2013

Effects of perennial and cover crops on hydrology in Iowa

Ryan Goeken
Iowa State University

Recommended Citation

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Effects of perennial and cover crops on hydrology in Iowa

by

Ryan John Goeken

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Sustainable Agriculture

Program of Study Committee:
Matthew J. Helmers, Major Professor
Michael Castellano
Richard Cruse

Iowa State University

Ames, Iowa

2013

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ABSTRACT

Since European settlement, and beginning in the 1940's, two dramatic shifts in land use have occurred in Iowa – the first from prairie and forest to tile-drained farmland, and the second from diverse rotations to a heavier concentration of corn-soybean rotations and continuous corn. These shifts in land use and management have altered hydrological and biogeochemical cycles in the Upper Midwest, but perennial and cover crops have the potential to assist in mediating changes in these cycles.

The first study in this thesis examines how the perennial forage (PF) crop orchardgrass (*Dactylis glomerata*) affects subsurface drainage as compared to a corn-soybean rotation or continuous corn (row crops, or RC). Over the entire drainage season (March - November) over 22 years, PF did not reduce subsurface drainage, but during May, PF reduced subsurface drainage by 32% ($p < 0.05$). May is a critical period for drainage in Iowa, as wet field conditions and a lack of vegetative cover contribute to a majority of drainage and leaching of NO_3-N from row crop fields during this period.

The second study investigates how cereal rye (*Secale cereale* L. ssp. *cereal*) cover crop influences soil water dynamics in two fields in Iowa. During the spring growth period of rye, at a site in central Iowa, rye plots to be planted to soybeans significantly increased the rise in magnitude of soil moisture following rainfall events in the top 0-20 cm of soil as compared to fallow plots. Different types of rainfall events caused differing responses in soil water redistribution.

In the third study, the effect of a rye cover crop on soil water content and soil water storage during the spring and early summer in a drought year is examined. In one field in

central Iowa, rye was able to conserve water in the top soil layers (0-20 cm) and increase soil water storage in a corn-soybean rotation.

Because of public health and ecological concerns, and in light of economic and ecological uncertainties posed by climate change, more research should be directed toward perennial and cover crops because of their beneficial contributions to hydrological processes and biogeochemical cycling.

CHAPTER 1. GENERAL INTRODUCTION

Background

Changes in land cover and land management throughout the Upper Midwest have altered hydrological processes in the region (Schilling 2005). Before European settlement, prairie covered approximately 85% of Iowa, and the remaining land existed as forest, oak savanna, wetlands, rivers and lakes (Naturalists 2001). Since European settlement in the 1800's, almost 30 million acres of prairie have been repurposed for agricultural and urban use, leaving less than one-tenth of a percent of the original prairie in existence (Naturalists 2001). At first, more diverse cropping rotations with perennial and cover crops such as wheat, rye and alfalfa were planted with corn. Beginning in the 1940's, with the advent of large-scale industrial production of artificially fixed nitrogen fertilizer, the import and growing popularity of soybeans, and better and higher-yielding corn varieties, these more diverse rotations were quickly replaced with corn-soybean rotations and continuous corn fields in which the land lay bare during the winter and spring (Schilling 2005, Zhang and Schilling 2006a). Different land covers intercept, use, and distribute water in different ways (Asbjornsen et al. 2007, Dabney 1998, Marin et al. 2000), so land use changes in Iowa have altered hydrological processes such as the flow of rivers, subsurface drainage, and soil water dynamics (Schilling 2005). Because much of the highly fertile land in Iowa had a very high water table historically, beginning in the late 1800's, the water table was lowered with artificial "tile" drainage (Baker et al. 2004). This land management practice affects hydrological processes, drying the soil and, in turn, increasing the baseflow of rivers (Schilling 2005). Nitrogen from different sources dissolves in soil water, which is quickly shuttled from the soil profile to surface waters by subsurface drainage tiles. In the spring, when fields lie bare, neither precipitation nor nitrogen is used by crops; this causes a large influx of nitrogen into local surface waters and ultimately into the Gulf of Mexico, where a hypoxic “dead zone” exterminates many forms of life in the ocean (Mitsch et al. 2001).

Because of the ecological and health concerns associated with current land cover and land management, many researchers are recommending the integration of perennial and cover crops into crop rotations (Dabney 1998, Unger and Vigil 1998). These crops could help mediate changes in hydrological processes and scavenge nitrates during the spring months, partially restoring hydrological balances and reducing harmful results of pollution. They also may be able to assist in conserving soil water; this is of concern as the threat of climate change may alter precipitation patterns in the Upper Midwest (Mishra et al. 2010). The objectives of this thesis are to:

1. Explore how perennial crops could affect subsurface drainage in Iowa
2. Investigate how cover crops influence soil water patterns

Thesis Organization

Chapter 2 explores how perennial forage affects subsurface drainage in a tile-drained field in northwest Iowa. Chapter 3 details research done at two sites, including the research site employed in Chapter 2 and another field in central Iowa. This research includes an analysis of cereal rye cover crop’s effects on soil water dynamics. Chapter 3 includes a more extensive literature review of previous research done on cover crops’ effects on hydrology and soil water and on the temporal and spatial variability of soil water in different environments and how this variability affects hydrological processes. Chapter 4 explores how a rye cover crop may affect soil water content and soil water storage during an extreme drought that occurred in 2012.

Chapter 5 summarizes conclusions drawn from this thesis and discusses links between soil water dynamics and subsurface tile drainage in Iowa and how perennial and cover crops could be used to mediate changes in hydrology and nutrient leaching in the Upper Midwest. This chapter also suggests directions for further research into perennial and cover crops' ability to affect hydrological processes. References for each chapter are given at the end of the individual chapters.

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CHAPTER 2. COMPARISON OF TIMING AND VOLUME OF SUBSURFACE DRAINAGE UNDER PERENNIAL FORAGE AND ROW CROPS IN A TILE-DRAINED FIELD IN IOWA

A paper submitted to *Transactions of the ASABE*

Ryan J. Goeken[1], Xiaobo Zhou, Matthew J. Helmers[2][3]

Abstract

Subsurface drainage systems in Iowa increase productivity of annual row crops such as corn and soybeans, but also contribute to alterations in the hydrological balance of the region and to leaching of nutrient pollutants such as NO_3-N. This study's objective was to determine whether perennial forage orchardgrass is able to reduce the volume and change the timing of subsurface drainage in tiled fields in Iowa, therefore contributing to reductions in NO_3-N leaching and moderating changes in hydrology. Research was conducted at Iowa State University's Agricultural Drainage Water Research Site, located in northwest Iowa. Six 0.05 ha plots (three control and three treatment plots), each including subsurface drainage with continuous flow monitoring, were planted to row crops (RC), consisting of either a corn-soybean rotation or continuous corn from 1990-2004 (the pre-treatment period). During the treatment period (2006-2011), control plots remained in RC while treatment plots were planted to perennial forage (PF), a mixture of orchardgrass, red clover, and ladino clover, succeeding to a monoculture of orchardgrass. During the pre-treatment period, control and treatment plots showed no difference in subsurface drainage. During the treatment period, over the entire drainage season (March-November), PF did not reduce subsurface drainage, but during the month of May, PF reduced subsurface drainage by 32% ($p < 0.05$). Early

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[1] Primary researcher and author
[2] Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, IA 50010
[3] To whom correspondence should be addressed. E-mail: mhelmers@iastate.edu

spring, including May, is a critical period for drainage in Iowa, as wet field conditions and a lack of vegetative cover contribute to a majority of drainage and leaching of NO_3-N from row crop fields during this period. Further research including different perennial species is needed, and investigations in different geographical regions are needed as differences in precipitation and weather will affect the timing and volume of subsurface drainage.

Introduction

The use of subsurface drainage systems in Iowa has assisted in greatly increasing agricultural productivity of annual row crops such as corn and soybeans (Baker et al. 2004). To harness the productive potential of the land, subsurface drainage was installed extensively in Iowa in the late 19th and early 20th centuries to drain somewhat poorly to poorly drained soils. In Iowa alone, approximately 3.6 million ha of cropland are estimated to be artificially drained, amounting to 25% of the state’s agricultural land (Baker et al. 2004). The installation of these drainage systems aids in timely seedbed preparation, planting, and harvesting, and protects crops from periods of flooded soil conditions, allowing gas exchange between crop roots and the soil, which is crucial to plant metabolic processes. The widespread use of subsurface drainage coupled with a change in land use and vegetative cover may be impacting the hydrological balance of the region, however (Asbjornsen et al. 2007). Changing the landscape from a perennial prairie to annual row crops changes water uptake patterns (Asbjornsen et al. 2007); because annual row crops grow for a shorter period of the year as compared to perennial plants, evapotranspiration and water uptake from row crops occur mostly during the late spring and summer, while evapotranspiration and water uptake occur for a larger part of the year in perennials, including the early spring (Hatfield et al. 2009). The switch from perennial to annual landscapes can increase the amount of water lost to subsurface drainage, contributing to an increase in the baseflow of Iowa's rivers (Schilling 2005). Most of the NO_3-N that enters streams in Iowa is from subsurface drainage as well (Schilling 2005). Therefore, there is a double effect increasing the amount of NO_3-N in waterways; subsurface drainage increases the amount of water that flows into streams, and this greater amount of water also has a relatively high concentration of NO_3-N. Changes in cropping practices (changing the landscape from predominantly small grains, grass and hay to row crops) have a more significant effect on NO_3-N concentrations in streams than nitrogen fertilizer use, timing, or even historical precipitation differences (Hatfield et al. 2009). At recommended nitrogen application rates in corn-soybean rotation and in continuous corn, the NO_3-N concentrations in subsurface drainage water commonly surpass 10 mg L^{-1}, the U.S. public health drinking water standard (Helmers et al. 2012). High concentrations of NO_3-N in drinking water can have adverse effects on human health, and the large volumes of this nutrient entering streams in the Mississippi River Basin contribute to the hypoxic zone in the Gulf of Mexico (Mitsch et al. 2001).

The timing and volume of subsurface drainage are dependent on many factors, including precipitation timing and intensity, soil moisture conditions, and crop water demand (Lawlor et al. 2008). Lawlor et al. (2008) showed that even in years when there is equal rainfall, drainage volumes from a single field can be significantly different. This variation in drainage volume is due in large part to the timing and the intensity of specific rainfall events and the soil moisture conditions that result. Crop water demand is also important in determining subsurface drainage volumes. In addition to duration of growing season, the root depth, type and density will also affect a crop's water use. Perennial grass species will most likely uptake a larger percentage of water from soil layers near the surface as compared to corn (Dong et al. 2010, Kranz et al. 2008, Nippert and Knapp 2007), and so water use varies greatly spatially and temporally between different cropping systems. Many relatively short-term studies have shown a decrease in subsurface drainage flow with perennial crops and CRP grasses (Huggins et al. 2001, Oquist et al. 2007, Randall et al. 1997). A previous study at the site used in this study found no change in annual or drainage season flow volume due to different perennial crops or cover crops (Qi et al. 2011a). The study did not examine variability in drainage over shorter time periods however, and because about 70% of NO_3-N losses through subsurface drainage in the Midwest occur before row crops are established (in the early spring) (Randall and Vetsch 2005), an analysis of drainage over this crucial but short time period is warranted. In light of this, the objective of this study was to determine the timing and volume of subsurface drainage occurring in two different cropping systems: perennial forage (PF), which included pasture plots planted to orchardgrass (*Dactylis glomerata*), red clover (*Trifolium pretense*), and ladino clover (*Trifolium repens*), succeeding to a monoculture of orchardgrass, and row crop (RC) (either continuous corn or a corn-soybean rotation).

Materials and Methods

Site description

The field study was performed at the Agricultural Drainage Water Research Site in northwest Iowa near Gilmore City in Pocahontas County. The site is located in Garfield Township at SW 1/4, Section 27, T92N, R31W. The most ubiquitous soils are Nicollet (fine-loamy, mixed, superactive, mesic Aquic Hapludoll) and Webster and Canisteo (fine-loamy, mixed, superactive, mesic Typic Endoaqualls) clay loams with 3% to 5% organic matter, having an average slope of 0.5% to 1.5%. They are naturally poorly to naturally somewhat poorly drained glacial till soils. An automatic on-site meteorological station monitored weather conditions, including rainfall. Rainfall patterns at the site were compared to long-term averages (27 years from 1984-2010) determined from readings at the National Climate Data Center station at Pocahontas (COOP ID 1367) located 19 km west of the research site.

The total research area is 4.5 ha, of which 3.8 ha are used as experimental plots; the remainder is border and buffer. There are seventy-eight 0.05 ha plots (15 x 38 m). In 1989, subsurface drainage lines were installed parallel to the long dimension through the center of each plot and on the borders between plots. Only center drainage lines are monitored for drainage volume. Three center drainage lines from three adjacent plots drain into an aluminum culvert containing three separate sumps and sampling/monitoring systems. Back pressure diverts a small fraction of all drainage to a 20 L glass sampling bottle allowing for continuously monitored flow volume measurement and flow-integrated sampling of subsurface drainage. A detailed description of drainage monitoring design is presented in Lawlor et al. (2008).

