years of study should be considered.

Introduction

With climate change, world population growth, and food production demands rising, sustaining or improving soil health is vital to the survival of agriculture for future generations. Soil conservation is paramount with continuation of monoculture cropping systems that use chemical inputs to maintain yields and lack biological inputs. The addition of a cover crop during fallow periods in monocultures may provide environmental benefits that are lacking in monoculture cropping systems. Finding an appropriate cover crop for successful preservation of soil resources can be challenging, but winter rye is a highly suitable cover crop for the Upper Mississippi River Basin following corn silage harvest because of its cold hardiness and early spring regrowth. The relatively early corn harvest in silage systems allows for early establishment of winter rye to prevent soil erosion from a cropping system that generates minimal crop residue on the soil surface. Additional benefits that a winter rye cover crop can offer are retention of nitrogen in the soil, suppression of weeds, and additional forage for ruminants. Winter rye is particularly effective at reducing nitrate leaching during dormant periods of crop production. A meta-analysis found a 70% average reduction in nitrate leaching when cover crops were used (Tonitto et al. 2006). Staver and Brinsfield found that winter rye reduced nitrogen loads by 80% in subsurface groundwater and in deeper aquifers under corn rotations (1998).

In 2010 and 2011, corn silage was harvested on 141,639 hectares, which is about 2% of total land farmed in Minnesota (USDA NASS, 2011 and USDA NASS, 2012). The lack of crop residue in corn silage cropping systems is a concern because with reduced crop residue inputs, soil will typically lose organic matter; as a result, soil quality may decline. There has also been an increase in higher frequency and intensity of storm events across the contiguous U.S. A century ago, the most extreme storms contributed only 1% of total annual rainfall. Now extreme storms contribute 20% of total rainfall in the continental U.S. while total precipitation has only increased by 7% over the past century (Rosenzweig et al, 2000). Continual research and implementation of sustainable management practices is important to sustaining soil quality and health in the agricultural landscape.

This study's main focus is on implementing a management practice of incorporating a winter rye cover crop into a corn silage-soybean cropping rotation and evaluating surface runoff in a paired watershed design. We hypothesized that the use of a winter rye cover crop planted after corn silage harvest can reduce non-point source pollution through surface runoff compared to conventional corn silage management. The objective of this study was to evaluate the potential of a winter rye cover crop to minimize surface runoff, sediment, and nutrient transport from agricultural landscapes by providing cover during the fall and spring dormant periods. Since many farmers prefer to harvest winter rye for forage, we evaluated the potential addition of winter rye as feed for dairy cows.

Methods and Materials

The study was conducted on a farm located near Lewiston, MN (43.969^0 N, 91.776^0 W) in 2009 to 2012. Two adjacent watersheds on Seaton silt loam with 0 to 6% slope (Fine-silty, mixed, superactive, mesic Typic Hapludalfs) were chosen for edge-of-field surface runoff monitoring. This study consisted of two treatments in a paired watershed experimental design. The treatments were drilled winter rye and fallow following two years corn silage and one year soybean rotation. Winter rye cultivator “Rymin” was seeded in treatment watershed on 23 September 2009 and 15 October 2010 at a rate of 101 kg ha^{-1} following corn silage using a grain drill with 17.78 cm row spacing. Winter rye was chemically terminated using glyphosate in mid-May prior to subsequent crop planting. Wing-walls were constructed using methods outlined by the United States Geological Survey and the University of Wisconsin-Madison (Stuntebeck, 2008). Construction began in mid October and ended on 29 October 2009. Watersheds were surveyed and trenched to a 61 cm depth for plywood wall installation. The wall in the control watershed (without rye) is 76 m. The wall in the treatment watershed measures 60 m. After wall installation and backfilling, the wall was reinforced with 1.8 m T-posts spaced 2-5 m apart. Each watershed had a culvert in the bordering drainage ditches. The flume placement allowed the outflow of water to go directly toward the culvert to minimize ponding downstream of the flume. Platforms for the ISCO shelter and rebar support for the flumes were also installed in both watersheds. One H-flume, 0.91 m in height (Plasti-Fab Inc., Tualatin, OR) coupled with ISCO 3700 portable sampler and 4230 bubbler flow meter (Teledyne ISCO Inc., Lincoln, NE) was used at each watershed in accordance with USGS recommendations (Stuntebeck, 2008).

Equipment enclosures, flumes, ISCO portable samplers, and bubbler flow meters were installed in January 2010 and flow monitoring was initiated on 3 February 2010.

Winter Rye

Winter rye biomass was collected on 19 November 2009, 17 May 2010, 30 November 2010, and 19 May 2011. Biomass yield was determined by harvesting an area of 0.18 m^3 three times at seven GPS referenced locations within the watershed. Samples were dried at 65°C for 72 h prior to weighing. A subsample was ground, passed through a 1 mm sieve, and analyzed for total N (TKN), neutral detergent fiber and phosphorus by wet analysis by Stearns DHIA Laboratories, Sauk Centre, MN.

Yield Measurements

Corn plants were collected on 7 September 2010. Determination of corn biomass was completed by hand harvesting corn plants in a 3 m length of 76 cm spaced row at 14 locations in each watershed. Each sample was weighed on site and subsampled for moisture content. Subsamples for each location were dried for 3 days at 70°C. Dry matter was determined based on weight and moisture content.

Soybean plants were collected on 6 October 2011, 4 days prior to field harvest. Soybean plants were hand harvested in 3 m rows (with 76 cm row spacing) at 7 locations in each watershed. A mechanical sheller was used to thresh the beans from the pods. Subsamples for each location were dried for 3 days at 70°C to determine moisture content. Beans were weighed and yield was determined.

Water Samples

The automated field sites were programmed to sample on a volume basis with one sample collected for every 29.08 m^3 of surface runoff during snowmelt or rainfall events. Three samples are composited per 1 L polypropylene bottle (Teledyne ISCO Inc., Lincoln, NE). The sample collection at 29.08 m^3 was chosen so that during a runoff event, there would be sufficient sampler capacity to capture the entire event based on a predicted average water height of 0.15 m and a flow rate of 0.017 m^3s^{-1}. Water samples were immediately placed on ice in a cooler within 24 hrs and subsequently filtered using a 0.2 micron filter (VWR International, Chicago, IL) with a non-surgical syringe (120 mL was filtered from each bottle). Filtered samples were analyzed for NO_3-N, NH_4-N, and dissolved reactive Phosphorus using a Quikchem 8500 Lachat Ion analyzer (Hach Company, Loveland, CO). Total dissolved phosphorus was determined for filtered samples (University of Minnesota Soil Testing Laboratory) using a rapid flow analyzer (RFA) method with Alpkem RFA 300 (RFA, 1986 and Astoria-Pacific, Clackamas, OR). Unfiltered samples were analyzed for Total Suspended Solids (TSS), Sediment Carbon, Sediment Nitrogen, and Total Phosphorus (TP). TSS was determined with ESS Method 340.2 (Environmental Protection Agency, US). TP analysis was performed by the University of Minnesota Soil Testing Laboratory using a RFA method with Alpkem RFA 300 (RFA, 1986 and Astoria-Pacific, Clackamas, OR). Sediment carbon and sediment nitrogen were determined using Elementar Vario EL combustion analyzer (Elementar Americas, Inc., Mt. Laurel, NJ).

Soil Samples

Soil samples were collected on 09 October 2009, 24 May 2010, 5 October 2010, 19 May 2011, and 10 October 2011. Sixteen sample locations were chosen in a grid pattern for each watershed to capture slope characteristics (summit, back slope, and foot slope). Prior to each sampling date, locations were found using research grade global positioning system (GPS) mapping equipment. Two soil cores were collected at each sample location to a depth of 90 cm using a truck mounted Giddings probe (3.8 cm diameter). Cores were subsampled by depth in the following increments: 0-15 cm, 15-30 cm, 30-60 cm, and 60-90 cm and composited at each location. Soil samples were sub-sampled for physical analysis and were dried at 105°C to determine gravimetric water content and bulk density. There was no difference between gravimetric water content or bulk density for the watersheds. The remaining sample was dried at 37°C, ground through a <0.5 mm sieve, and analyzed for soil NO_3-N, NH_4-N, and Mehlich III P using a Quikchem 8500 Lachat Ion analyzer (Hach Company, Loveland, CO). The same sampling protocol and analysis were followed for each year of study.

Ground Cover Determination

Photographs for ground cover determination were collected on 20 November 2009, 20 May 2010, 30 November 2010, 18 May 2011, and 10 October 2011. Ten digital photographs were taken in each watershed using a camera mounted on a stand facing downward at a height of 1.2 m. The photographs were analyzed using USDA Sample-Point Measurement Software 1.48 (Booth 2006). This software allows for an overlay of a 100-point grid to be placed over each photograph. Ground cover is determined by visual observation at each point.

Paired Watershed Design Comparisons

The control and treatment watersheds were adjacent to one another and had the same shape but differed in size. The treatment watershed was 1.2 ha and the control was 3 ha. The watershed boundaries and area were found using research grade global positioning system (GPS) mapping equipment. Both watersheds exhibited the same flow pattern in slope characteristics, but the distance from upper portion of watershed to equipment used to monitor surface runoff was different. The distance surface runoff traveled from the upper boundary to the flume in the treatment watershed was 110 m. The distance in the control watershed was 180 m. In addition, the treatment watershed faced north and south, whereas the control watershed faced east and west. This was an important feature of the watersheds and how they behaved during snowmelt events with respect to solar radiation. The differences in the two watersheds were not desirable; however, locating two exact watersheds that are adjacent to one another is nearly impossible. This was our best case scenario for this study.

Management of Watersheds

Both watersheds were managed slightly differently throughout the study. Winter rye was planted in the treatment watershed in 2009 and 2010 and did not allow for fall tillage or manure injection to take place. In the control watershed, fall chisel-disc tillage and manure injection occurred prior to freezing of soil in the fall of both years. Contour planting in the spring was done in both watersheds. In spring 2010, winter rye harvest delayed corn planting, which resulted in the farmer using a short season corn silage plant compared to normal corn silage planting in the control watershed. However, corn silage in the treatment watershed was able to catch up in maturity to the corn silage in the control watershed. Similarities between the watersheds included contour planting of corn silage and soybean crops. The differences in management were fall tillage and manure injection in control compared to only winter planting in the treatment watershed.