Study design and statistical analysis

The analysis presented in this paper is based on a blocked plot design including six plots in the research area. Monthly and drainage season (March-November) drainage volumes for 1990-2011 were determined for each of these plots. The study period was split into two periods: the pre-treatment period (1990-2004) and the treatment period (2006-2011). Since it was an establishment year for PF, 2005 was left out of the analysis. During the pre-treatment period, all six plots were planted in RC, and during the treatment period, three of the plots were left in RC while the remaining three plots were planted to PF. The six plots were grouped into three pairs; these pairs were chosen because they were the plots with the most similar average yearly drainage volume during the pre-treatment period (Table 2.1). Each of these pairs belonged to one block. In 2000, a blocking system was devised in which the plots at the study site were split into four blocks according to drainage volume (including a low flow block, a medium-low flow block, a medium-high flow block, and a high flow block). (Qi et al., 2011). A more detailed description of blocking for the entire research site can be found in Qi et al. (2011). The plots used in the study are included in the three blocks with lowest flow, and the highest flow block was excluded because during the study period, subsurface flow exceeded precipitation.

Table 2.1. Research plot setup. Pre-treatment period was 1990-2004, treatment period was 2006-2011.

Pair	Plot ID	Average yearly drainage (mm) for pre-treatment period	Cropping system for treatment period
1	20-1	174	RC
	17-2	165	PF
2	20-2	235	RC
	19-1	234	PF
3	16-2	296	RC
	14-2	300	PF

SAS 9.1 software was used to determine the difference between drainage season (March-November) subsurface drainage in the control and treatment plots (SAS Institute 2003). To do so, a blocked t-test ($\alpha = 0.05$) was used. For the monthly data, a blocked t-test ($\alpha = 0.05$) was used to determine the difference in subsurface drainage between the control and treatment plots in the months of April, May, June, and July. These four months were selected for analysis because the largest amounts of subsurface drainage and NO_3-N leave row crop fields in Iowa during this period.

Results and Discussion

Research site precipitation

The drainage season is a period in which the ground is usually not frozen and is able to discharge soil water as drainage; this period was considered to be March through November. The long term normal drainage season precipitation for Pocahontas, Iowa was 704 mm. During the 22 years of the study, the average drainage season precipitation was 680 mm, or 3% below the long-term normal for the area. Drainage season precipitation ranged from 458 mm in 1997, or 35% below normal, to 908 mm in 2010, or 29% above normal (Table 2.2). Eight of the 22 drainage seasons were wetter than normal, ranging from 2% to 29% wetter. The other 14 drainage seasons were between 1% and 35% drier than normal. Nine of the 22 drainage seasons had precipitation totals within 10% of the normal, all of which were during the pre-treatment period (1990-2004). In table 2.2, growing season (May-September) precipitation is also found. The growing season average precipitation for the study period was 490 mm, only 2 mm wetter than the normal. Overall precipitation averages for the months of May, June and October during the study period surpassed the normal for each month by 2%, 18%, and 3%, respectively, with all other months drier than normal, ranging from 2% to 28%.

During the pre-treatment period (1990-2004), the average drainage season precipitation was 677 mm, or 4% below the long-term normal for the area. During these years, precipitation averages for May and June surpassed the normal precipitation by 6% and 16%, respectively, while all other months were drier than normal, ranging from 6% drier in July, August, and October, to 26% drier in November with a deficit of 9 mm. During the treatment period (2006-2011), the average drainage season precipitation was 705 mm, almost exactly the same as the normal of 704 mm.

Table 2.2. Precipitation at the research site during the study period (mm).

	Month									Growing	Drainage
Year	March	April	May	June	July	Aug.	Sep.	Oct.	Nov.	Season[a]	Season[a]
1990	0	38	117	290	150	80	50	24	13	686	761
1991	108	131	168	131	76	65	44	38	50	483	811
1992	53	61	50	90	187	80	16	77	53	423	667
1993	51	113	125	179	143	160	28	31	12	636	843
1994	2	52	41	179	89	51	37	48	30	396	528
1995	54	54	91	93	54	127	99	54	7	464	633
1996	45	24	114	116	82	199	50	60	60	562	751
1997	35	60	55	82	86	15	78	40	6	317	458
1998	57	56	104	171	102	53	24	76	17	454	660
1999	37	212	115	83	70	57	24	15	21	348	633
2000	28	34	93	113	152	92	35	67	70	485	684
2001	22	78	171	79	117	72	42	51	54	481	686
2002	25	61	77	51	87	279	35	77	3	529	695
2003	28	36	109	222	126	42	46	12	0	545	621
2004	97	72	146	121	58	48	143	15	20	517	720
2005	21	89	129	134	63	45	39	20	43	409	582
2006	69	93	22	61	28	135	91	19	21	337	538
2007	46	83	90	44	41	336	97	107	1	609	845
2008	35	88	151	152	105	80	65	100	37	553	812
2009	36	56	66	74	128	48	37	151	23	352	619
2010	N/A[b]	70	81	331	176	85	108	14	41	782	908
2011	6	86	102	185	73	22	24	4	8	406	510
Average	41	75	101	135	100	99	55	50	27	490	680
Normal[c]	49	80	99	115	112	101	61	49	37	488	704

[a] Growing season was May through September, and drainage season was March through November.
[b] Climate data not available for site.
[c] Source: Climatological Data for Iowa, National Climate Data Center for Pocahontas, IA, 1984-2010.

Variability among drainage seasons was great, however, as none of the years were within 10% of the normal, ranging from 28% drier than normal in 2011 to 29% wetter than normal in 2010. Also, during the treatment period, precipitation averages for June, August, September, and October surpassed the normal by 23%, 17%, 15%, and 35%, respectively, while all other months were drier than normal, ranging from only 1% drier in April to 42% drier in November with a deficit of 15 mm. During the pre-treatment period, the average growing season precipitation was 488 mm, the same as the normal for this period. During the treatment period, the average growing season precipitation was 506 mm, or 4% wetter than the normal.

Subsurface drainage volume and timing

In general, only a small amount of drainage occurred in March, followed by a sharp increase in April, and the most drainage occurred in May and June, decreasing to small amounts in September, October, and November, whereas precipitation increased more gradually throughout the year to the highest amount in June, from which it decreased (Fig. 2.1). During the research period, average growing season drainage was 77% and 78% of drainage season drainage for the control and treatment plots, respectively. In six of the years, all during the pre-treatment period, growing season drainage was 100% of the drainage season drainage for control plots; this was repeated for the treatment plots in eight of the pre-treatment period years. The year with the smallest percentage of drainage season drainage occurring during the growing season was 2006, in which 37% and 21% of drainage occurred during the growing season for the control and treatment plots, respectively.

The average drainage season subsurface drainage for the control plots over the research period was 226 mm (Table 2.3). Drainage ranged from 5 mm in 2000 to 437 mm in 2007. For the pre-treatment period, average drainage season subsurface drainage was 199 mm, and for the treatment period, it was 294 mm.

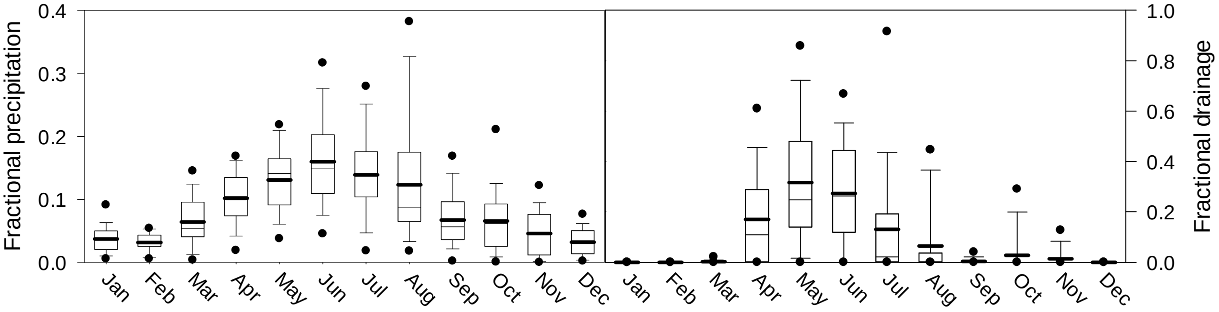

Figure 2.1. Box plot diagrams of precipitation and subsurface drainage volumes. Fractional precipitation is the average from 1990-2010 based on weather data NCDC data at Pocahontas. Fractional drainage is the average from 1990-2011 in the control plots. Points on each box indicate the following: bottom point = 5th percentile, error bar below box = 10th percentile, lower boundary of box = 25th percentile, upper boundary of box = 75th percentile, error bar above box = 90th percentile, top point = 95th percentile, thin line within box = median value, thicker line within box = mean value.

During the pre-treatment period, drainage season drainage ranged from 5 to 398 mm, while it ranged from 114 to 437 mm in the treatment period. During the research period, the largest amount of drainage occurred in the month of June, with an average of 69 mm, followed by May with an average of 65 mm; March and September had the least amount of drainage with an average of 1 mm. During the pre-treatment period, May had the largest amount of drainage, while during the treatment period, June had the most drainage. On average, for the control plots, 76% of drainage season drainage occurred during the months of April through June. During the pre-treatment period, 78% of drainage season drainage occurred in the months of April, May, and June, and during the treatment period, 73% of drainage season drainage occurred during these three months. Over the entire research period, April, May, and June were the months with the highest average amounts of drainage. Over the same period, these months had the highest drainage to precipitation ratio (D:P), as well. During both the pre-treatment and treatment periods, May had the largest D:P while March had the smallest. Drainage season D:P ranged from 0.01 in 2000 to 0.54 in 2011, with an overall average drainage season D:P of 0.32. The average drainage season D:P for the pre-treatment period was 0.28, while it was 0.41 for the treatment period.

Even in years with nearly identical precipitation, drainage can vary widely, as is seen in the years 2000 and 2001 (Table 2.3). In 2000 there was 684 mm of precipitation, while in 2001 there was 686 mm, but there was only 5 mm of drainage during 2000 as compared to 189 mm in 2001.

Table 2.3. Subsurface drainage (mm) at research site for control plots.

Year	Month									Growing Season		Drainage Season	
	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Drainage	D:P[a]	Drainage	D:P
Before PF establishment													
1990	0	16	53	141	58	0	0	0	0	253	0.37	268	0.35
1991	0	104	138	103	0	0	0	0	53	241	0.50	398	0.49
1992	0	55	11	38	84	0	0	7	0	133	0.31	194	0.29
1993	0	123	53	71	49	54	0	0	0	227	0.36	350	0.42
1994	0	0	0	8	6	0	0	0	0	14	0.03	14	0.03
1995	0	0	159	61	0	0	0	0	0	220	0.47	220	0.35
1996	0	0	75	94	11	161	10	0	0	352	0.63	352	0.47
1997	0	35	35	0	1	0	0	0	0	35	0.11	70	0.15
1998	0	0	75	47	10	0	0	0	0	132	0.29	132	0.20
1999	0	0	122	14	2	0	0	0	0	138	0.40	138	0.22
2000	0	0	0	0	5	0	0	0	0	5	0.01	5	0.01
2001	0	18	136	30	0	5	0	0	0	170	0.35	189	0.27
2002	0	8	62	20	0	62	7	2	0	151	0.29	162	0.23
2003	0	39	77	140	63	0	0	0	0	280	0.51	318	0.51
2004	0	15	82	74	0	1	0	0	0	157	0.30	171	0.24
Avg.	0	28	72	56	19	19	1	1	4	167	--	199	--
Avg. D:P	0.00	0.36	0.64	0.40	0.14	0.10	0.03	0.01	0.07	--	0.33	--	0.28
After PF establishment													
2006	0	72	41	0	1	0	0	0	0	42	0.13	114	0.21
2007	5	106	47	6	0	142	2	128	0	197	0.32	437	0.52
2008	0	99	95	173	7	0	0	0	0	275	0.50	374	0.46
2009	0	24	26	27	33	0	0	47	16	86	0.24	173	0.28
2010	9	11	22	271	32	26	1	0	24	351	0.45	395	0.44
2011	0	83	50	134	7	0	0	0	0	191	0.47	274	0.54
Avg.	2	66	47	102	13	28	0	29	7	190	--	294	--
Avg. D:P	0.02	0.79	0.69	0.53	0.11	0.12	0.00	0.25	0.21	--	0.35	--	0.41
Total Avg.	1	39	65	69	18	21	1	9	4	174	--	226	--
Total Avg. D:P	0.01	0.48	0.66	0.44	0.13	0.10	0.02	0.08	0.11	--	0.34	--	0.32

[a] D:P = ratio of drainage to precipitation. Precipitation data from on-site meteorological station.

During April and May in 2001, there was nearly 2X the precipitation as during the same period in 2000; there is generally no vegetative cover in row crop fields in Iowa during April and May, and so a large amount of drainage would be expected if soil moisture was adequate. Lawlor et al. (2008) found that years with equal precipitation are able to have statistically different drainage volumes in plots, as drainage volumes are directly tied to soil moisture, rainstorm timing and intensity, and the crop water demand during a given part of the growing season.

The average drainage season subsurface drainage for the treatment plots over the research period was 237 mm (Table 2.4). Drainage ranged from 15 mm in 2000 to 472 mm in 1993.

Table 2.4. Subsurface drainage (mm) at research site for treatment plots.

	Month									Growing Season		Drainage Season	
Year	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Drainage	D:P[a]	Drainage	D:P
Before PF establishment													
1990	0	13	75	214	72	0	0	0	0	361	0.53	374	0.49
1991	0	82	99	117	0	0	0	8	29	216	0.45	335	0.41
1992	0	55	3	69	82	0	0	6	36	155	0.37	253	0.38
1993	0	216	105	62	22	64	0	0	3	252	0.40	472	0.56
1994	0	0	0	49	0	0	0	0	0	49	0.12	49	0.09
1995	0	0	248	42	0	0	0	0	0	290	0.63	290	0.46
1996	0	0	96	181	12	45	7	1	0	340	0.61	341	0.45
1997	0	0	49	2	0	0	0	0	0	52	0.16	52	0.11
1998	0	0	84	63	18	0	0	0	0	166	0.37	166	0.25
1999	0	0	112	6	3	0	0	0	0	121	0.35	121	0.19
2000	0	0	0	1	14	0	0	0	0	15	0.03	15	0.02
2001	0	29	129	29	0	0	0	0	0	158	0.33	187	0.27
2002	0	0	43	11	0	60	7	0	0	120	0.23	120	0.17
2003	0	23	77	184	63	0	0	0	0	324	0.59	347	0.56
2004	0	0	70	63	0	0	0	0	0	133	0.26	133	0.19
Avg.	0	28	79	73	19	11	1	1	5	183	--	217	--
Avg. D:P	0.00	0.32	0.72	0.50	0.13	0.06	0.02	0.02	0.10	--	0.36	--	0.31
After PF establishment													
2006	0	64	15	0	2	0	0	0	0	17	0.05	82	0.15
2007	5	99	20	0	0	151	0	62	0	171	0.28	337	0.40
2008	0	88	92	184	0	0	0	9	12	276	0.50	385	0.47
2009	0	32	18	11	39	0	0	62	29	68	0.19	192	0.31
2010	12	7	6	309	47	34	5	0	15	401	0.51	435	0.48
2011	0	86	40	156	16	0	0	0	0	212	0.52	298	0.58
Avg.	3	63	32	110	17	31	1	22	9	191	--	288	--
Avg. D:P	0.02	0.76	0.37	0.52	0.15	0.14	0.01	0.18	0.32	--	0.34	--	0.40
Total Avg.	1	38	66	84	19	17	1	7	6	186	--	237	--
Total Avg..D:P	0.01	0.40	0.62	0.50	0.14	0.08	0.02	0.07	0.17	--	0.36	--	0.33

[a] D:P = ratio of drainage to precipitation. Precipitation data from on-site meteorological station.

For the pre-treatment period, average drainage season subsurface drainage was 217 mm, and for the treatment period, it was 288 mm. During the pre-treatment period, drainage season drainage ranged from 15 to 472 mm, while it ranged from 82 to 435 mm in the treatment period. During the research period, the largest amount of drainage occurred during the month of June, with an average of 84 mm, followed by May with an average of 66 mm; March and September had the least drainage with an average of 1 mm each. During the pre-treatment period, May had the highest average amount of drainage, while during the treatment period, June had the highest average drainage. For treatment plots, on average, 79% of drainage season drainage occurred during the months of April through June. During the pre-treatment period 83% of drainage season drainage occurred in the months of April, May, and June, and during the treatment period, 71% occurred during this time period. For treatment plots, April, June, and May had the largest D:P, respectively. During the pre-treatment period, May had the largest D:P while March had the smallest, and during the treatment period, April had the largest D:P and September had the smallest. Drainage season D:P ranged from 0.02 in 2000 to 0.56 in both 1993 and 2003, with an overall average drainage season D:P of 0.33. The average drainage season D:P for the pre-treatment period was 0.31, while it was 0.40 for the treatment period

For the complete drainage season (March-November), the pre-treatment period showed no significant difference in drainage between treatments in any individual year or on average (Table 2.5). On average, the treatment period had no significant difference in drainage between treatments, although drainage was reduced significantly in the PF plots in the 2006 and 2007.

Table 2.5. Difference between subsurface drainage (mm) in control (Con.) and treatment (Treat.) plots over study period in critical months of April-July.[a]

Year	Month								Drainage Season	
	April		May		June		July			
	Con.	Treat.	Con.	Treat.	Con.	Treat.	Con.	Treat.	Con.	Treat.
Before PF establishment										
1990	16a	13a	53a	75a	141a	214a	58a	72a	268a	374a
1991	104a	82a	138a	99a	103a	117b	0a	0a	398a	335a
1992	55a	55a	11a	3a	38a	69a	84a	82a	194a	253a
1993	123a	216a	53a	105a	71a	62a	49a	22a	350a	472a
1994	0a	0a	0a	0a	8a	49a	6a	0a	14a	49a
1995	0a	0a	159a	248a	61a	42a	0a	0a	220a	290a
1996	0a	0a	75a	96a	94a	181a	11a	12a	352a	341a
1997	35a	0a	35a	49a	0a	2a	1a	0a	70a	52a
1998	0a	0a	75a	84a	47a	63a	10a	18a	132a	166a
1999	0a	0a	122a	112a	14a	6a	2a	3a	138a	121a
2000	0a	0a	0a	0a	0a	1a	5a	14a	5a	15a
2001	18a	29a	136a	129a	30a	29a	0a	0a	189a	187a
2002	8a	0a	62a	43a	20a	11a	0a	0a	162a	120a
2003	39a	23a	77a	77a	140a	184a	63a	63a	318a	347a
2004	15a	0a	82a	70a	74a	63a	0a	0a	171a	133a
Average	28a	28a	72a	79a	56a	73a	19a	19a	199a	217a
After PF establishment										
2006	72a	64a	41a	15a	0a	0a	1a	2a	114a	82b
2007	106a	99a	47a	20b	6a	0a	0a	0a	437a	337b
2008	99a	88a	95a	92a	173a	184a	7a	0a	374a	385a
2009	24a	32a	26a	18a	27a	11b	33a	39a	173a	192a
2010	11a	7a	22a	6b	271a	309a	32a	47a	395a	435a
2011	83a	86a	50a	40a	134a	156a	7a	16a	274a	298a
Average	66a	63a	47a	32b	102a	110a	13a	17a	294a	288a

[a] Means within years and on average (within rows) followed by the same letter are not significantly different at p = 0.05.

Table 2.5 shows the difference in monthly drainage between control and treatment plots in the months of April-July. These months were chosen for analysis because a large majority of the drainage flow occurs during this period (85% and 87% of yearly flow for control and treatment plots, respectively). Also, because of a large amount of precipitation and a lack of living land cover in row crops fields, most NO_3-N is leached during this period. In all four months, during the pre-treatment period there was no significant difference on average, although there was a significant difference in drainage between the control and treatment plots in June of 1991. In contrast, during the month of May in the treatment period, the treatment plots showed a significant decrease (32%) in subsurface drainage as compared to the control plots. Both May 2007 and 2010 showed a significant difference in drainage between control and treatment plots within the year.

Conclusions

Although forage plots planted to perennial orchardgrass did not significantly reduce subsurface drainage over the drainage season, this perennial forage did significantly reduce subsurface drainage during the month of May as compared to row crops. The spring months, including May, are a critical time in row crop fields in Iowa for subsurface drainage, as this is the period when the most drainage occurs and when most NO_3-N is lost due to leaching. The results presented in this study suggest that perennial cropping systems could reduce deleterious effects of subsurface drainage in Iowa. More research is needed, however. There are many types of perennial cover that can be integrated into Iowa’s agricultural landscape, and each of these types of perennial cover can be used for different purposes and in different cropping systems. For example, some perennial crops, such as warm and cool season grasses and different legumes are utilized in long-term pastures, while some perennials, such as alfalfa, can be integrated into extended rotations, these perennials only being allowed to grow for a year or two at a time. Differences in physiological traits and interactions among plant species and management strategies utilized with perennial crops will likely cause different responses in subsurface drainage. In fact, orchardgrass itself comes in many different varieties, each yielding differently; the crop’s forage yield also varies widely among states in the Midwestern United States (Henning and Risner 1993). These different patterns in growth will likely cause different responses in subsurface drainage. The variance in how perennial crops will grow in different geographic regions, coupled with differences in soil moisture conditions and precipitation and weather patterns will also affect how subsurface drainage responds to perennial cropping systems. Therefore, further research including the integration of perennial crops into agricultural systems should include diverse types and mixtures of species and these studies should be spread over different geographic areas. Furthermore, in order to re-integrate perennial crops into our agricultural systems, there must be not only environmental, but economic incentives. Current programs heavily favor row crops in the Midwest, and so it is difficult to integrate perennial crops into an agricultural system or rotation. Therefore, in order to reap the benefits from perennial crops, research must be directed at not only production aspects of the agricultural system, but also towards political, social, and economic factors as well.

Acknowledgements

This research is part of a regional collaborative project supported by the USDA-NIFA, Award No. 2011-68002-30190, “Cropping Systems Coordinated Agricultural Project:

Climate Change, Mitigation, and Adaptation in Corn-based Cropping Systems." Project Web site: sustainablecorn.org. Funding for this project was also provided by the Iowa Department of Agriculture and Land Stewardship.

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CHAPTER 3. EFFECT OF RYE COVER CROP ON SOIL WATER DYNAMICS DURING SPRING RAINFALL EVENTS FOR A CORN-SOYBEAN ROTATION IN IOWA

A paper to be modified for submission to *Catena*

Abstract

Land use and management changes have altered hydrological and biogeochemical cycles in the Upper Midwest. Cover crops such as cereal rye (*Secale cereale*) are a promising way to mediate changes in these cycles through increased infiltration and decreased erosion, drainage, and NO_3-N leaching. The objective of this paper is to use soil volumetric water content data measured at short time intervals during the primary rye growth period in spring to determine how rainfall characteristics and land cover affect infiltration and redistribution of water through the soil profile after individual rainfall events in plots with and without a rye cover crop. Continuous volumetric water content measurements at five soil depths (10, 20, 40, 60 and 100 cm) at 1-hr and 5-min intervals during the rye growing season (March 1 – May 9 of 2012) were used to examine soil water dynamics during and after rainfall events in two fields, one in northwest and another in central Iowa, using four treatments: corn without rye (C), corn with rye (rC), soybeans without rye (S), and soybeans with rye (rS). The main crop in the treatment name denotes the crop that would be planted following rye growth and termination, and so plots without rye were fallow during the study period. There were no significant differences in cumulative infiltration among treatments at either site. At the site in central Iowa, rye (rS) significantly increased the magnitude of the rise in soil water content during rainfall events as compared to fallow plots (S and C) at a 10 cm depth. These results indicate rye may have the greatest effect on soil

water dynamics in the upper soil layers. During small and medium rainfall events, in rye plots, water mostly did not percolate deeper than 20 cm, most likely due to greater soil water storage capacity and rye transpiration. In fallow plots, water percolated deeper. During intense rainfall events, in rye plots, water percolated deeper in all treatments, most likely because the upper soil layers became saturated. The presence of rye, along with different types of rainfall events, produced different soil water redistribution patterns.

Introduction

Because of environmental concerns such as erosion, changes in hydrological systems, climate change, and nutrient leaching, the use of cover crops in agriculture is of interest. Cover crops include a wide range of types and species of plants used as fits the particular functionality needed and the geographical area in which they are planted, but generally a cover crop is a living ground cover planted into or after a main crop, and it is usually terminated before the planting of the next main crop (Hartwig and Ammon 2002). In the Upper Midwest of the United States, a large percentage of agricultural land is planted to corn and soybeans, and this land lays fallow during the late fall, winter, and early spring. Because vegetation cover has a large effect on soils and hydrological processes within a landscape (Marin et al. 2000, Wang et al. 2013), cover crops could be part of a solution to remedy agroecological problems such as nutrient leaching, soil erosion, changing hydrological systems, and diminished soil fertility and productivity, which are caused in part by a lack of vegetative cover during the non-growing season (Dabney 1998, De Bruin et al. 2005, Hartwig and Ammon 2002, Islam et al. 2006, Unger and Vigil 1998). Cover crops are able to influence the landscape through their effects on the plant-atmosphere continuum (above the soil surface and at its interface with the atmosphere) and the ability to alter soil characteristics and soil water regimes in the subsurface zone (below the soil surface) (Islam et al. 2006). Each of these effects is interrelated as climate, soil, and vegetation are linked through climatic and hydrological cycles.