Authenticity of Data

Measuring real-time surface runoff for accuracy is challenging. During all runoff events, if the flume was not level, readings of flow rate were then incorrect. To correct this issue, the flume was leveled during each visit to the field sites, and the flumes were never unbalanced. Freezing of the sampling line, ice buildup in the flume, and malfunction of the sampler were the three main challenges to this study when surface runoff was observed. Determination of runoff start and end times was confirmed based on flow rates, time of runoff, and air temperatures at the time of runoff for fall and spring runoff events. Manual manipulation of data then occurred during times of incorrect runoff measurements (Stuntebeck 2008). The majority of the incorrect runoff flows were when ice buildup occurred in the flume during the night. Sampler malfunction occurred mostly during spring snowmelt events. Freezing night temperatures would cause the ice buildup in the flume and provided incorrect flow measurements. These incorrect flow measurements would trigger the sampler to take a water sample.

Some of the snowmelt that may have occurred during times the technician's absence compromised our collection of runoff samples because ice buildup in the flume caused the sampler to use up all available collection bottles. These occurrences were not frequent, but based on the overall total volume of runoff from each watershed more bottles could have been collected. The control watershed had 24 bottles collected and the treatment watershed had 62 bottles. Based on total runoff from both watersheds, 32 and 79 bottles should have been collected from control and treatment watersheds, respectively. The missing collection samples for the control watershed occurred in the spring of 2010 when there was 282 m^3 ha^{-1} of runoff, which should have triggered runoff samples into nine bottles. Seventeen bottles were not collected in the treatment watershed and they were missing from summer 2010 and spring 2011 events. There was 75% and 79% sample-volume coverage for control and treatment watersheds, respectively. Discovery and Pioneer farms in Wisconsin, which are operated by United States Geological Survey (USGS), had 90% annual sample-volume coverage during a 6 year period from 12 edge-of-field sites (Stuntebeck 2008).

Results and Discussion

Winter Rye, Yield, Ground Cover, and Soil Composition

Winter rye biomass was 15% greater in spring 2010 than 2011 because of earlier planting in fall. Fall growth in 2009 was 471% greater than fall 2010 (Table 4-1). Establishing winter rye following corn silage earlier in the fall will potentially provide more biomass in the spring if environmental conditions are favorable. Winter rye had 3% TKN and 0.39% phosphorus. Nitrogen accumulation for winter rye in fall 2009 and spring 2010 was 25 kg ha^{-1} and 190 kg ha^{-1}, respectively. Nitrogen accumulation for winter rye in fall 2010 and spring 2011 was 4 kg ha^{-1} and 162 kg ha^{-1}, respectively. Neutral detergent fiber was 43%, compared to alfalfa with a typical NDF value of 43-51% and mixed grass forage with a typical NDF of 60% (National Research Council 2001, Miller and Hoover 1998).

Optimal growth of winter rye is crucial if harvesting for animal feed or to prevent soil erosion. In 2010, spring growth of winter rye yielded 6.34 metric tons ha^{-1}, which was used as rye-silage for dairy herd on the cooperating farm. Rye can have effects on subsequent crop yield because of water and nutrient usage, and termination of winter rye in the spring can delay crop planting. This was observed in 2010 corn silage yields. A 30% reduction in corn silage yield occurred in the treatment watershed compared to the control (Table 4-2). Wet field conditions did not allow for winter rye to be harvested, which led to delayed corn silage planting. The delay of corn silage between watersheds was a month. A short season corn silage variety was then used in the treatment watershed, so yield loss was less extreme. Even with addition of rye biomass with corn silage yields, there was still a 10% reduction in yield (Table 4-2). Soybean yield for 2011 was 3.3 metric tons ha^{-1}and 3.3 metric tons ha^{-1} in the control and treatment, respectively.

Ground cover varied between watersheds and between years (Table 4-3). Residue cover decreased in the control watershed from fall to spring, whereas residue cover increased in the treatment watershed. This was due to residue decomposition in the control and presence of winter rye growth in the treatment from fall to spring. Ground cover in the control during the fall was either slightly above or below the 30% conservation standard by NRCS. This is considered adequate cover to reduce soil erosion. However, in the spring of both years, ground cover in the control watershed was less than ideal to prevent soil erosion. In fall of 2011, ground cover was similar between watersheds after soybean harvest because no planting of winter rye occurred in the treatment watershed that fall.

In spring 2010 and 2011, winter rye reduced soil NO_3-N concentrations compared to the control watershed suggesting that the rye effectively scavenged excess soil NO_3-N during the spring (Fig. 4-1). From fall 2009 to spring 2010, soil NO_3-N concentrations increased in the control watershed because manure was injected at a rate of 93,500 L ha^{-1} immediately following corn silage harvest (Fig. 4-1). Fall 2011 soil NO_3-N concentrations were similar between watersheds following soybean harvest with no addition of winter rye.

Ammonium concentrations in the soil fluctuate frequently during the year because it is subject to many changes in the soil system. Nitrogen transformation of ammonium includes nitrification, immobilization, and volatilization. These transformations or fluctuations of ammonium are evident in the soil of the control and treatment watersheds (Figure 4-2). There was no difference between NH_4-N concentrations from year to year. The addition of manure in the control watershed in both years caused frequent transformations of ammonium throughout the year.

Soil Mehlich III-P concentrations varied slightly between fall and spring from 2009 to 2011. Phosphorus concentrations did not vary in the treatment watershed from fall to spring when winter rye was present suggesting that winter rye did not uptake P. In the control watershed P concentrations increased from fall to spring because of fall manure application (Figure 4-3).

Total Water Volume

Differences in total surface runoff were observed in 9 out of 26 months. These 9 months included the 5 major surface runoff events that had sample collections (see runoff losses below). The treatment watershed had 60% more runoff than the control watershed. The majority of the difference in annual runoff occurred during spring snowmelt events of 2010 and 2011, as well as the 23 September 2010 rainfall event. Higher rates of flow were observed in both watersheds in 2010 than 2011. The control watershed had more frequent rates of flow in 2010, whereas the treatment watershed had more frequent flow of runoff in 2011 (Figure 4-4). The higher rates of flow did not correlate to higher total volumes of runoff. The treatment watershed had a higher total runoff because runoff was occurring for longer periods of time than the control watershed. Evidence of this was the spring 2010 snowmelt where the treatment watershed runoff began on 3 March 2010 and ended on 14 March 2010 and runoff on the control watershed began 7 March 2010 and ended on 8 March 2010. The total volume of runoff from each watershed was similar at the beginning of the snowmelt period, but both the duration of runoff and the total volume of runoff from the treatment watershed were greater. The spring 2011 snowmelt produced a greater surface runoff than spring 2010. There were three snowmelt periods on 16 February, 11 March, and 20 March in 2011 (Figure 4-4).

The snowmelt events produced 75% more runoff in the treatment watershed than the control. This was due to snow catchment with the winter rye and the north-south facing aspects of the watershed. Snow cover insulates soils from freezing and allows for better infiltration of snowmelt in the spring (Schimel et al. 1996). Less snow cover causes a deeper penetration of frost in the soil profile, thus limiting water infiltration in the spring when snowmelt occurs (Shanley and Chalmers 1999). Both of these processes occurred in the two watersheds. First, the treatment watershed held more snow in both years and resulted in more snowmelt runoff. Secondly, the south aspect of the treatment watershed allowed for the snow to melt during the winter months when temperatures were at 0°C or higher and then refreeze during the night when temperatures dropped. This fluctuation of slight melting and then refreezing caused an ice layer of 7.62 cm in the treatment watershed for both years which allowed for more water to runoff and not infiltrate the soil when snowmelt occurred. Furrows created by tillage in the control impeded runoff and promoted infiltration, which may have limited the total volume of runoff from the control watershed. There were no such furrows in the treatment watershed, as rye seeding, resulted in a smooth soil surface. Contour ripping or tillage in the fall allows for better infiltration of northern latitude soils (Pikul et al. 1996). These major management differences in the watersheds provided the differences in snowmelt runoff for the two years.

Summer runoff events of 2010 occurred more frequently in the control watershed than the treatment watershed (Figure 4-5). Both watersheds had summer runoff events on 17 June 2010 and 23 June 2010 with rainfall rates of 3.86 cm and 3.2 cm respectively. However, the control watershed had greater maximum rates of runoff compared to the treatment watershed. The control watershed maximum rates of runoff were 0.108 $m^3 s^{-1}$ on 17 June 2010 and 0.099 $m^3 s^{-1}$ on 23 June 2010, corresponding to a head of 0.36 m and 0.34 m, respectively (Fig. 4-4). The treatment watershed maximum rates of runoff were 0.003 $m^3 s^{-1}$ and 0.0012 $m^3 s^{-1}$, respectively (Fig. 4-4). Their corresponding head heights of water were 0.06 m and 0.04 m, respectively. These summer events accumulated 262 m^3 ha^{-1} of runoff in the control compared to 133 m^3 ha^{-1} in the treatment watershed.

Both watersheds had fall runoff events on 15 September 2010 and 23 September 2010 with rainfall rates of 8.1 cm and 18 cm, respectively. However, the control watershed had a greater maximum rate of runoff on 15 September 2010 compared to the treatment watershed. The control watershed maximum rate of runoff was 0.107 m^3 s^{-1}, and the treatment watershed maximum rate of runoff was 0.09 m^3 s^{-1}, corresponding to a head height of 0.36 m and 0.34 m, respectively (Fig. 4-4). In contrast to the 15 September 2010 rainfall event, the maximum runoff rates were higher in the treatment watershed than the control watershed on 23 September 2010. The runoff rates at peak flow were 0.08 m^3 s^{-1} (head height of 0.32 m) and 0.05 m^3 s^{-1} (head height of 0.25 m), respectively (Fig. 4). In this event the control watershed had 110 m^3 ha^{-1} of runoff and the treatment watershed had 751 m^3 ha^{-1} (Figure 4-5). The 23 September 2010 rainfall event was massive, and the runoff caused a blow out on the wall of the control watershed. The maximum rate of runoff for the control watershed is misleading because runoff escaped underneath the wall (blowout issue) during this runoff period. It is unknown when the blowout occurred during the storm event and what volume of runoff escaped. .