Cover crops are able to influence the aboveground environment by reducing light transmission through the production of a canopy which can moderate fluctuations in soil temperatures (De Bruin et al. 2005). They can also alter the amount of precipitation remaining in a field by trapping snow (Dabney 1998, Unger and Vigil 1998). Cover crops affect evaporation by altering net radiation, wind speed, vapor pressure deficit, and surface soil temperatures (Dabney 1998, Unger and Vigil 1998). Cover crops and their residue mulches can greatly alter evaporation and transpiration rates between precipitation events as well (Unger and Vigil 1998). They are also able to influence runoff and soil erosion by increasing the surface roughness of the field and holding the soil in place with their root systems (Dabney 1998, Unger and Vigil 1998). The canopy created by cover crops intercepts precipitation, decreasing the amount of precipitation that reaches the soil and dissipating the energy of raindrops, therefore reducing precipitation's ability to dislodge soil particles and create surface soil seals, which can impede infiltration (Dabney 1998, Huang et al. 2013, Islam et al. 2006, Unger and Vigil 1998).

Cover crops also have an influence on the subsurface zone. Through root growth and associated fungal hyphae, cover crops can aid in binding the soil together, another mechanism that reduces erosion (Dabney 1998, Unger and Vigil 1998). Cover crops can also improve soil structure and thus the soil's water-holding capacity (Hartwig and Ammon 2002). The growth of cover crops can alter the soil porosity matrix directly through root growth and indirectly by improving habitat and encouraging the activity of soil mesofauna and macrofauna (Dabney 1998, Unger and Vigil 1998). An increase in biological activity in the soil also results in greater soil permeability and aeration, which aids crop emergence and crop root growth (Hartwig and Ammon 2002).

Also, by changing the albedo of the land surface and through shading, cover crops are able to influence subsurface soil temperatures; therefore, if they grow in the fall, cover crops may diminish the depth to which soils freeze or slow soil thawing and warming in the spring (Dabney 1998, Unger and Vigil 1998). Cover crops may be able to decrease leaching losses of nutrients through two mechanisms: decreasing drainage in fields with subsurface drainage through transpiration of soil water (Qi and Helmers 2010) and scavenging nutrients during a time of the year when the land would be bare (Hartwig and Ammon 2002, Unger and Vigil 1998). Cover crops may also increase infiltration (Dabney 1998, Unger and Vigil 1998) through the mechanical means of reducing raindrop impact and slowing runoff through modification of soil porosity and structure (Huang et al. 2013) and through drying of the soil through evapotranspiration (ET) (Qi et al. 2011b). In general, cover crops can directly affect inputs of soil water through precipitation partitioning, the means by which rainfall is divided into canopy interception, throughfall and stemflow (Marin et al. 2000).

Soil water dynamics are important at multiple scales. At a regional scale, soil water and the atmosphere work together to affect climate, and soil water is one factor that regulates the hydrological cycle (Asbjornsen et al. 2007, De Lannoy et al. 2006). At a smaller scale, in a field, soil water can influence runoff and erosion (De Lannoy et al. 2006). In the field, soil water also influences how precipitation is partitioned between ET and deep infiltration (Daly and Porporato 2005). Because soil water is such an important factor in determining climate, hydrology, and crop growth, much research has been done to understand what influences soil water and its spatiotemporal variability. Soil water varies widely over time and space, even at small geographic scales (Gómez-Plaza et al. 2000), and this variability is caused by many different factors (Levia and Frost 2003, 2006) such as landscape characteristics (Bergkamp 1998, De Lannoy et al. 2006, Fu et al. 2003, Gómez-Plaza et al. 2000, Svetlitchnyi et al. 2003), soil properties (Fu et al. 2003, Hawley et al. 1983), rainfall characteristics (Fu et al. 2003, Sala et al. 1992, Wang et al. 2008), vegetation and land use (De Lannoy et al. 2006, Fu et al. 2000, Roux et al. 1995, Wang et al. 2008), and field management (Ewing et al. 1991). The landscape can affect soil water through many factors, including slope (Gao et al. 2011, Huang et al. 2013, Tromp-van Meerveld and McDonnell 2006) and the depth of the groundwater table (Islam et al. 2006). Soil properties such as texture (De Lannoy et al. 2006, Miller et al. 1983) can influence soil's ability to infiltrate, retain, store, and drain water. Rainfall characteristics such as the amount of rainfall in a season, rainfall event size (Clark et al. 1997, Heisler-White et al. 2008), rainfall intensity (Levia and Frost 2003, 2006, Yaseef et al. 2009), and the distribution of rainfall events throughout the season (Clark et al. 1997) can affect how soil water is stored. The presence of vegetation on a land surface can influence soil water greatly (Wang et al. 2008, Zhang and Schilling 2006b) as vegetation affects the amount and distribution of precipitation that becomes soil water through transpiration, canopy interception (Brye et al. 2000), and the ability to affect water input in the soil through throughfall and stemflow (Iida et al. 2005, Levia and Herwitz 2005). Different species of plants have quite different effects on soil water due to differences in growth patterns in time and space and root and canopy structures (Asbjornsen et al. 2007, Clark et al. 1997). The spatial distribution of land uses through a landscape can also affect soil water dynamics (Fu et al. 2003). Lastly, field management, such as time of planting and harvesting cover and main crops (Clark et al. 1997, Ewing et al. 1991, Islam et al. 2006), residue management (Ewing et al. 1991), tillage techniques (Ewing et al. 1991), and subsurface drainage management influence soil water dynamics.

The use of cover crops in annual cropping systems is a promising way to conserve soil water and therefore affect variability of soil water in a positive way. One cover crop of interest in the Upper Midwest is cereal rye (*Secale cereale* L. ssp. *cereal*). It is particularly well suited for use in this region because it is extremely weather hardy (Bushuk 2001, De Bruin et al. 2005) and produces a high volume of biomass in the early spring (De Bruin et al. 2005). Rye is able to germinate at temperatures slightly above freezing (Bushuk 2001), and appreciable growth begins around 5°C (Leonard and Martin 1963). It is able to survive temperatures around -25° to -35°C even with limited snow cover, which gives rye the ability to overwinter even in the extreme northern USA and into Canada (Stoskopf 1985).

Because rye is able to germinate early, and a large amount of drainage and NO_3-N leaching occurs during the early spring period in the Upper Midwest, rye is a promising way to reduce these deleterious effects of row cropping through early season ET and incorporation of N into growing tissues (Qi et al. 2011b). There are tradeoffs when integrating rye into a row crop system, however, as rye has the potential to decrease main crop yields. In some studies, though, after rye is terminated, its residue has contributed to greater corn yield (through increased infiltration) (Clark et al. 1997), and its mulch and allelopathic compounds are able to assist in weed suppression (De Bruin et al. 2005). These same allelopathic compounds may decrease corn yields, however (Clark et al. 1997). Rye may also be able to decrease runoff through physically slowing water runoof velocity, which allows more time for water to infiltrate, and through decreased soil water due to plant transpiration, which would encourage infiltration (Dabney 1998). Rye can also significantly decrease drainage during the spring and early summer where subsurface drainage tile is installed (Qi and Helmers 2010, Strock et al. 2004). The ability to decrease runoff, subsurface drainage, and to use excess soil N allows rye to decrease NO_3-N leaching, as well (De Bruin et al. 2005, Ditsch et al. 1993, McCracken et al. 1994). In one study, rye before soybean used soil N significantly more than soybean without rye, corn without rye, and corn with rye (Qi et al. 2011a). The rye treatment before soybean reduced NO_3-N concentration in subsurface drainage significantly only when compared to the corn treatment, however (Qi et al. 2011a). In that study, corn yield was not significantly affected by rye growth and soil N use (Qi et al. 2011a). In another study, however, more N was needed for application to fields so as to avoid a significant drop in corn yield when rye was planted before (Clark et al. 1997). Conflicting findings in different studies show that rye does (Qi and Helmers 2010) or does not (Clark et al. 1997, Krueger et al. 2011) decrease growing season (for both cover crop and main crop seasons) soil water and soil water storage, depending on field and weather conditions. Rye may reduce soil water content only during the spring, however, with soil water levels typically approximating levels expected in fields consisting of only row crops, because water use by corn is delayed and so there is lower ET during the corn growing season (Krueger et al. 2011) or because of other factors such as mulching from rye residue. In general, though, soil water depletion is expected to be highest in years when rye biomass is the greatest (Baker and Griffis 2009).

Because different land covers affect how precipitation infiltrates and is redistributed and stored within the soil, and because these dynamics affect drainage and NO_3-N leaching and possibly main crop growth following rye, understanding redistribution of soil water under rye is important. The effects of rye on soil water dynamics and hydrological processes are complex, depending on rainfall characteristics and land cover, along with other factors. Many studies have investigated how different cover crops and vegetative covers affect soil water content and soil water storage over growing seasons and at longer time scales, but the ability to continuously monitor soil water through new technology provides more opportunities to understand the mechanisms controlling soil water under different land covers. In order to understand how rainfall characteristics and land cover might affect redistribution of precipitation through the soil profile, analysis of soil water data at very short time intervals is needed, as water can redistribute quite quickly through the profile during and after rainfall events. As such, the objective of this paper is to determine how a rye cover crop and rainfall characteristics affect infiltration and soil water redistribution.

Materials and Methods

Research sites

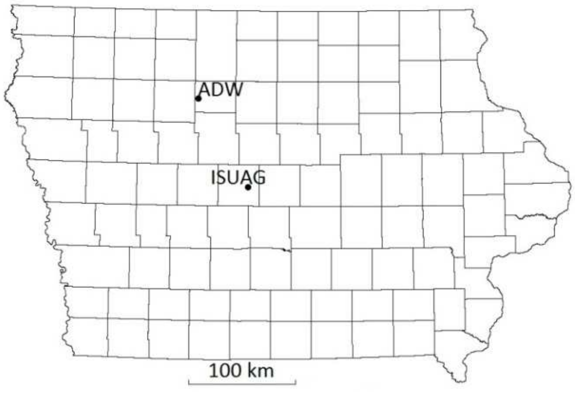

Figure 3.1. Location of ADW and ISUAG sites in Iowa.

The field study was performed at two sites in Iowa: the Agricultural Drainage Water Research Site (ADW) and the Iowa State University Agronomy and Agricultural Engineering

Research Farm (ISUAG) (Fig. 3.1). Two sites were used in order to compare results where climate and, therefore, rye growth would be different. ADW is located in northwest Iowa near Gilmore City in Pocahontas County (42°74’77” N, 94°49’52” W). The most ubiquitous soils are Nicollet (fine-loamy, mixed, superactive, mesic Aquic Hapludoll) and Webster and Canisteo (fine-loamy, mixed, superactive, mesic Typic Endoaqualls) clay loams with 3% to 5% organic matter, having an average slope of 0.5% to 1.5%. They are naturally poorly to naturally somewhat poorly drained glacial till soils. The total research area is 4.5 ha, of which 3.8 ha are used as experimental plots. There are seventy-eight 0.05 ha plots (15 x 38 m), each containing subsurface tile drainage. An automatic on-site meteorological station monitored weather conditions, including rainfall. Rainfall patterns at the site were compared to long-term averages (30 years from 1971-2000) determined from readings at the National Climate Data Center station Pocahontas (IA6719) located 19 km west of the research site.

ISUAG is located in central Iowa near Boone in Boone County (42°00’94” N, 93°78’06” W). The most ubiquitous soils are Clarion loam (fine-loamy, mixed, superactive, mesic Typic Hapludoll) with an average slope of 2% to 5%, Nicollet loam (fine-loamy, mixed, superactive, mesic Aquic Hapludoll) with an average slope of 1% to 3%, and Webster silty clay loam (fine-loamy, mixed, superactive, mesic Typic Endoaquoll) with an average slope of 0% to 2%. These soils are naturally poorly to naturally moderately well drained glacial till soils. The total research area is 0.9 ha, divided into 0.009 ha plots. The amount and placement of subsurface drainage at ISUAG is unknown, as the site was previously used as an agricultural field. An automatic on-site meteorological station monitored weather conditions. This station ([A130209] Ames) is a part of the Iowa Environmental Mesonet, Iowa State University Agricultural Climate series. Rainfall patterns at the site were compared to long-term averages (30 years from 1971-2000) determined from readings at the National Climate Data Center station AMES-8-WSW (IA0200) located approximately 5 km northwest of the research site.

Soil characteristics

In 2011, in each plot, 15-20 soil samples for texture analysis were taken to a depth of 60 cm using a 2.5 cm diameter metal push probe. The percentages of sand, silt, and clay for depth increments 0-10 cm, 10-20 cm, 20-40 cm, and 40-60 cm were determined. To determine the bulk density of the soils, a hand core system with soil core rings with a height and diameter of 7.6 cm were used. In the spring of 2011, in each plot, three replicates of each of the following depths were sampled: 0-10 cm, 10-20 cm, 20-40 cm, and 40-60 cm. Samples were taken at the quarter row position (out of machinery wheel tracks) in corn plots and in the same position in soybean plots. The bulk density of each soil core was determined by drying the soil at 105°C for 48 hrs in a soil oven and dividing the dry soil weight by the wet volume of soil.