NO_3-N, NH_4-N, and Phosphorus loss in Surface Runoff

The treatment watershed had greater NO_3-N and NH_4-N loads than the control watershed in 2 out of the 3 events where samples were collected (Table 4-4). In the 22-23rd September 2010 rainfall event, the treatment watershed had a 170% more NO_3-N load than the control. In the same event, the NH_4-N load from the treatment watershed was 40% greater than the control. The snowmelt of 2011 produced 650% more NO_3-N and 833% more NH_4-N loads in the treatment watershed than the control. The one instance when the control watershed had more load was the summer rainfall events on 17 June 2010 and 23 June 2010. In these rainfall events the control had 156% and 1014% more NO_3-N and NH_4-N loads, respectively, than the treatment watershed. For the snowmelt of 2010 and the 18 May 2011 rainfall events comparisons could not be made because the sampler malfunctioned for the control watershed. This was due to the sampler distributer being jammed. For the snowmelt of 2011, this jamming issue was because water froze on the distributer and impeded its function. The 18 May 2011 event had the same issue, but ice buildup did not occur.

None of the samples collected from the watersheds were over 10 mg L^{-1} of nitrate. These concentrations are below the EPA water quality standard of 10 mg L^{-1} in drinking water. This standard of 10 mg L in drinking water was established to prevent human infant deaths caused by blue-baby syndrome. Blue-baby syndrome is an environmentally-caused health disorder in which the blood in unable to carry enough oxygen to vital tissues and organs (Knobeloch et al. 2000). The control watershed had the highest concentrations of nitrate of 9.44 mg L^{-1} and 9.24 mg L^{-1} on 29 July 2010 rainfall event and in the spring 2011 snowmelt, respectively (Figure 4-6). Ammonium concentrations were also higher in the control than the treatment watershed (Figure 4-7). The highest concentration of ammonium was observed on 5 May 2010 with a concentration of 11.4 mg L^{-1}. However, the treatment watershed had more surface runoff from events which resulted in higher loads than the control (Table 4-4).

The treatment watershed had greater total phosphorus (TP) load than the control watershed in two out of the three events where samples were collected (Table 4-5). In the 22 September and 23 September 2010 rainfall event, the treatment watershed had 669% more TP than the control watershed. The majority of the TP in that event was sediment-bound P, or particulate phosphorus (PP). In the 2011 snowmelt event, the treatment watershed had 1553% more TP than the control. Similar to the September rainfall event, PP was the source of the phosphorus. In the summer 2010 rainfall events on 17 June and 23 June, TP was 575% higher in the control than the treatment watershed. The TP was mostly comprised of PP in this event as well. Total dissolved phosphorus (TDP) was higher than PP in four of the surface runoff events (two in the control and two in the treatment) (Table 4-5.) Dissolved inorganic phosphorus (DIP), also known as phosphate, was in the major form of total dissolved phosphorus in all of the samples collected. DIP is readily available to plants as a phosphorus source. It is also readily available to algae in rivers, lakes, and streams, where in excess it can cause eutrophication. The majority of the phosphorus concentrations collected (99%) from the surface runoff in both watersheds would have caused accelerated eutrophication in lakes (Figure 4-9). Accelerated eutrophication of lakes happens when concentrations of 0.025 mg L^{-1} are added. The maximum recommended DIP concentrations for streams and rivers is 0.1 mg L^{-1}. Only 88% of samples were over the maximum recommended concentrations for streams and rivers. This edge-of-field monitoring was not near any lakes, rivers, or streams. These concentrations in the runoff would probably never reach a waterway at these concentrations, because the distance is too great and the runoff from these watersheds empties into pasture land.

The highest levels of TP were observed in the treatment watershed in the spring 2011 snowmelt event, where TP was 11 mg L^{-1} (Figure 4-8). The highest observed TP concentration for the control watershed was 4.68 mg L^{-1} on 23 June 2010 (Figure 4-8). The highest concentrations of DIP or phosphate in runoff were seen in the control watershed. These higher concentrations were in 8 samples ranging from 0.75 to 1.26 mg L^{-1} (Figure 4-9). These concentrations were observed in the September 2010 storm and spring 2011 snowmelt. The highest concentration of DIP in the treatment was 0.64 mg L^{-1} on 15th August 2010 (Figure 4-9).

Sediment Loss

Similar to nitrogen and phosphorus loads, sediment loads were higher in the treatment watershed in 2 out of the 3 events where samples were collected from both watersheds (Table 4-6). In the September 2010 storm, the treatment had 78% more sediment than the control. In the snowmelt event of 2011, the treatment watershed had 99% more sediment load than the control. The summer rainfall of 2010 produced 97% more sediment load in the control than in the treatment. From what was sampled in the watersheds, 248 metric tons ha^{-1} of soil was lost from the treatment watershed and 32 metric tons ha^{-1} was lost from the control watershed in surface runoff. Next to world population growth, soil erosion is a major threat to human survival for future generations. Soil is being lost 10 to 40 times faster than it is being replenished (Pimentel, 2006). The

C/N ratio for the treatment watershed was 8.7 whereas the control was 7.7. The highest total suspended solid (TSS) concentrations were in the treatment watershed and occurred in the spring 2011 snowmelt event. These concentrations ranged from 220040 to 396990 mg L^{-1} (Figure 4-10). The highest TSS concentration in the control was observed on 5 May 2010 and was 177800 mg L^{-1} (Figure 4-10).

Conclusion

The treatment (rye) watershed had 60% more surface runoff than the control (fallow) watershed from 2010 to 2012 and consequently had more nutrient and sediment loss. Winter rye cover cropping as a best management practice is thought to reduce surface water runoff and off field transport of nutrients and sediment. While the majority of studies show this result, this study did not reach the same conclusions. The differences in surface runoff and loss of nutrients and sediment are most likely due to the differences in watershed characteristics and management of the fields. Both watersheds exhibited the same shape and slope, but differed in field size and distance that surface runoff traveled from the upper portion to monitoring equipment. Evaluating surface runoff in a paired watershed in an on-farm research setting has limitations not encountered on a research station. Flexibility had to be shared between the researchers and farmer involved because loss of economical gains from these watersheds was not a viable option when trying to control aspects within the management of the two watersheds. Another major fault of the study is the duration of evaluating surface runoff in these two systems. Two years does not capture climatic variations in weather from year to year, suggesting that more years of study should occur to control variation in weather from year to year. One major accomplishment was that we were able to have equipment in place when the 23 September storm occurred, which caused the largest flooding event since 18 August 2007. A 100-year storm for this region is 15.24 cm of total rainfall over a 24-hour period.

References

Booth DT, Cox SE, and Berryman RD. 2009. Point sampling digital imagery with 'SamplePoint'. Environmental Monitoring and Assessment 123: 97-108.

Knobeloch L, Salna B, Hogan A, Postle J, and Anderson H. 2000. Blue Babies and Nitrate-Contaminated Well Water. Environmental Health Perspectives July 108(7): 675-678.

Lachat Instruments. 2000a. Nitrate/nitrite, nitrite in surface water, wastewater. Quikchem Method no. 10-107-04-1-A. Lachat Instruments, Milwaukee, WI.

Lachat Instruments. 2000b. Ortho phosphate in waters. Quikchem Method no. 10-115-01-1-A. Lachat Instruments, Milwaukee, WI.

Miller TK and Hoover WH. 1998. Nutrient Analyses of Feedstuff Including Carbohydrates. Animal Science Report No. 1. West Virginia University, Morgantown.

National Research Council. 2001. Nutrient Requirements of Dairy Cattle (7th rev. ed.) Natl. Acad. Sci., Washington, DC.

Pikul JL, Wilkins Jr. DE, Aase JK, and Zuzel JF. 1996. Contour ripping: A tillage strategy to improve water infiltration into frozen soil. Journal of Soil and Water Conservation. 51: 76-83.

Pimentel D. 2006. Soil Erosion: A Food and Environmental Threat. Environment, Development, and Sustainability 8: 119-137.

Schimel JP, Kieland K, and Chapin FS. 1996. Nutrient availability and uptake by tundra plants. In:Landscape Function: Implications for Ecosystem Response to Disturbance: A case study of Arctic Tundra. J.D. Tenhunen, ed. Springer-Verlag, New York, NY. 201–221.

Shanley JB, and Chalmers A. 1999. The effect of frozen soil on snowmelt runoff at Sleepers River, Vermont. Hydrological Process 13:1843–1857.

Staver KW and Brinsfield RB. 1998. Using Cereal Grain Winter Cover Crops to Reduce Groundwater Nitrate Contamination in the Mid-Atlantic Coastal Plain. Journal of Soil and Water Conservation 53 (3): 230-240.

Stuntebeck TD, Komiskey MJ, Owens DW, and Hall DW. 2008. Methods of Data Collection, Sampling Processing, and Data Analysis for Edge-of-Field, Streamgaging, Subsurface-Tile, and Meteorological Stations at Discovery Farms and Pioneer Farm in Wisconsin, 2001-7. U.S. Department of Interior and U.S. Geological Survey.

Tonitto C, David MB, and Drinkwater LE. 2006. Replacing Bare Fallows with Cover Crops in Fertilizer-Intensive Cropping Systems: A Meta-Analysis of Crop Yield and N Dynamics. Agriculture, Ecosystems and Environment 112: 58-72.

USDA-NASS. 2011. Minnesota State Agricultural Overview of 2011. Census of Agriculture, Volume 1, Geographic Area Series. http://www.nass.usda.gov/Statistics_by_State/Ag_Overview/AgOverview_MN.pdf

USDA-NASS. 2012. Minnesota Agricultural Statistics Crop County Estimates. http://www.nass.usda.gov/Statistics_by_State/Minnesota/Publications/County_Estimates/2012/cornsilage12.pdf.

Table 4-1. Winter rye biomass yield near Lewiston, MN from 2009 to 2011.

Season	Year	Biomass (kg ha^{-1})
Fall	2009	845
Spring	2010	6342
Fall	2010	148
Spring	2011	5385

Table 4-2. Corn silage biomass yields and reductions near Lewiston, MN for 2010.

Watershed	Corn Silage	Rye Biomass	Yield Loss	With Rye Yield Loss
	- - - metric tons ha^{-1} - - -		- - - - - - - % - - - - - - -	
Control	32.48	-	-	-
Treatment	22.88†	6.34	30	10

† Corn silage was planted in treatment watershed one month after the control watershed was planted, due to delay of harvesting winter rye because of wet field conditions.

Table 4-3. Ground Cover in control and treatment watersheds near Lewiston, MN from 2009 to 2011.

	Year	Control	Treatment
		%	%
Fall	2009	25	64.8
Spring	2010	2.9	100
Fall	2010	43.9	56.8
Spring	2011	11.3	90.2
Fall	2011	19.5	21.2

Table 4-4. NO_3-N and NH_4-N loads in surface runoff from specific snowmelt or rainfall events near Lewiston, MN from 2010 to 2011.

	Control		**Treatment**	
Event	**NO_3-N**	**NH_4-N**	**NO_3-N**	**NH_4-N**
	- - - - - - - - - - - - kg ha^{-1} - - - - - - - - - - - -			
Snowmelt 2010	-[†]	-[†]	1.0	0.09
Summer 2010 Rain Showers	0.23	2.03	0.09	0.002
Sept 22nd , 23rd 2010	0.27	0.15	0.73	0.21
Snowmelt 2011	0.36	0.15	2.7	1.4
May 18th 2011	-[†]	-[†]	0.01	0.01

† missing data is due to sampler malfunction during events

Table 4-5. Phosphorus loads in surface runoff from specific snowmelt or rainfall events near Lewiston, MN from 2010 to 2011.

	Control					**Treatment**				
	TP	**PP**	**TDP**	**DIP**	**DOP**	**TP**	**PP**	**TDP**	**DIP**	**DOP**
Event	- - - - - - - - - - - - kg ha^{-1} - - - - - - - - - - - -									
Snowmelt 2010	- - - - - - - - - - - - - - - - - - - -[†]					0.2	0.05	0.15	0.14	0.01
Summer 2010 Rain Showers	0.27	0.2	0.07	0.04	0.03	0.04	0.01	0.03	0.03	-
Sept 22nd, 23rd 2010	0.16	0.04	0.12	0.11	0.01	1.23	0.83	0.40	0.34	0.06
Snowmelt 2011	0.15	0.05	0.10	0.09	0.01	2.48	1.78	0.70	0.70	-
May 18th 2011	- - - - - - - - - - - - - - - - - - - -[†]					0.01	0.003	0.007	0.007	-

† missing data is due to sampler malfunction during events

Table 4-6. Sediment, total nitrogen, and total carbon loads in surface runoff from specific snowmelt or rainfall events near Lewiston, MN from 2010 to 2011.

	Control			Treatment		
	Sediment	TN	TC	Sediment	TN	TC
Event	- - - - - - - - - - - - kg ha^{-1} - - - - - - - - - - - -					
Snowmelt 2010	-†	-†	-†	4206	14	95
Summer 2010 Rain Showers	15359	54	410	473	2	22
Sept 22nd, 23rd 2010	16099	66	538	72752	345	3032
Snowmelt 2011	343	1	11	169954	556	5221
May 18th 2011	-†	-†	-†	194	0.9	7.2

† missing data is due to sampler malfunction during events

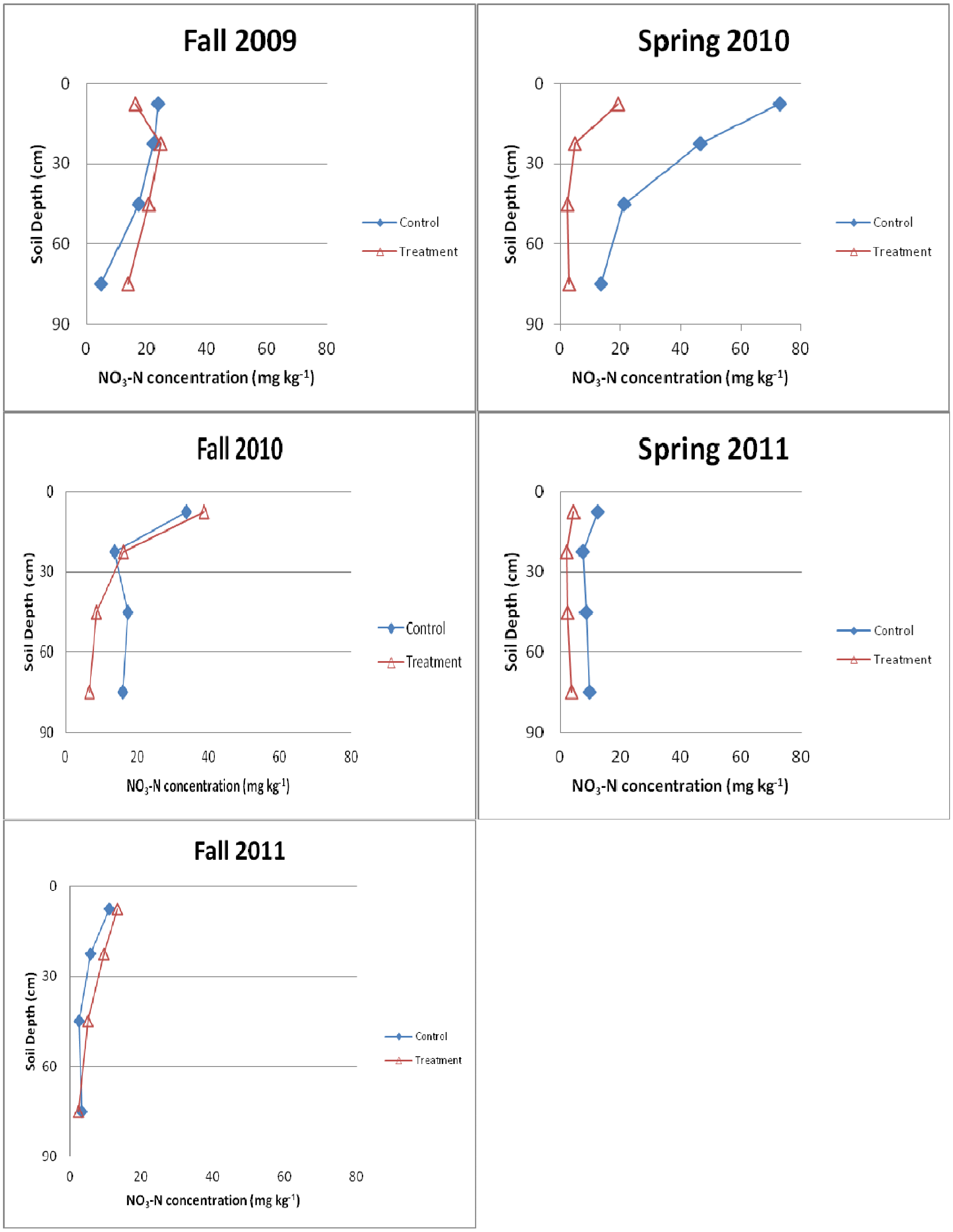


Figure 4-1. Soil NO_3-N concentrations from watersheds near Lewiston, MN for fall and spring from 2009 to 2011. Concentrations are reflected in the figure at the average point between sample increments.

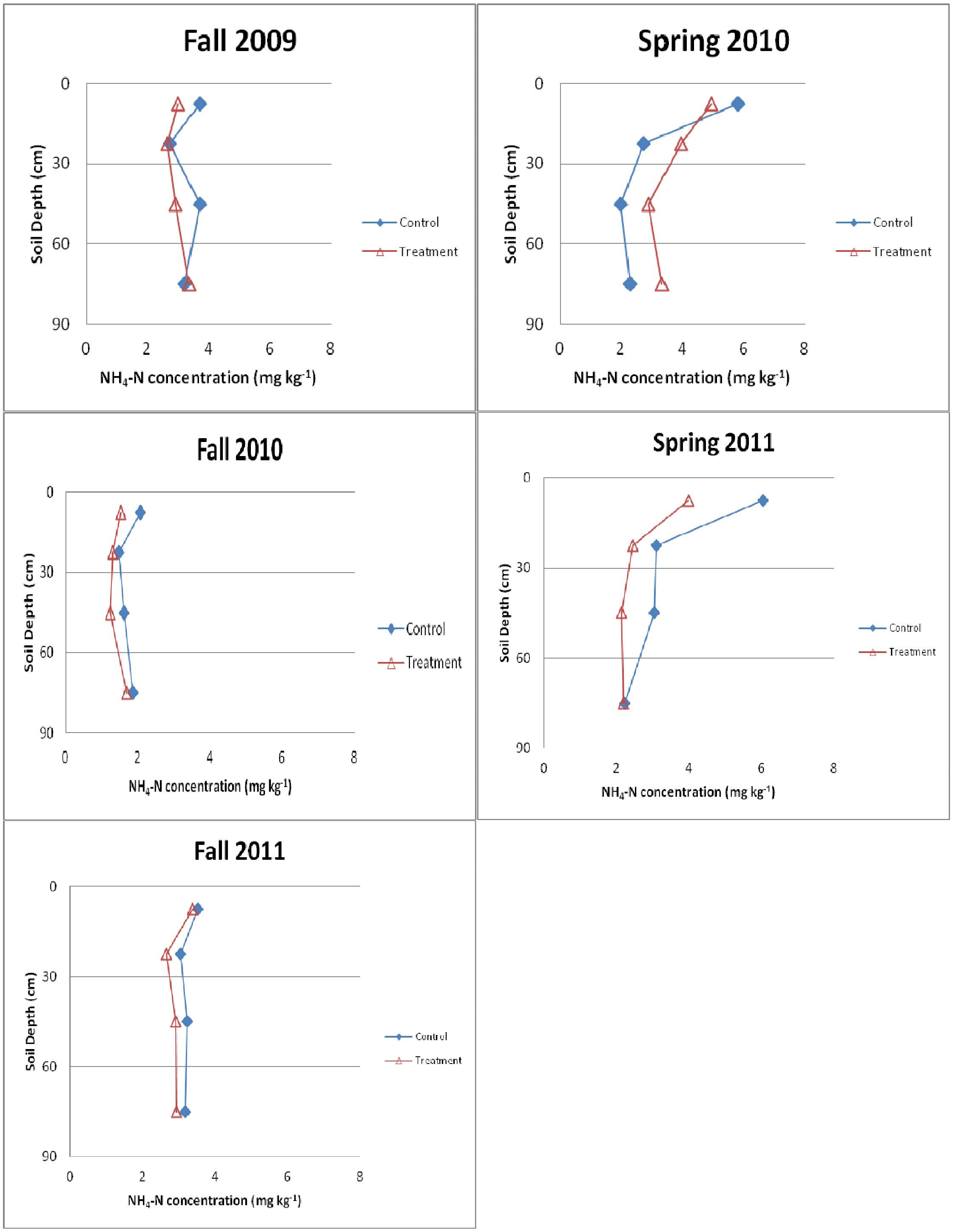


Figure 4-2. Soil NH$_4$-N concentrations from watersheds near Lewiston, MN for fall and spring from 2009 to 2011. Concentrations are reflected in the figure at the average point between sample increments.