Soils at the two sites are generally loamy soils (Table 3.1). Textures found, in order of decreasing predominance, are clay loam, loam, sandy clay loam, and sandy clay. The most ubiquitous soil texture throughout both sites is clay loam, but at ISUAG, soils tend to be a bit loamier, while at ADW, soils tend to be more clayey. In general, the bulk density of soils increases with depth throughout soil profiles, and the bulk density of soils at ADW increases to a greater degree through the profile than those at ISUAG. Texture and bulk density properties of soils can affect how precipitation infiltrates and how it is retained and moves within a soil profile. Analysis of variance (ANOVA) ($\alpha = 0.05$) was used to test whether texture varied significantly among treatments in the same field within a depth. Only silt content at a depth of 20 cm in corn plots at ADW varied significantly compared to other treatments. Because most comparisons in this research occur between plots within the same site, and because soil types are more consistent within sites, comparisons of soil water can be made with a fair amount of confidence.

Table 3.1. Soil characteristics at ADW and ISUAG.

Site	Treatment	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Bulk Density (g/cm^3)
ADW	C	0 - 10	46	20	34	0.95
		10 - 20	46	19	35	-[a]
		20 - 40	45	23	32	1.45
		40 - 60	44	25	31	1.59
	rC	0 - 10	39	32	29	0.91
		10 - 20	36	32	32	-[a]
		20 - 40	36	32	32	1.45
		40 - 60	36	32	32	1.56
	S	0 - 10	37	34	30	0.96
		10 - 20	37	33	31	1.41
		20 - 40	34	36	31	1.37
		40 - 60	37	33	31	1.50
	rS	0 - 10	37	34	30	0.92
		10 - 20	34	35	32	1.37
		20 - 40	34	34	33	1.39
		40 - 60	33	35	33	1.49
ISUAG	C	0 - 10	45	35	20	1.24
		10 - 20	44	30	26	1.56
		20 - 40	47	31	23	1.56
		40 - 60	48	29	22	1.65
	rC	0 - 10	38	40	21	1.39
		10 - 20	38	36	25	1.52
		20 - 40	37	37	26	1.48
		40 - 60	41	33	26	1.59
	S	0 - 10	34	41	25	1.23
		10 - 20	31	41	28	1.47
		20 - 40	30	41	29	1.45
		40 - 60	28	42	30	1.50
	rS	0 - 10	31	41	27	1.24
		10 - 20	32	41	27	1.44
		20 - 40	28	43	29	1.43
		40 - 60	28	42	30	1.52

[a] Data not available.

Soil water measurements

In order to obtain continuous soil water data, a Decagon Em50 Data Logger was used in conjunction with five soil sensors (measuring dielectric permittivity of the soil), each with a 0.3 L volume of influence (Decagon Devices, Inc., Pullman, WA), installed at depths of 10, 20, 40, 60, and 100 cm below the soil surface at quarter-row position in each plot. A 5TE sensor was installed at the 10 cm depth, recording soil temperature, volumetric water content, and electrical conductivity (EC), while 5TM sensors were used for the remaining depths, measuring only soil temperature and volumetric water content. Soil sensors were capable of measuring volumetric saturation values between 0% and 100% with an accuracy of ± 2% and a resolution of 0.08%. A trench 60 cm deep and 20 cm wide was dug, and the top 4 soil sensors were installed parallel to the soil surface into the side wall of the trench. For the deepest soil sensor, a smaller hole (40 cm deep and roughly 5 cm wide) was dug at the bottom of the larger trench, and the soil sensor at 100 cm was installed at the bottom perpendicular to the soil surface. At ADW, measurements at all five depths were recorded in hourly increments from March 1 to March 20, and then sensors were turned off for field management; sensors were reactivated March 27, and data was recorded in increments of 5 minutes from then until May 9, the end of the study period. At ISUAG, soil measurements at all five depths were recorded in hourly increments from March 1 to April 2, and then in increments of 5 minutes until May 9. At both sites, measurements continued past May 9, but these were not included in this analysis as the objective of this study was to understand soil water dynamics only during the period when rye was growing.

Study design, field management, and rye sampling

The study period was March 1 through May 9 of 2012. These dates were chosen as it was the period when rye would be actively growing before it was terminated. For the study, 16 plots were chosen, eight each at ADW and ISUAG. At each site, there were two replicates of the following four treatments: corn without rye (C), corn with rye (rC), soybeans without rye (S), and soybeans with rye (rS). In each plot, corn and soybeans were planted in rotation, and so the main crop in each treatment name refers to the crop that would be planted following rye growth and termination in the spring of 2012. At ADW, rye seed was drilled into the soil following corn and soybean harvest on October 12, 2011 at a rate of 100 kg/ha. On the day of termination, in each plot, rye was sampled with hand grass clippers along a 30 cm long length of three adjacent rows at three randomly selected locations, dried, and weighed for biomass determination. At ISUAG, rye was drilled into the soil following corn and soybean harvest on October 3, 2011 at a rate of 63 kg/ha. On the day of termination, rye was sampled using a square with 0.3 m long edges; rye within the square was cut with a hand grass clippers, dried, and weighed for biomass determination. Rye was terminated with glyphosate herbicide in the spring (Table 3.2).

Table 3.2. Timing of cover crop management at ADW and ISUAG sites.

	Site	
Management	ADW	ISUAG
Rye seeding	12 Oct 2011	3 Oct 2011
Termination of rye followed by corn	12 Apr 2012	6 Apr 2012
Termination of rye followed by soybean	9 May 2012	11 May 2012

Data analysis

SAS 9.3 software was used to determine differences among soil texture in C, rC, S, and rS treatments at both ADW and ISUAG (SAS Institute 2011). ANOVA ($\alpha = 0.05$) was used to separate means of the percentage of sand, silt and clay among treatments.

ANOVA ($\alpha = 0.05$) in SAS 9.3 was also used to determine differences among the means of cumulative infiltration during single rainfall events among treatments. The soil water storage (SWS) from 0-100 cm was calculated using data from soil sensors, and based on the principle of soil water balance, the cumulative infiltration for a rainfall event can therefore be described as:

$$I = SWS_f - SWS_i$$

where I is the cumulative infiltration (mm), SWS_f is the final SWS or the maximum after the rainfall event (mm), and SWS_i is the initial SWS just before the rainfall event begins (mm).

SAS 9.3 software was used to determine differences among increases in soil water during rainfall events which occurred in the top soil layers (10 and 20 cm) among treatments at both ADW and ISUAG (SAS Institute 2011). Below 20 cm, there was not a discernible trend in soil water content change, so these layers were not included in the analysis. To quantify differences, the magnitude to which the volumetric soil water content increased after each rainfall event throughout the study period was calculated. This value was found for each soil layer (10 and 20 cm) for each treatment (C, rC, S, and rS) after every rainfall event at each study site. Visual analysis and equality of variances tests revealed that data was not normally distributed, so a natural log transformation of volumetric water contents was employed. PROC GLM tests were used to test for differences among the four treatments within depths at each site. These tests separated means using a least significant difference test at $p = 0.05$ ($LSD_{0.05}$) to test for significant treatment effects on soil water contents at each depth.

Results and Discussion

Weather

Air temperatures at both ADW and ISUAG were much above normals observed at NCDC stations throughout the study period, most notably during March when maximum daily temperatures were 10.3° C warmer than normal at ADW and 9.2° warmer than normal at ISUAG (Table 3.3). During March, daily minimum temperatures were 7.9° warmer than normal at ADW and 7.4° warmer than normal at ISUAG; at both sites, this shifted average minimum temperatures from below to above freezing (Table 3.3). In April, the warm trend continued, but it was less dramatic. In the first nine days of May, the maximum and minimum daily temperatures were warmer again, but the minimums were further from normal than the maximums; minimums were 6.6° higher at ADW and 5.7° higher at ISUAG, while maximums were 3.8° higher at ADW and 3.5° higher at ISUAG.

Table 3.3. Air temperature and precipitation normals vs. observed weather at ADW and ISUAG sites during the study period. Pocahontas is 19 km west of ADW, and AMES-8-WSW is 5 km northwest of ISUAG.

	Max. Temp. (°C)	Min. Temp. (°C)	Daily Avg. Temp. (°C)	Precip. (mm)	Max. Temp. (°C)	Min. Temp. (°C)	Daily Avg. Temp. (°C)	Precip. (mm)
Pocahontas Normal[a]					**AMES-8-WSW Normal**[b]			
March	6.2	-4.8	0.7	55.9	8.2	-2.6	2.8	52.1
April	14.9	1.8	8.3	78.5	16.4	3.4	9.9	88.9
May 1-9	20.0	6.1	13.0	27.2	20.6	7.7	14.1	29.7
Total				161.5				170.7
ADW 2012					**ISUAG 2012**			
March	16.5	3.1	9.4	52.8	17.4	4.8	11.0	43.4
April	18.0	4.3	10.8	102.6	17.9	5.8	11.8	84.3
May 1-9	23.8	12.7	17.3	46.7	24.1	13.4	18.4	27.9
Total				202.2				155.7

[a] Source: Climatological Data for Iowa, National Climate Data Center for Pocahontas, IA, 1971-2000.
[b] Source: Climatological Data for Iowa, National Climate Data Center for AMES-8-WSW, 1971-2000.

Precipitation was nearer normal during the research period than was temperature. Observed precipitation was 125% and 91% of normal at ADW and ISUAG, respectively

(Table 3.3). Rainfall followed the normal trend fairly closely except for a dry period during the first 12 days of April when only 0.8 mm of precipitation fell at ADW, and only 1.3 mm at ISUAG (Fig. 3.2). At ADW, this dry period was followed by 2 periods of moderate rainfall (37 mm in 4 days and 47 mm in 4 days), while at ISUAG, 1 period of moderate rainfall (46 mm in 3 days) followed the dry period, followed by a smaller amount of rainfall (21 mm in 4 days) (Fig. 3.2).

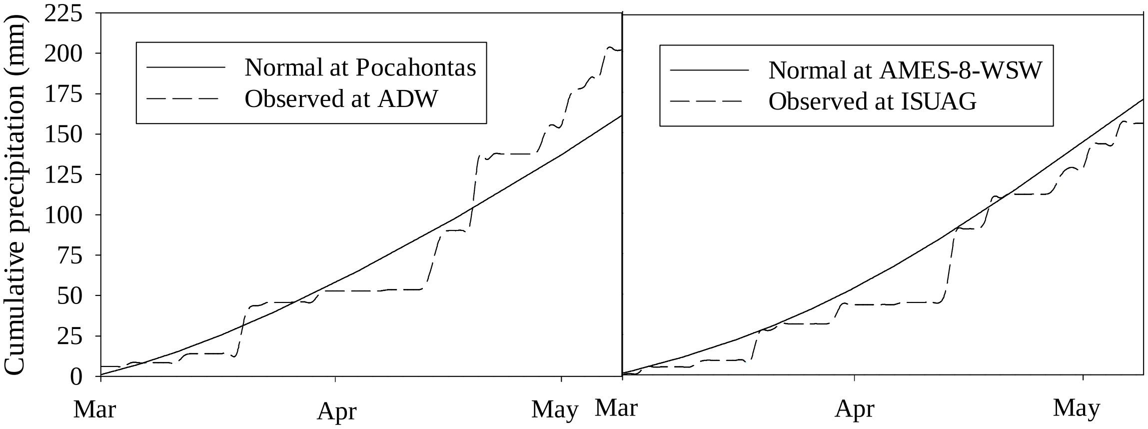

Figure 3.2. Normal cumulative precipitation vs. observed cumulative precipitation at the research sites during the study period (March 1 – May 9). Source for normals: Climatological Data for Iowa, National Climate Data Center for Pocahnotas and AMES-8-WSW, 1971-2000.

Precipitation at the two research sites was characterized by a wide range of events, ranging from very short and light rainfall events to long-lasting, intense storms (Fig. 3.3). ISUAG saw less total precipitation during the study period, and, compared to ADW, this site also saw more of its rainfall come in events with lower intensity and smaller total amounts; half of the storms at ISUAG had storm totals of less than 5 mm of precipitation (Table 3.4).

Table 3.4. Frequency distribution of rainfall intensity (data taken from all periods when rain was actively falling) and the cumulative precipitation of single rainfall events at both research sites during the research period (21 rainfall events at ADW and 20 at ISUAG).