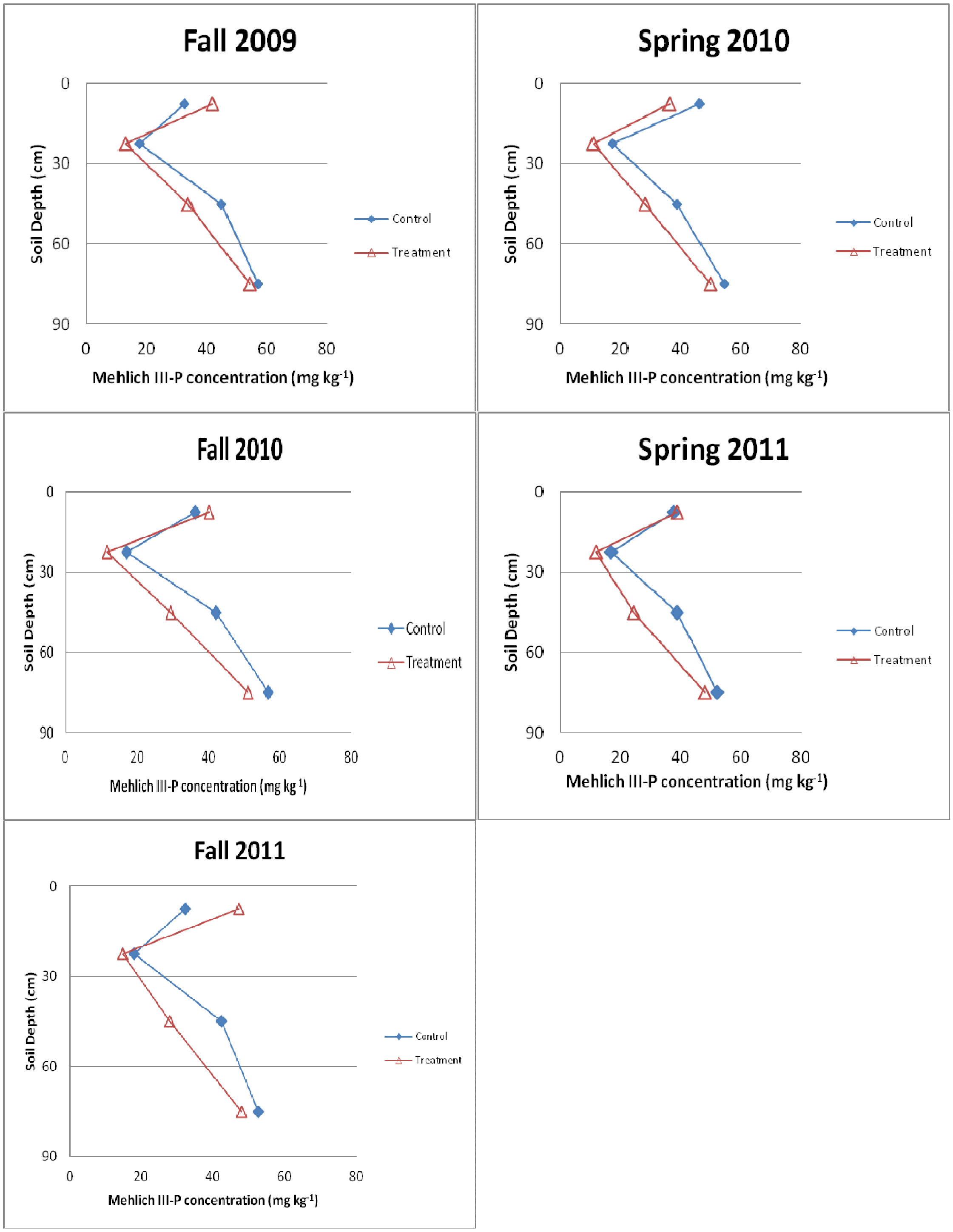


Figure 4-3. Soil Mehlich III-P concentrations from watersheds near Lewiston, MN for fall and spring from 2009 to 2011. Concentrations are reflected in the figure at the average point between sample increments.

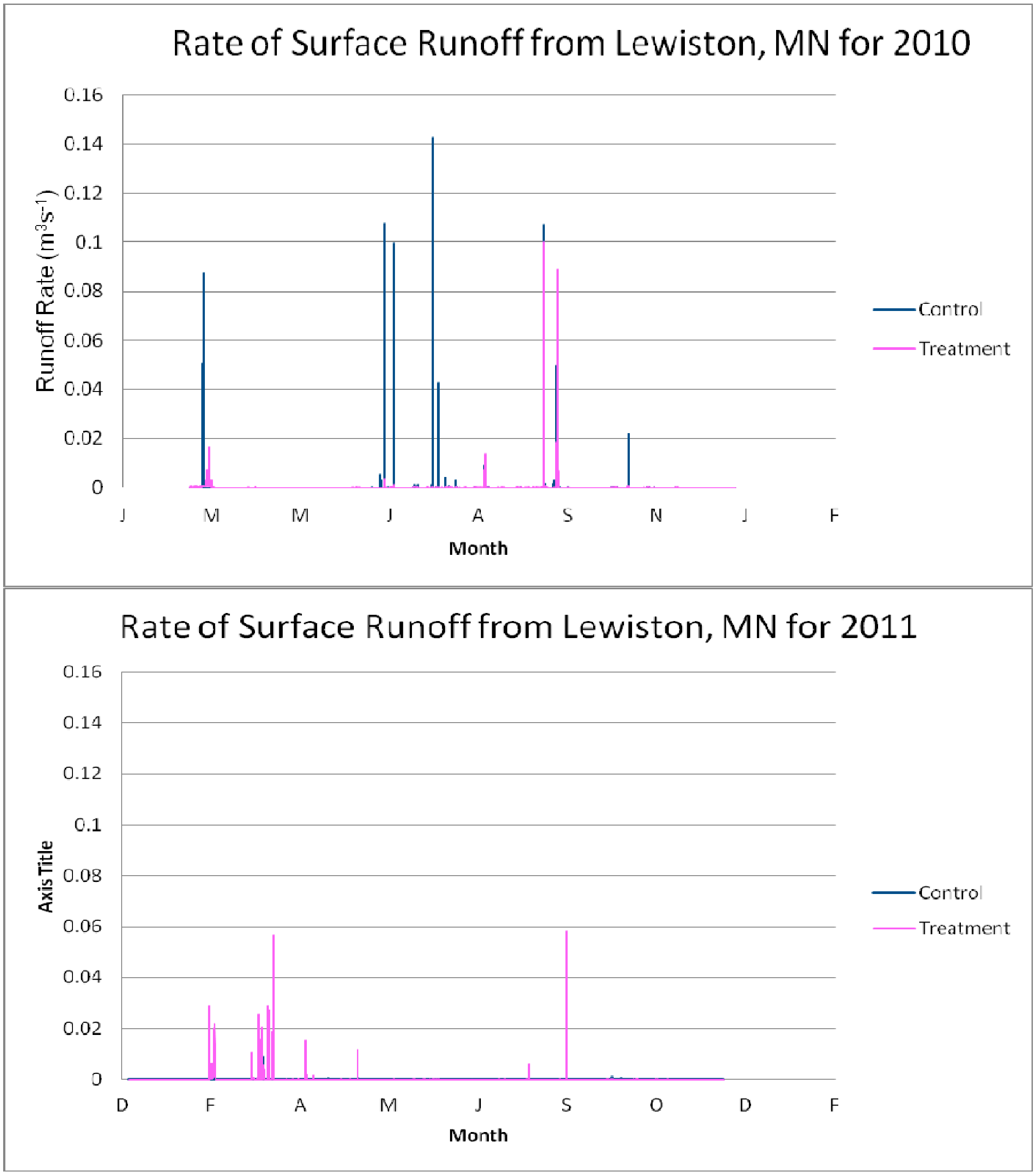


Figure 4-4. Rates of surface runoff flow for both watersheds near Lewiston, MN in 2010 and 2011.