	Rainfall intensity (mm/h)				
	<1	1-2.5	2.5-5	5-10	>10
ADW (%)	52.3	24.3	15.0	6.5	1.9
ISUAG (%)	61.3	23.6	8.5	5.7	0.9
	Precipitation during single rainfall event (mm)				
	<5	5-10	10-25	>25	
ADW (%)	38.1	28.6	28.6	4.8	
ISUAG (%)	50.0	15.0	30.0	5.0	

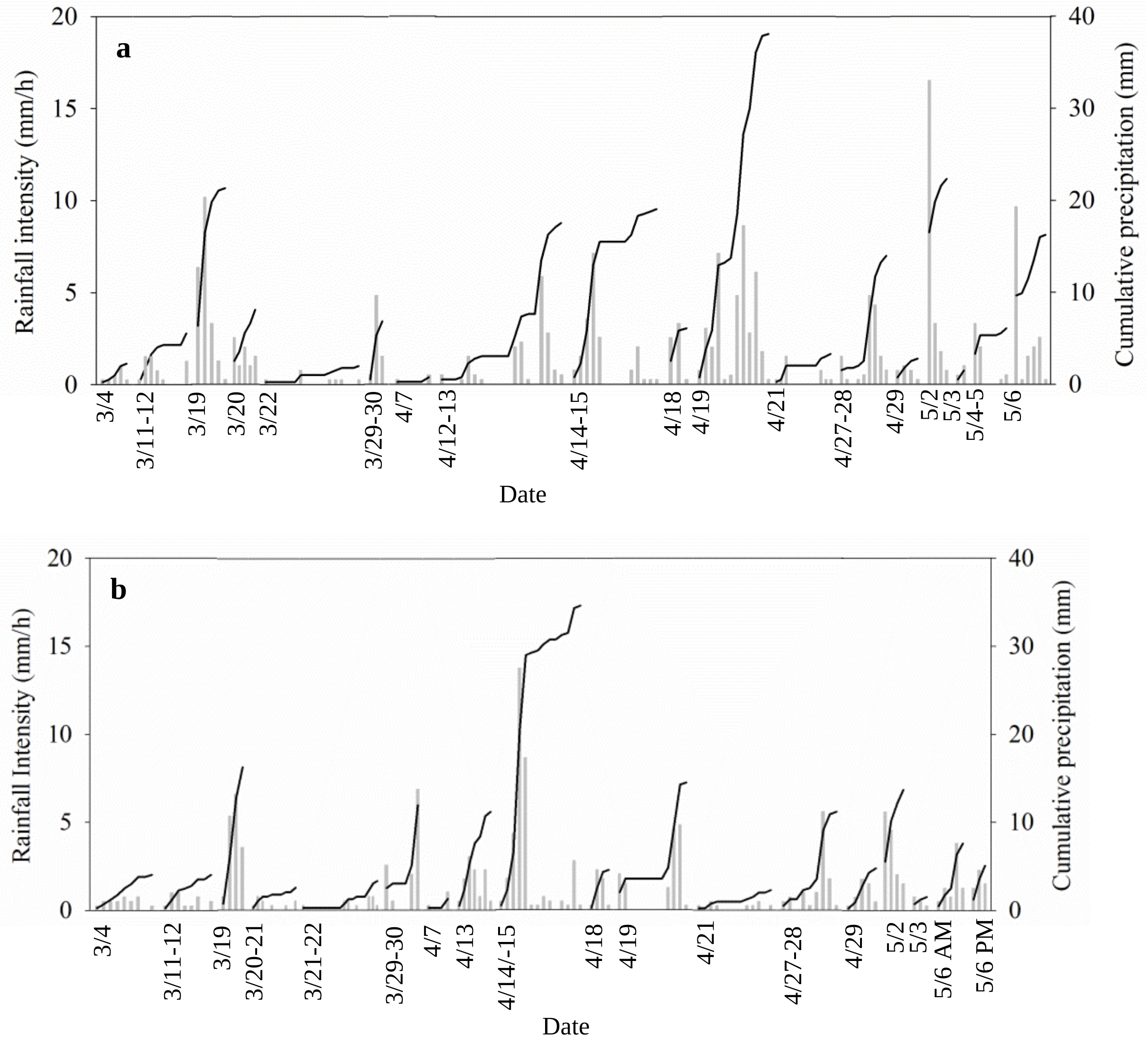

Figure 3.3. The rainfall intensity (grey bars) and cumulative precipitation (black lines) of individual rainfall events at ADW (a) and ISUAG (b). Rainfall events with a cumulative precipitation of less than 1 mm were not included.

Rye yields

Rye yields at both sites prior to soybeans were more than twice that obtained when rye was followed by corn (Table 3.5). At ADW, rye followed by soybean was allowed to grow 4.5 weeks longer than rye followed by corn, and at ISUAG, it was allowed 5.5 weeks more. This time period was during the warmer interval in late April and May, when rye growth rate was most likely higher than in March and early April. Overall, rye yields at ISUAG were about 7x higher than at ADW. ISUAG saw less precipitation than normal and had less precipitation than ADW in 2012, but nighttime lows during April and May were about 1°C higher at ISUAG than at ADW, and in general, temperatures at ISUAG were higher, both of which could have assisted rye growth.

Table 3.5. Average rye yields for 2012 at ADW and ISUAG sites.

Site and treatment	Rye yield (kg/ha)
ADW rC	136
ADW rS	322
ISUAG rC	1039
ISUAG rS	2207

Soil water dynamics

In order to more closely investigate how water redistributes through the soil profile, two different periods of rainfall were examined, both of which occurred at ISUAG. These events were examined because of the much greater amount of rye growth seen at the ISUAG, which increases the ability to see potential treatment effects on soil water dynamics. The first period chosen is a single rainfall event of a moderate length, intensity, and with moderate cumulative event precipitation which occurred in the middle of the night on March 29 and 30, before rye was terminated in either corn or soybean plots. The event lasted 6 hrs, total precipitation was 11.9 mm, and the average rainfall intensity was 2 mm/hr, with a maximum intensity of 6.9 mm/hr and a minimum of 0 mm/hr. A one-week period without rain preceded this rainfall event. In all plots (those preceding both corn and soybean), at the 10 cm soil depth, soil water content in plots with rye increased to a greater degree than in the associated plots without rye (Fig. 3.4). In the 20 and 40 cm depths, soil water content in plots without rye increased more than in plots with rye. Soil water did not redistribute past the soil surface layer in plots with rye, whereas water percolated deeper into the soil in plots without rye. In this case, it is possible that the rainfall was light enough that rye was able to use the soil water before the wetting front advanced to the deeper soil layers. During this period, three out of the four plots with rye had an antecedent soil water content that was roughly equal to or greater than that of the plots without rye, and so it seems that this rainfall may have been light enough for the rye to use the water in ET before the wetting front could advance into the 20 and 40 cm soil depths. The increase in total profile (0-100 cm) water storage was roughly equal for all plots (data not presented), so it is also possible that the top soil layer in rye plots was more able to retain water than the top soil layer in plots without rye; rye had been established five years previously, so rye root and associated microfauna growth may have had some effect on soil porosity and water retention within the top soil layer (Dabney 1998, Unger and Vigil 1998). Also, in corn plots without rye, soils were quite sandy throughout the profile, which may have contributed to a quickly advancing wetting front. Because water did not percolate deeply in rye plots, in a slightly drier year or a year with a moderate total amount of rainfall and mainly moderately intense rainfall events with moderate rainfall totals, drainage could be decreased in rye plots, which would aid in decreasing NO_3-N leaching. In wetter years, as the next rainfall period example will show, rye could have the opposite effect, however.

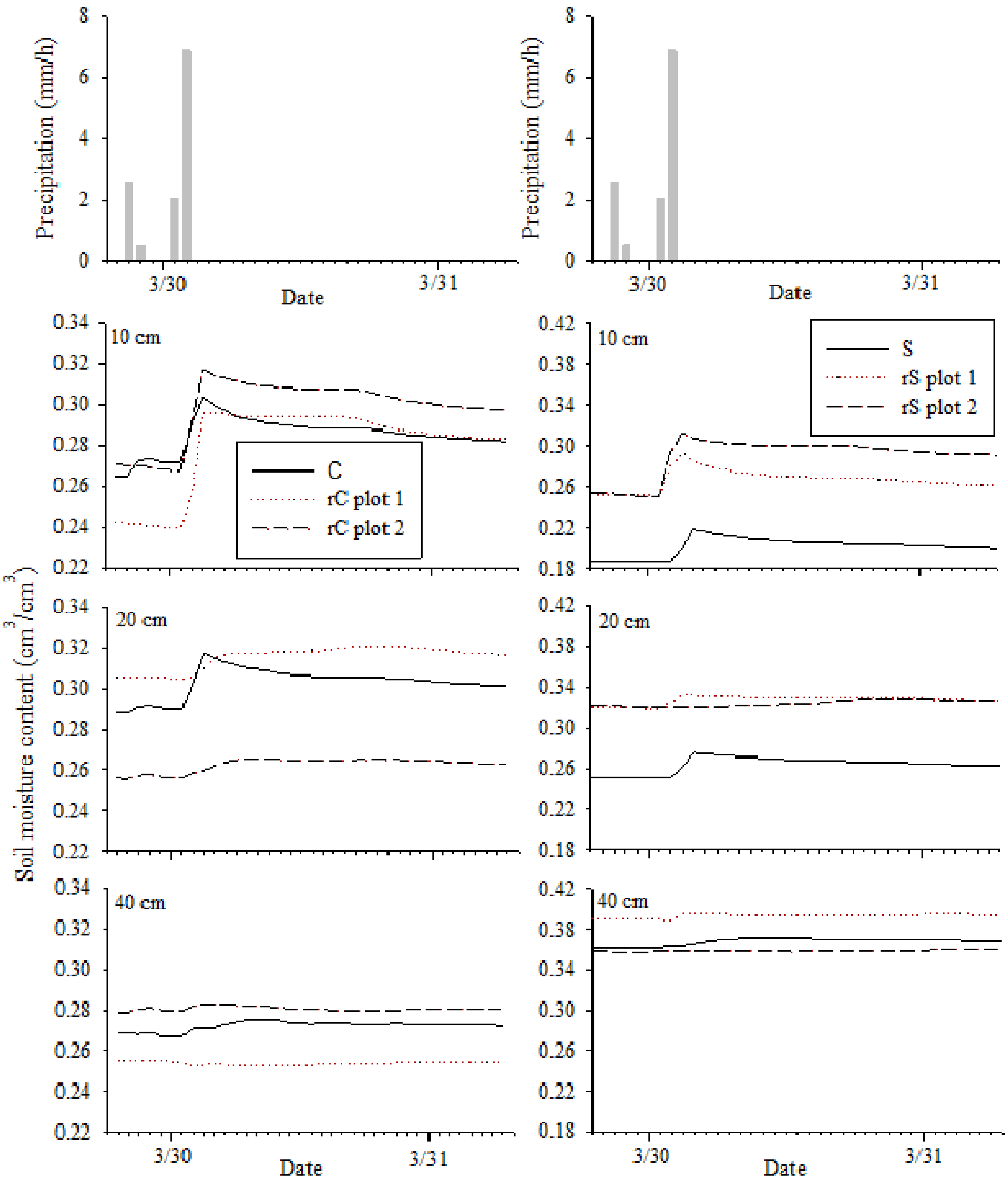

Figure 3.4. Hourly rainfall intensity and volumetric soil water content of soils at ISUAG in plots without and with rye for the 3/29-30 rainfall event (preceding corn on the left, and preceding soybean on the right). Soil water content measurements were taken at 1 hr intervals.

The second period to be examined was a sequence of two rainfall events occurring on April 13 and April 14-15; rye was still growing in plots preceding soybeans, but it had been terminated 1 week prior in plots preceding corn, although rye residue was still present. The April 13 event lasted 7 hrs, total precipitation was 11.2 mm, and the average rainfall intensity was 1.6 mm/hr, with a maximum intensity of 3 mm/hr and a minimum of 0.5 mm/hr. This event was similar to the March 29-30 event discussed above, except that the rainfall was more evenly distributed throughout the event. The second event during this period, occurring April 14-15, lasted 14 hrs, with a total precipitation of 34.5 mm and an average rainfall intensity of 2.5 mm/hr with a maximum intensity of 13.7 mm/hr and a minimum of 0 mm/hr. Before this entire period, there had been a 6-day dry period, but the rainfall 6 days before was very light, so the dry period was effectively 2 weeks long. Soil water from the April 13 event was still redistributing through the profile when the April 14-15 event began, and this antecedent soil water affected soil water dynamics during and after the larger event.

In plots preceding soybean (Fig. 3.5), for the April 13 event, soil water reacted similarly as during the March 29-30 event. Plots with rye had similar or less soil water content as compared to the plot without rye, but at the 10 cm depth, soil water content increased more in plots with rye, while at the 20 cm depth, soil water content increased more in the plot without rye. During and after the April 14-15 event, however, at all depths, (10-100 cm), soil water content increased equally or to a greater degree in plots with rye as compared to the plot without rye. The amount and intensity of rain during this period was much greater than in the last two storms described. It is likely that this amount of precipitation saturated the top soil layers and came too quickly for the rye to utilize through ET. Because the increase in water storage through the profile due to rainfall was greater in plots with rye (80.2 mm in rS versus 59.0 in S), a greater amount of precipitation entered the soil and redistributed throughout the whole soil profile to 100 cm, suggesting that infiltration was greater in rye plots. In wetter springs with more intense precipitation, rye may increase soil water content throughout the whole profile, and this wetting front would reach drainage tile more often; therefore in wet years with intense precipitation events, rye, through increased infiltration, may actually increase drainage if rye growth is not sufficient to use the excess water in ET. This may be offset partially by decreased runoff, however.

In plots preceding corn (Fig. 3.6), where rye residue was present, soil water behavior was similar to that in plots preceding soybean, except at the 60 cm depth, where the plot without rye had the largest increase in soil water content. In all the other depths, the plot without rye had greater or similar antecedent soil water content as compared with plots with rye, but at a 60 cm depth, this plot had a lower antecedent soil water content, which may account for the difference in its response to the precipitation event. The response shown in these plots suggests that even after rye is killed, its residue and possibly its effects on the soil structure may increase infiltration and therefore increase soil water storage, since at this time rye will not decrease soil water content after the precipitation event because it is not actively using the water for growth (Unger and Vigil 1998).

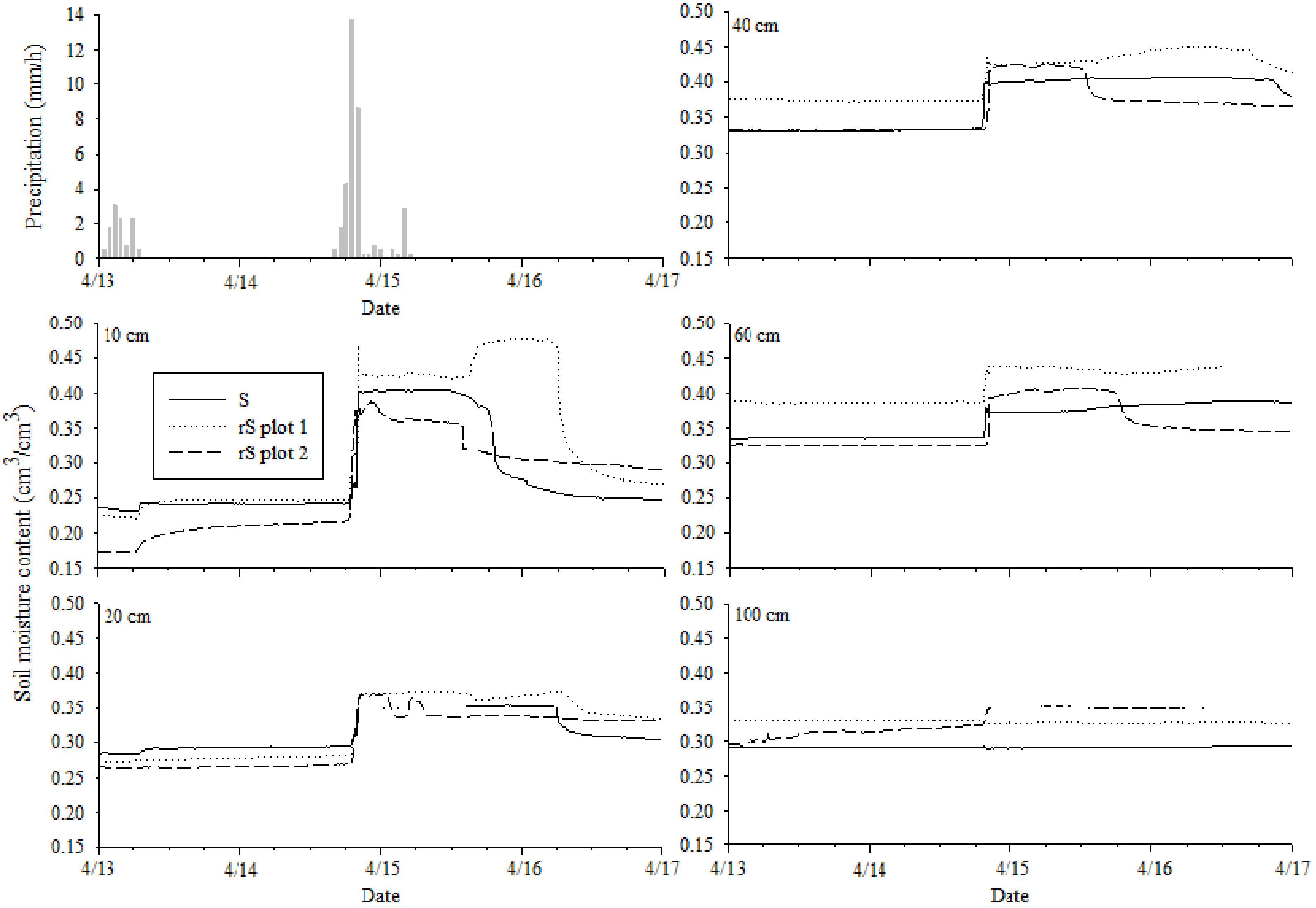

Figure 3.5. Hourly rainfall intensity and volumetric soil water content of soils at ISUAG in plots without and with rye, preceding soybeans. Soil water content measurements were taken at 5 min intervals. Data is absent from last hours of 4/16 from rS plot 1 at 60 cm depth because of sensor malfunction.

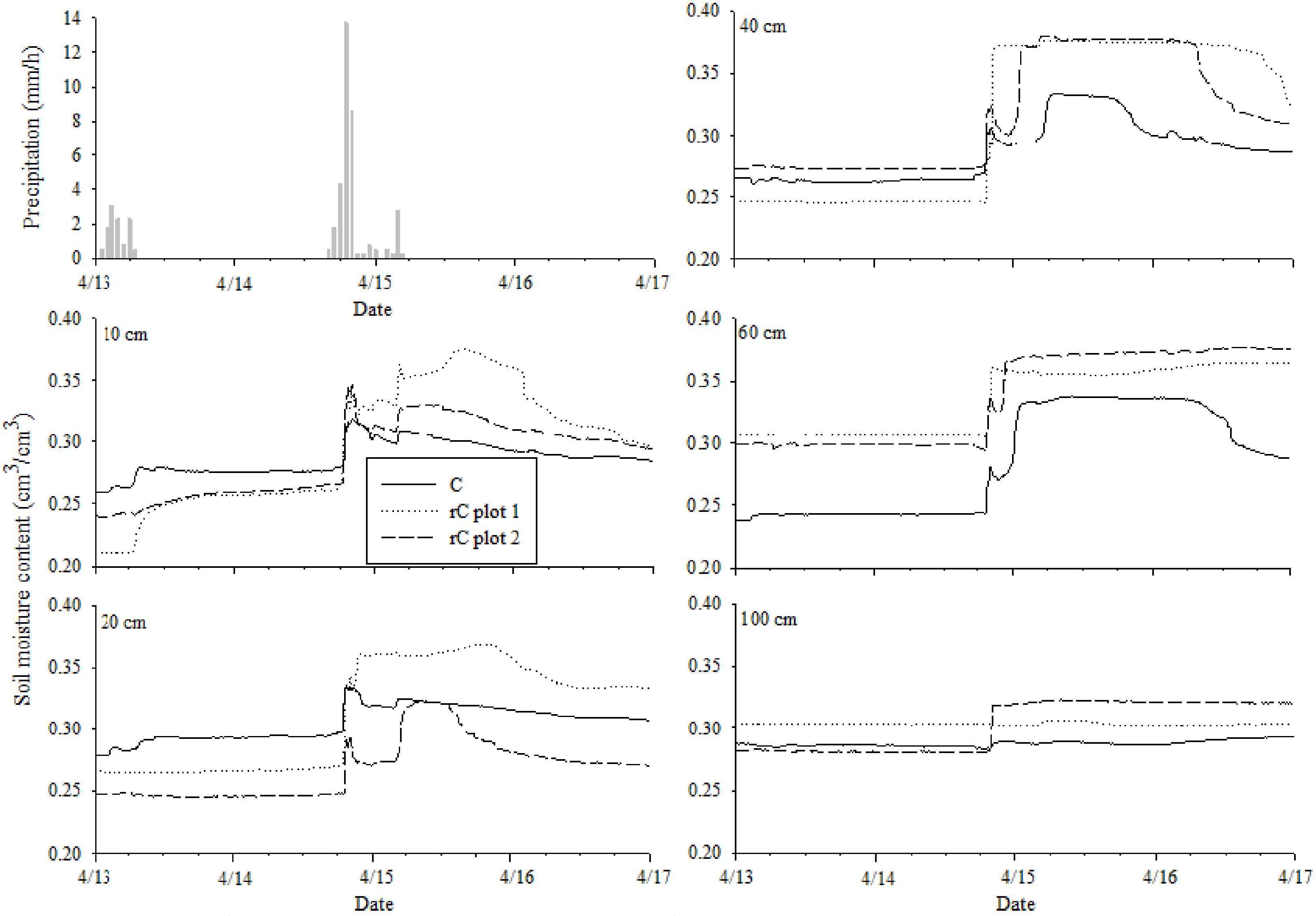

Figure 3.6. Hourly rainfall intensity and volumetric soil water content of soils at ISUAG in plots without and with rye residue, preceding corn (rye was terminated April 6). Soil water content measurements were taken at 5 min intervals.

The above indicates that a rye cover crop may be able to increase the amount of water stored in the top layers of soil for a moderate rainfall event and in all soil from 0-100 cm for an intense rainfall event, so ANOVA was used to determine treatment differences in the magnitude of infiltration through the soil profile from 0-100 cm at both sites. At ADW, the test returned an F-Value of 0.06 with a p-value of 0.979, and at ISUAG, an F-Value of 0.47 with a p-value of 0.703, so there were no significant treatment differences in the magnitude of infiltration at either site. There was a visual trend of increasing infiltration with increasing precipitation amounts (Fig. 3.7). Although for all rainfall events there were no differences in infiltration among treatments, visually, there is an increasing trend in the differences in infiltration among treatments as event precipitation increases (Fig. 3.7). For the heaviest rainfall event (April 19) of 38.1 mm at ADW, cumulative infiltration values were 30.4, 34.0, 21.4, and 30.5 mm for C, rC, S, and rS, respectively. For the heaviest rainfall event (April 14-15) of 34.5 mm at ISUAG, cumulative infiltration values were 58.0, 63.2, 59.0, and 80.2 mm for C, rC, S, and rS, respectively. As climate change may be accompanied by larger, more intense storms (Mishra et al. 2010), use of rye may have a greater positive effect on infiltration.

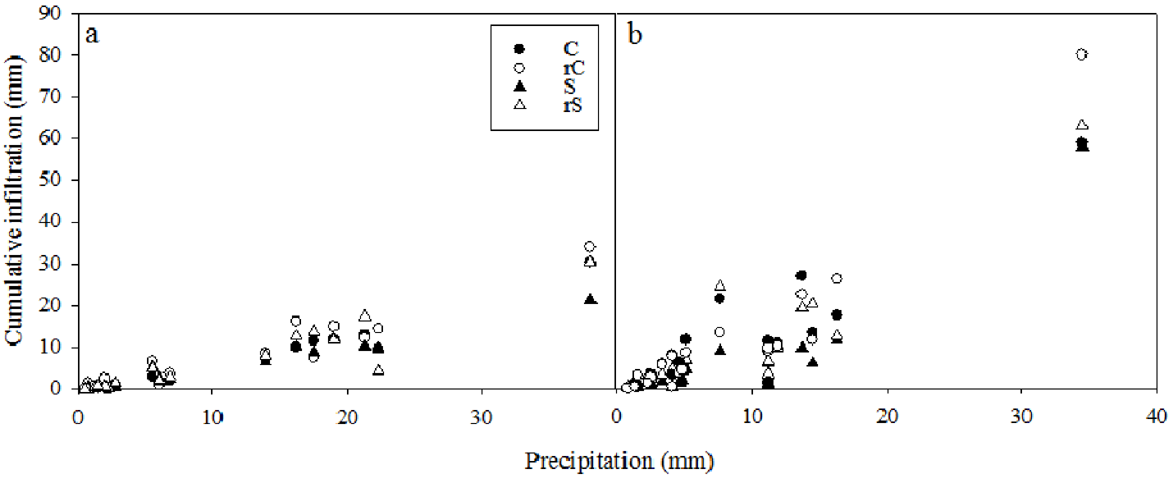

Figure 3.7. Cumulative infiltration during single rainfall events vs. precipitation of a single rainfall event for ADW (a) and ISUAG (b).

At ADW, cumulative infiltration over the entire research period was greatest in plots with rye, and infiltration to precipitation ratios (I:P) were 0.57, 0.69, 0.51, and 0.62 for C, rC, S, and rS, respectively (Fig. 3.8). In comparison to ADW, at ISUAG, a smaller amount of rainfall fell, but infiltration was greater. Infiltration was high in rC, S, and rS plots, with I:P ratios of 0.85, 1.22, 1.34, and 1.42 for C, rC, S, and rS, respectively. An I:P ratio above 1 signifies that infiltration exceeded precipitation; the ISUAG site has slopes up to 5%, higher than at ADW, which could result in run-on. In plots with rye, preferential flow due to macropores created by increased numbers of soil fauna could also contribute to the large amounts of infiltration (Dabney 1998, Unger and Vigil 1998).