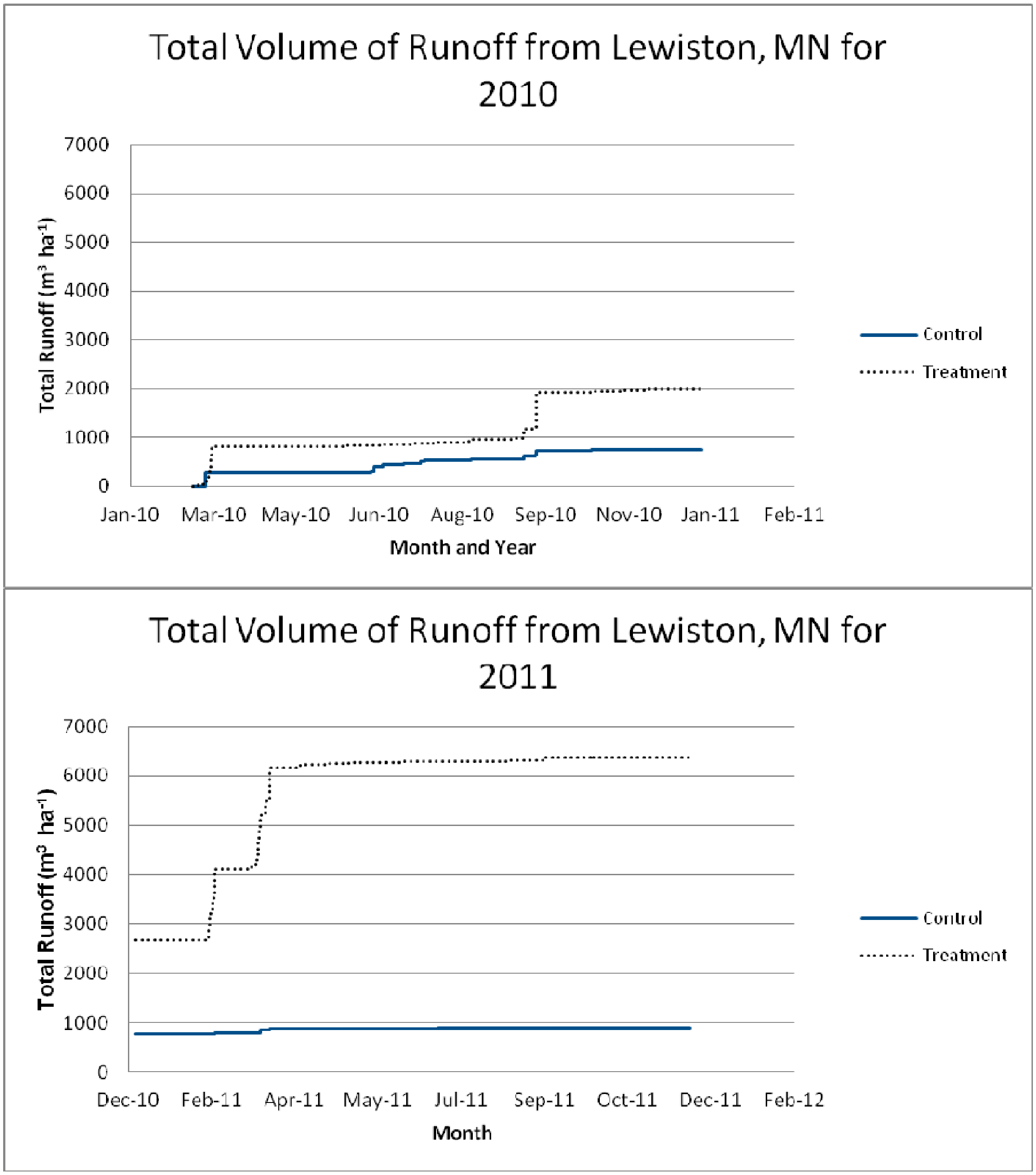


Figure 4-5. Total volume of runoff on area basis for both watersheds near Lewiston, MN in 2010 and 2011.

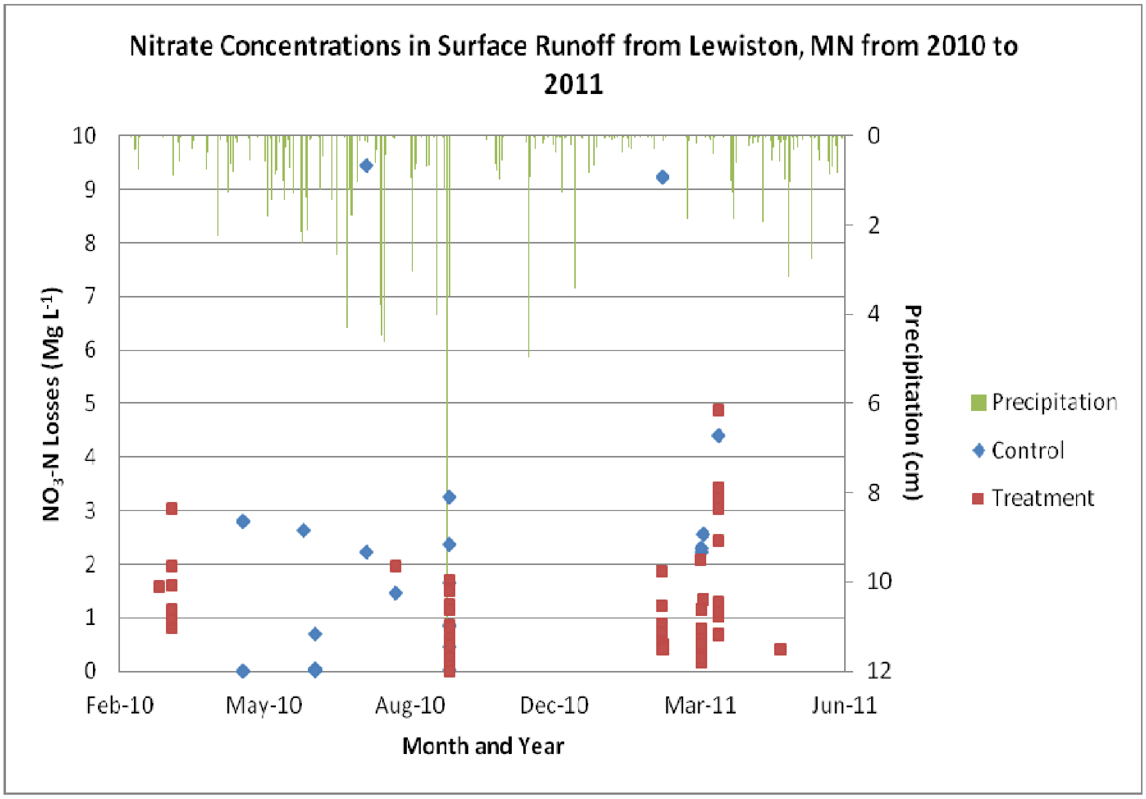


Figure 4-6. Nitrate concentrations for control and treatment watersheds near Lewiston, MN from 2010 to 2011. Squares and diamonds are concentrations from samples taken during surface runoff events.

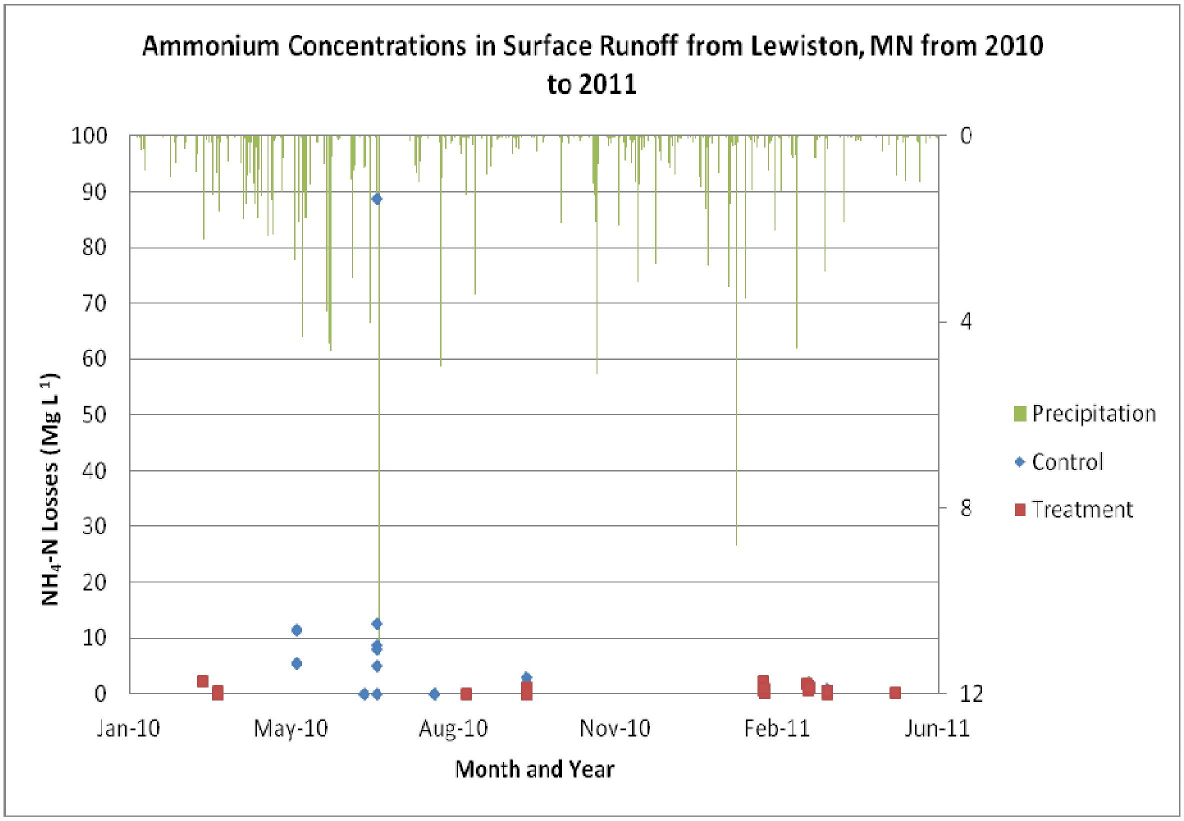


Figure 4-7. Ammonium concentrations for control and treatment watersheds near Lewiston, MN from 2010 to 2011. Squares and diamonds are concentrations from samples taken during surface runoff events.

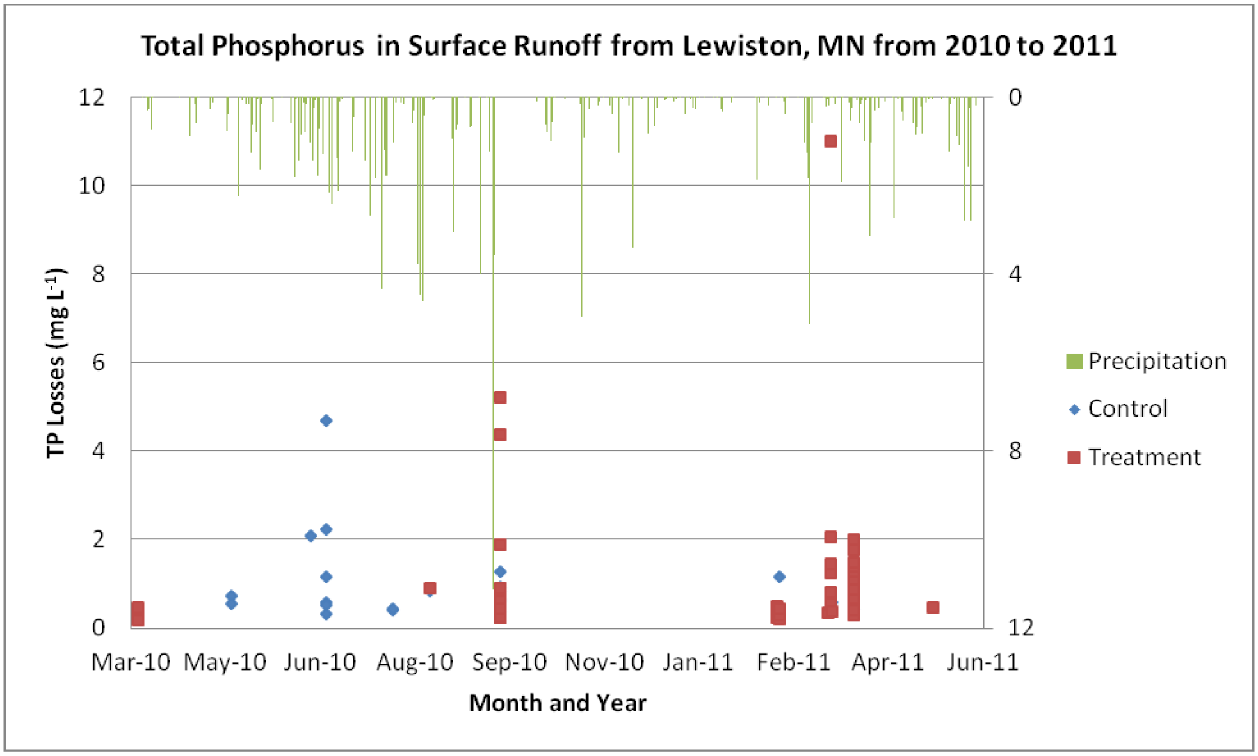


Figure 4-8. Total phosphorus concentrations for control and treatment watersheds near Lewiston, MN from 2010 to 2011. Squares and diamonds are concentrations from samples taken during surface runoff events.

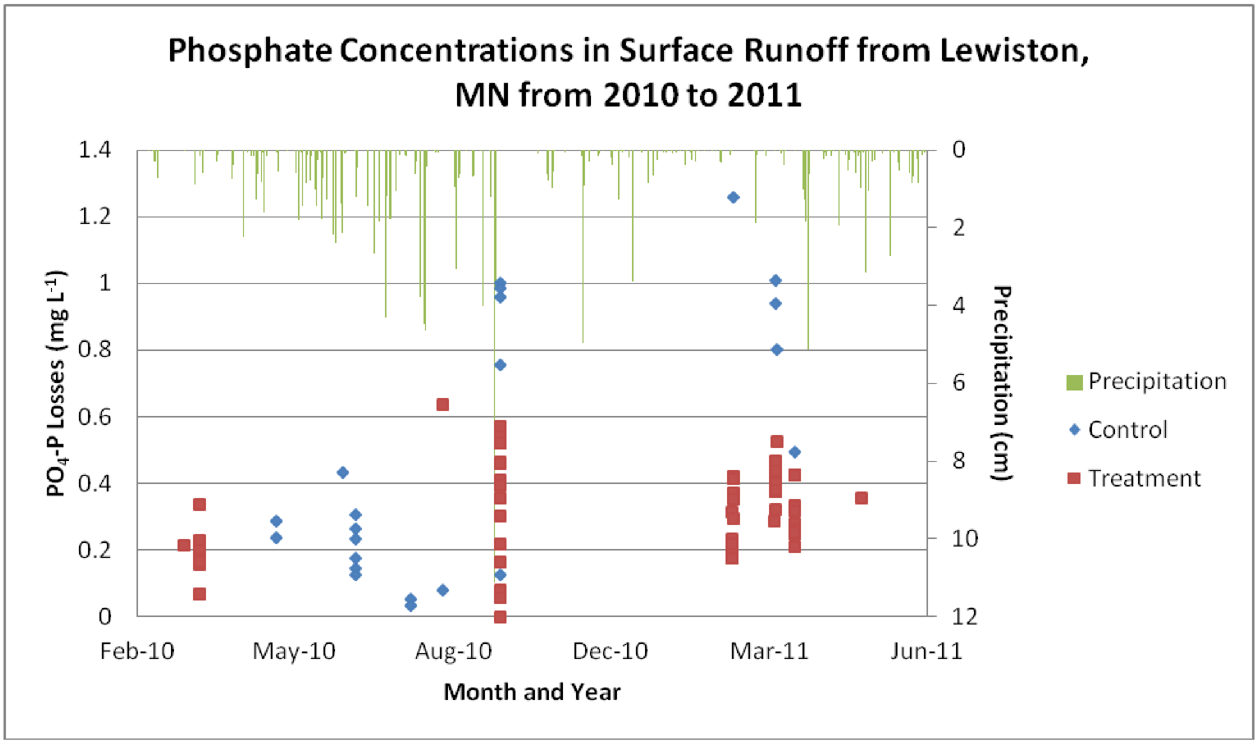


Figure 4-9. Dissolved Inorganic Phosphorus or Phosphate concentrations for control and treatment watersheds near Lewiston, MN from 2010 to 2011. Squares and diamonds are concentrations from samples taken during surface runoff events.

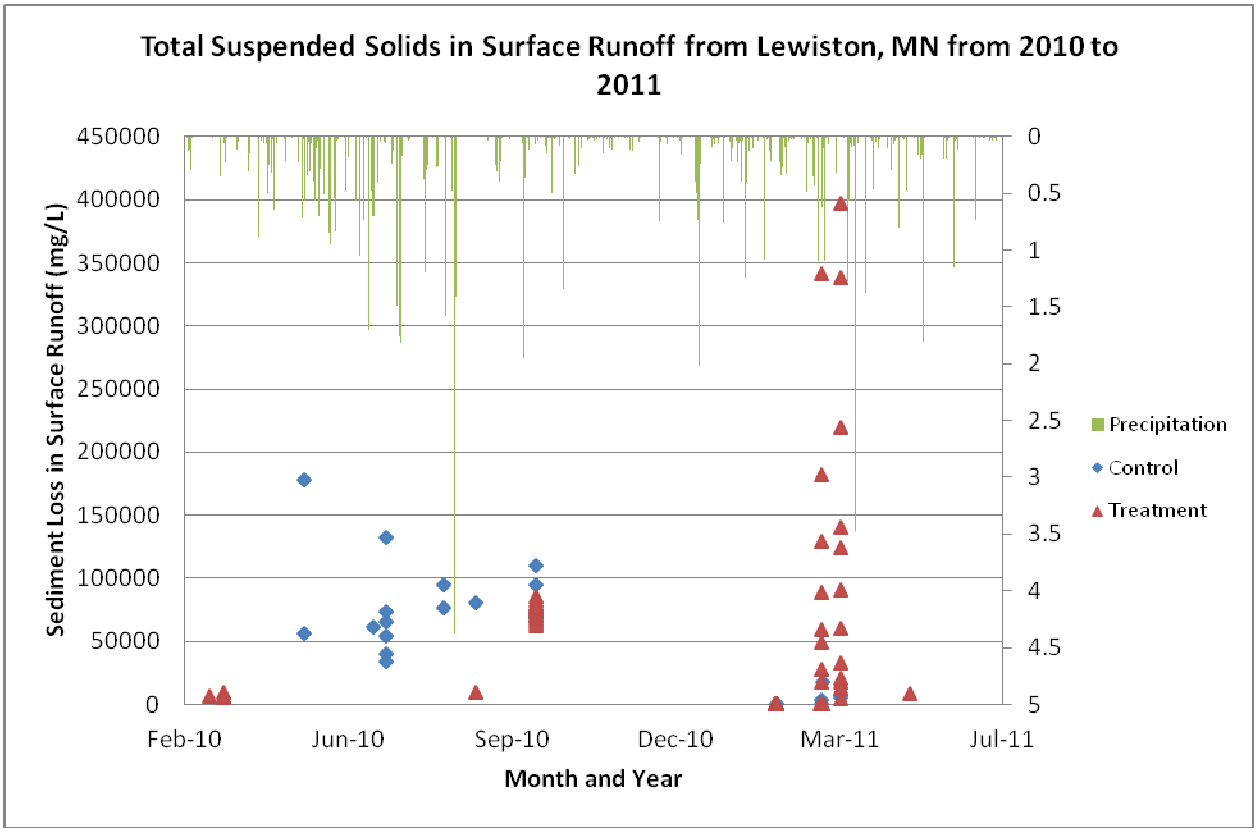


Figure 4-10. Sediment concentrations for control and treatment watersheds near Lewiston, MN from 2010 to 2011. Triangles and diamonds are concentrations from samples taken during surface runoff events.

Bibliography

Ball Coelho BR, Roy RC, and Bruin AJ. 2005. Long-term Effects of Late-Summer Overseeding of Winter Rye on Corn Grain Yield and Nitrogen Balance. Canadian Journal of Plant Science 85: 543-554.

Blanco-Canqui H, Lal R, Post WM, Izaurralde RC, and Owens LB. 2006. Corn Stover Impacts on Near-Surface Soil Properties of No-Till Corn in Ohio. Soil Science 70: 266-278.

Blanco-Canqui H. 2010. Energy Crops and Their Implications on Soil and Environment. Agronomy Journal 102: 403-419.

Booth DT, Cox SE, and Berryman RD. 2006. Point sampling digital imagery using ‘SamplePoint’. Environmental Monitoring and Assessment 123, 97–108. doi:10.1007/s10661-005-9164-7.

Booth DT, Cox SE, and Berryman RD. 2009. Point sampling digital imagery with ‘SamplePoint’. Environmental Monitoring and Assessment 123: 97-108.

David MB, Drinkwater LE, and McIsaac GF. 2010. Sources of Nitrate Yields in the Mississippi River Basin. Journal of Environmental Quality 39: 1657-1667.

Dougherty WJ, Fleming NK, Cox JW, and Chittleborough DJ. 2004. Phosphorus Transfer in Surface Runoff from intensive Pasture Systems at Various Scales: A Review. Journal of Environmental Quality 33: 1973-1988.

EPA. 2012. Water Quality Criteria. United States Environmental Protection Agency. http://water.epa.gov/scitech/swguidance/standards/crit.cfm

Feyereisen GW, Wilson BN, Sands GR, Strock JS, and Porter PM. 2006. Potential for a Rye Cover Crop to Reduce Nitrate Loss in Southwestern Minnesota. Agronomy Journal 98: 1416-1426.

Frei C, Schar C, Luthi D, and Davies HC. 1998. Heavy Precipitation Processes in a Warmer Climate. Geophysical Research Letters Vol. 25: 9, P. 1431, 1998 doi:10.1029/98GL51099

Ghidey F and Alberts EE. 1998. Runoff and Soil Losses as Affected by Corn and Soybean Tillage Systems. Journal of Soil and Water Conservation, 53(1): 64-70.

Gillingham AG and Thorrold BS. 2000. A Review of New Zealnd Research Measuring Phosphorus in Runoff from Pasture. Journal of Environmental Quality 29: 88-96.

Hart MR, Quin BF, and Nguyen ML. 2004. Phosphorus Runoff from Agricultural Land and Direct Fertilizer Effects: A Review. Journal of Environmental Quality 33:1954-1972.

He ZL, Zhang MK, Stoffella PJ, Yang XE, and Banks DJ. 2006. Phosphorus Concentrations and Loads in Runoff Water under Crop Production. Soil Science 70:1807-1816.

Hively WD, Lang M, McCarty GW, Keppler J, Sadeghi A, and McConnell LL. 2009. Using Satellite Remote Sensing to Estimate Winter Cover Crop Nutrient Uptake Efficiency. Journal of Soil and Water Conservation, 64(5): 303-313.

Kessavalou A and Walters D. 1999. Winter Rye Cover Crop Following Soybean Under Conservation Tillage: Residual Soil Nitrate. Agronomy Journal 91:643–649.

Knobeloch L, Salna B, Hogan A, Postle J, and Anderson H. 2000. Blue Babies and Nitrate-Contaminated Well Water. Environmental Health Perspectives July 108(7): 675-678.

Krueger E, Ochsner TE, Porter PM, and Baker JM. 2011. Winter Rye Cover Crop Management Influences on Soil Water, Soil Nitrate, and Corn Development. Agronomy Journal 103: 316–323.

Krueger E, Ochsner TE, Baker JM, Porter PM, and Reicosky DC. 2012. Rye-Corn Silage Double-Cropping Reduces Corn Yield but Improves Environmental Impact. Agronomy Journal 104:888-896.

Kuo S and Jellum E. 2002. Influence of Winter Cover Crop and Residue Management on Soil Nitrogen Availability and Corn. Agronomy Journal 94:501–508.

Lachat Instruments. 2000a. Nitrate/nitrite, nitrite in surface water, wastewater. Quikchem Method no. 10-107-04-1-A. Lachat Instruments, Milwaukee, WI.

Lachat Instruments. 2000b. Ortho phosphate in waters. Quikchem Method no. 10-115-01-1-A. Lachat Instruments, Milwaukee, WI.

Laflen JM and Moldenhauer WC. 1979. Soil and water losses from corn–soybean rotations. Soil Science 43:1213–1215.

Lindstrom MJ, Skidmore EL, Gupta SC, and Onstad CA. 1979. Soil conservation limitations on removal of crop residues for energy production. Journal of Environmental Quality 8:533–537.

Miller TK and Hoover WH. 1998. Nutrient Analyses of Feedstuff Including Carbohydrates. Animal Science Report No. 1. West Virginia University, Morgantown.

Mueller DK. and Helsel DR. 1999. "Nutrients in the Nation's Waters--Too Much of a Good Thing?" U.S. Geological Survey Circular 1136. National Water-Quality Assessment Program. http://water.usgs.gov/nawqa/circ-1136.html.

National Research Council. 2001. Nutrient Requirements of Dairy Cattle (7th rev. ed.) Natl. Acad. Sci., Washington, DC.

Nearing MA, Jetten V, Baffaut C, Cerdan O, Couturier A, Hernandez M, Bissonnais TL, Nichols MH, Nunes JP, Renschler CS, Souchere V, and Van Oost K. 2005. Modeling response of soil erosion and runoff to changes in precipitation and cover. Catena 61: 131-154.

Pauer JJ, and Auer MT. 2000. Nitrification in the water column and sediment of a hypereutrophic lake and adjoining river system. Water Research 34:1247–1254.

Pikul JL, Wilkins Jr. DE, Aase JK, and Zuzel JF. 1996. Contour ripping: A tillage strategy to improve water infiltration into frozen soil. Journal of Soil and Water Conservation. 51: 76-83.

Pimentel D. 2006. Soil Erosion: A Food and Environmental Threat. Environment, Development, and Sustainability 8: 119-137.

R Core Team. 2009. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. Vienna, Austria. ISBN 3-900051-07-0. http://www.R-project.org.

Rabalais N, Eugene Turner R, and Wiseman WJ. 2001. Hypoxia in the Gulf of Mexico. Journal of Environmental Quality 30:320–329.

Reicosky DC and Forcella F. 1998. Cover Crop and Soil Quality Interactions in Agroecosystems. Journal of Soil and Water Conservation 53(3):224-229.

RFA Methodolgy. 1986. Astoria-Pacific International PO Box 830, Clackamas, OR 97015.

Rosenzweig C, Iglesias A, Yang XB, Epstein PR, and Chivian E. 2000. Climate Change and U.S. Agriculture: The Impacts of Warming and Extreme Weather Events on productivity, Plant Diseases, and Pests. Center for Health and the Global Environment. IPCC report. Boston, MA.

Ruiz Diaz DA, Sawyer JE, Barker DW, and Mallarino AP. 2010. Runoff Nitrogen Loss with Simulated Rainfall Immediately Following Poultry Manure Application for Corn Production. Soil Science 74:221-230.

Schimel JP, Kieland K, and Chapin FS. 1996. Nutrient availability and uptake by tundra plants. In:Landscape Function: Implications for Ecosystem Response to Disturbance: A case study of Arctic Tundra. J.D. Tenhunen, ed. Springer-Verlag, New York, NY. 201–221.

Shanley JB, and Chalmers A. 1999. The effect of frozen soil on snowmelt runoff at Sleepers River, Vermont. Hydrological Process 13:1843–1857.

Sims JT, Simard RR, and Joern BC. 1998. Phosphorus loss in agricultural drainage: Historical perspective and current research. Journal of Environmental Quality 27:277–293.

Staver KW and Brinsfield RB. 1998. Using Cereal Grain Winter Cover Crops to Reduce Groundwater Nitrate Contamination in the Mid-Atlantic Coastal Plain. Journal of Soil and Water Conservation 53 (3): 230-240.

Stuntebeck TD, Komiskey MJ, Owens DW, and Hall DW. 2008. Methods of Data Collection, Sampling Processing, and Data Analysis for Edge-of-Field, Streamgaging, Subsurface-Tile, and Meteorological Stations at Discovery Farms and Pioneer Farm in Wisconsin, 2001-7. U.S. Department of Interior and U.S. Geological Survey.

Thomas MA, Engel BA, and Chaubey I. 2011. Multiple Corn Stover Removal Rates for Cellulosic Biofuels and Long-term Water Quality Impacts. Journal of Soil and Water Conservation 66(6): 431-444.

Tonitto C, David MB, and Drinkwater LE. 2006. Replacing Bare Fallows with Cover Crops in Fertilizer-Intensive Cropping Systems: A Meta-Analysis of Crop Yield and N Dynamics. Agriculture, Ecosystems and Environment 112: 58-72.

USDA-NRCS. 1996. Soil Quality Indicators: Soil Crusts. USDA Natural Resources Conservation Service. http://soils.usda.gov/sqi/publications/files/sq_sev_1.pdf

USDA. 1997. Usual Planting and Harvesting Dates for U.S. Field Crops. National Agricultural Statistics Service. Agricultural Handbook 628. December.

USDA-NASS. 2011. Minnesota State Agricultural Overview of 2011. Census of Agriculture, Volume 1, Geographic Area Series. http://www.nass.usda.gov/Statistics_by_State/Ag_Overview/AgOverview_MN.pdf

USDA-NASS. 2012. Minnesota Agricultural Statistics Crop County Estimates. http://www.nass.usda.gov/Statistics_by_State/Minnesota/Publications/County_Estimates/2012/cornsilage12.pdf.

UDSA-NASS. 2012. 2011 Minnesota State Agricultural Overview. National Agricultural Statistics Service.

Wischmeier WH. 1959. A Rainfall Erosion Index for a Universal Soil-Loss Equation. Soil Science 23(3): 246-249.

Appendix I

Plant tissue analysis of winter rye for chapter 1, 2, and 4 near Rosemount and Lewiston, MN.

Chapter	Treatment	Year/Season	TKN	TP	NDF
			- - - - - - - - - - -	%	- - - - - - - - - - -
1	Aerial	Fall	2.0	0.19	41.8
	Airflow	Fall	1.6	0.15	46.5
	Broadcast	Fall	1.5	0.19	43.7
	Aerial	Spring	2.7	0.31	38.7
	Airflow	Spring	2.6	0.23	41.4
	Broadcast	Spring	1.9	0.22	45.3
2	Standing Rye	2010	2.1	0.25	47.7
	Harvested Rye	2010	2.1	0.25	44.7
	Standing Rye	2011	2.7	0.53	44.1
	Harvested Rye	2011	2.2	0.51	48.3
3	Rye Watershed	2009, 2010, 2011	3.0	0.39	43.0