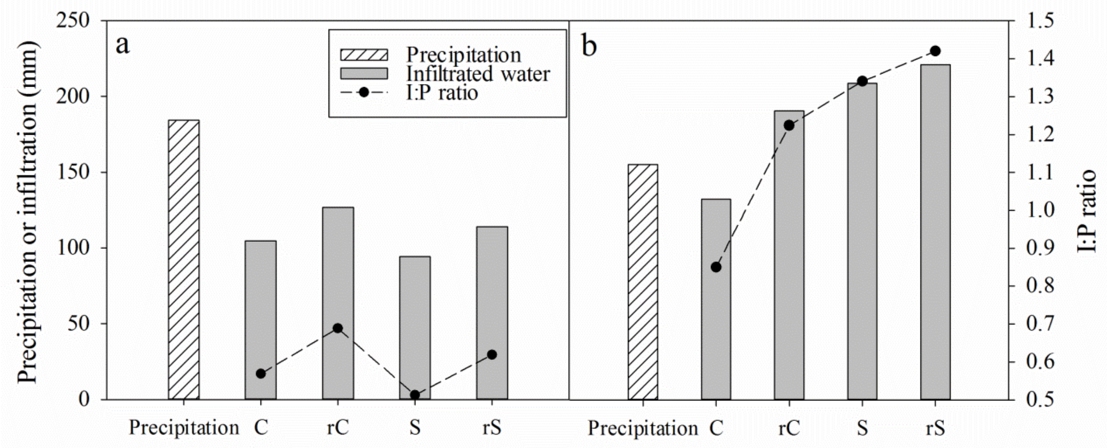

Figure 3.8. Cumulative precipitation and infiltration over entire study period at ADW (a) and ISUAG (b). I:P is infiltration to precipitation ratio. At ADW, precipitation (totaling 10.2 mm) and infiltration for rainfall events on 3/20 and 3/22 are omitted due to removal of sensors for field management.

A least squares difference test was used to investigate the difference in the magnitude of volumetric soil water content increase due to rainfall events at both sites at the 10 and 20 cm depths (Table 3.6).

Table 3.6. Differences between mean magnitude of volumetric soil water content increase following 21 rainfall events at ADW and 20 at ISUAG for 10 and 20 cm soil depths.

	Mean magnitude of volumetric soil water content increase following rainfall event (cm^3/cm^3)[a]			
	ADW		ISUAG	
Treatment	10 cm	20 cm	10 cm	20 cm
C	0.029a	0.016a	0.016b	0.010b
rC	0.026a	0.016a	0.026ab	0.018ab
S	0.018a	0.013a	0.025b	0.015ab
rS	0.026a	0.013a	0.052a	0.018a

[a] Means within depths at sites (i.e., within columns) followed by the same letter are not significantly different at p = 0.05.

At ADW, there were no differences among treatments at either the 10 or 20 cm depths. At the 10 cm depth at ISUAG, rS had a significantly higher average rise in magnitude of soil water content as compared to S and C, but not rC. At the 20 cm depth, rS only had a significantly higher average rise in soil water content as compared to C. Although soil water content in the upper soil layers increased to a greater magnitude after rainfall events in plots with rye at ISUAG, cumulative infiltration over the research period did not increase significantly in rye plots. Rye may have increased available water storage capacity in the top soil layers through transpiration and modification of the soil matrix (Dabney 1998, Kaspar and Singer 2011, Unger and Vigil 1998). Meisinger et al. (1991) estimated that the production of 2200 kg/ha of winter cover crop aboveground biomass (approximately the same amount of rye biomass produced in rS at ISUAG) would use 50 to 60 mm of water. This use of water in the upper soil layers by rye would decrease the soil's volumetric water content and allow for more infiltration in the upper layers of the soil. In multiple cases (Figs. 3.4, 3.5, 3.6), volumetric water contents in the upper soil layers in rye plots increased to a greater degree but also to a greater absolute amount as compared to plots without rye, indicating that the soil water-holding capacity is higher in upper soil layers in plots with rye, possibly caused by modifications to the soil structure through rye root growth and greater soil fauna activity (Dabney 1998, Unger and Vigil 1998). These modifications and greater water use would be expected to be the greatest in the top soil layers, as most rye root growth occurs within the top 25-35 cm of the soil (Nalborczyk and Sowa 2001).

Conclusions

At ISUAG, a significant increase in the magnitude of rise of soil water content after rainfall events in the top soil layers was found in plots with rye that would be planted to soybean, although no significant change in infiltration over the soil profile (0-100 cm) was found. This pattern indicates that soil water storage in the upper soil layers (to 20 cm) may be increased by rye through modifications to soil water holding capacity, caused by increased transpiration and greater soil fauna activity (Dabney 1998, Unger and Vigil 1998). Once rainfall infiltrated, the behavior of its redistribution throughout the soil profile varied among different types of rainfall events. Therefore, both land cover and rainfall characteristics affect how precipitation is redistributed through the soil profile as soil water. Depending on rainfall patterns, rye may not decrease soil water for main crop use. Because of its ability to increase infiltration and dry the soil through transpiration, it may only increase soil water variability. In years when most rainfall events are moderate to light, it is likely that rye would decrease subsurface drainage and NO_3-N leaching, as precipitation would likely not percolate deeper than the top soil layers, unless rainfall events occurred very close together. This decrease in drainage could mediate changes in the baseflow of rivers, as well, as long as sufficient amounts of cover were planted in watersheds. If more intense rainfall events were to occur, as is possible with climate change, it is possible that soil water throughout the whole soil profile could increase greatly under rye; in order to ensure high main crop yields, cover crop termination could strategically occur after periods of rainfall, as long as field conditions were favorable. An increase in soil water content throughout the soil profile could also increase drainage, as long as rainfall events occurred often enough. Some of this could be offset by decreased runoff due to increased infiltration in fields with rye. The results of this study indicate that different types of rainfall events elicit different responses in soil water dynamics, and so, because climate change may affect precipitation patterns, more research should be done to understand how shifts in these patterns will change how rye affects infiltration and redistribution through the soil profile. Also, because weather, soil properties, rye growth, and land and hydrological management will affect soil water dynamics, more research over a larger geographical area and with different management practices should be pursued.

Acknowledgements

This research is part of a regional collaborative project supported by the USDA-NIFA, Award No. 2011-68002-30190, “Cropping Systems Coordinated Agricultural Project: Climate Change, Mitigation, and Adaptation in Corn-based Cropping Systems.” Project Web site: sustainablecorn.org.

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CHAPTER 4. EFFECTS OF RYE COVER CROP ON SOIL WATER CONTENT AND SOIL WATER STORAGE DURING THE SPRING AND EARLY SUMMER IN A DROUGHT YEAR

Results from this paper to be added to results from research at Purdue University. Combined results to be submitted as a paper for a special issue of the *Journal of Soil and Water Conservation.*

Abstract

Land use and management changes have altered hydrological and biogeochemical cycles in the Upper Midwest. Cover crops such as cereal rye (*Secale cereale* L.) are a promising way to mediate these changes through increased infiltration and decreased erosion, drainage, and NO_3-N leaching. It is possible that use of a rye cover crop may decrease row crop yields, however, partially through decreased soil water. The objective of this paper is to determine how a rye cover crop affects soil water content and soil water storage during the spring as a living land cover and during the early summer as a mulch in plots planted to a corn-soybean rotation during a drought year. Continuous soil water content measurements at five depths (10, 20, 40, 60 and 100 cm) at 1-hr and 5-min intervals from March 1 to July 10 of 2012 were taken in two fields, one in northwest and another in central Iowa, using four treatments: corn without rye (C), corn with rye (rC), soybeans without rye (S), and soybeans with rye (rS). The main crop in the treatment name denotes the crop that would be planted following rye growth and termination. A repeated measures ANOVA test was used to determine whether the presence of rye changed soil water contents at two depths (0-10 cm and 10-20 cm), or soil water storage from 0 to 80 cm. This analysis was done for two different periods: the rye growth period (March 1 – main crop planting) and the main crop growth period (one week after main crop planting – July 10). At the site in northwest Iowa,

rye had no effect. At the site in central Iowa, during the rye growth period, soil water content at a depth of 0-10 cm and soil water storage were significantly higher in rye plots (0.029 cm^3 cm^{-3} and 1.9 cm, respectively). During the main crop growth period, soil water contents at depths of 0-10 cm and 10-20 cm were 0.041 and 0.033 cm^3 cm^{-3} higher, respectively, in rye plots. Therefore, at both sites, rye did not have a negative effect on soil water content or soil water storage.

Introduction

Because of environmental concerns such as changes in hydrological systems, climate change, and nutrient leaching, the use of cover crops in agriculture is of interest. Cover crops include a wide range of types and species of plants and are used as befits the particular functionality needed and the geographical area in which they are planted, but generally, a cover crop is a living ground cover planted into or after a main crop and is usually terminated before the planting of the next main crop (Hartwig and Ammon 2002). In the Upper Midwest of the United States, a large percentage of agricultural land is planted to corn and soybeans, and this land lays fallow during the late fall, winter, and early spring. Because vegetation cover has a large effect on soils and hydrological processes within a landscape (Marin et al. 2000, Wang et al. 2013), cover crops could be part of a solution to remedy the agroecological problems mentioned above, which are caused in part by a lack of vegetative cover during the non-growing season (Dabney 1998, De Bruin et al. 2005, Hartwig and Ammon 2002, Islam et al. 2006, Unger and Vigil 1998). Cover crops are able to influence the landscape above and below ground (Islam et al. 2006) through their canopy's effects on microclimate and soil temperatures (Dabney 1998, Unger and Vigil 1998), ability to increase infiltration (Dabney 1998, Huang et al. 2013, Islam et al. 2006, Unger and Vigil 1998), and root system effects on soil structure and water-holding capacity (Hartwig and Ammon 2002). These effects alter soil water dynamics, which are important in mediating changes in hydrological cycles, nutrient leaching, and possibly effects of climate change on crop production.

Soil water dynamics are important at multiple scales. At a regional scale, soil water and the atmosphere work together to affect climate, and soil water is one factor that regulates the hydrological cycle (Asbjornsen et al. 2007, De Lannoy et al. 2006). At a smaller scale, in a field, soil water can influence runoff and erosion (De Lannoy et al. 2006). In the field, soil water also influences how precipitation is partitioned between ET and deep infiltration (Daly and Porporato 2005), which will affect crop growth and subsurface drainage. Because soil water is such an important factor in determining climate, hydrology, and crop growth, researchers seek to understand what influences soil water and its variability. Soil water content varies widely over time and space, even at small geographic scales (Gómez-Plaza et al. 2000), and this variability is caused by many different factors (Levia and Frost 2003, 2006) such as landscape characteristics (Bergkamp 1998, De Lannoy et al. 2006, Fu et al. 2003, Gómez-Plaza et al. 2000, Svetlitchnyi et al. 2003), soil properties (Fu et al. 2003, Hawley et al. 1983), rainfall characteristics (Fu et al. 2003, Sala et al. 1992, Wang et al. 2008), vegetation and land use (De Lannoy et al. 2006, Fu et al. 2000, Roux et al. 1995, Wang et al. 2008), and field management (Ewing et al. 1991).

Because cover crops grow during periods when agricultural land would normally lay fallow, their use has the ability to alter the variability of soil water content. One cover crop of interest in the Upper Midwest is cereal rye (*Secale cereale* L.). It is particularly well suited for use in this region because it is extremely weather hardy (Bushuk 2001, De Bruin et al. 2005) and produces a high volume of biomass in the early spring (De Bruin et al. 2005). Because rye is able to germinate early, and a large amount of drainage and NO_3-N leaching occur during the early spring period in the Upper Midwest, rye is a promising way to reduce these deleterious effects of row cropping through early season ET (Qi et al. 2011b). In a three-year study in Iowa, in May, ET averaged 2.4 and 1.5 mm d^{-1} in rye plots and bare plots, respectively, an increase of 60% in rye plots (Qi and Helmers 2010). The ability to decrease runoff, subsurface drainage, and to use excess soil N allows rye to decrease NO_3-N leaching (De Bruin et al. 2005, Ditsch et al. 1993, McCracken et al. 1994). There may be tradeoffs when integrating rye into a row crop system, however, as rye has the potential to decrease main crop yields through its allelopathic compounds (Clark et al. 1997) and through depletion of soil water and N early in the growing season (Qi and Helmers 2010). Conflicting findings show that rye does (Qi and Helmers 2010) or does not (Clark et al. 1997, Krueger et al. 2011) decrease growing season (for both cover crop and main crop seasons) soil water content and soil water storage; this depends on weather conditions, cover crop management, and the total water holding capacity of the root-accessible portion of the soil (Kaspar and Singer 2011). Rye may reduce soil water content only during the spring, however, with soil water contents returning back to levels expected in fields consisting of only row crops, because water use by corn is delayed and so there is lower ET during the corn growing season (Krueger et al. 2011), or because rye residue is able to decrease evaporation (Unger and Vigil 1998). In general, though, soil water depletion is expected to be highest in years when rye biomass is the greatest (Baker and Griffis 2009).

The production of corn and soybeans in Iowa is an incredibly important part of Iowa's economy, as the total value of production for the two crops together was approximately $20 billion in 2011 (Iowa Ag Stats 2011). As climate change will most likely affect precipitation timing and intensity and temperatures, possibly intensifying the effects of wet and dry periods, it is important to understand how a potentially environmentally beneficial rye cover crop may affect soil water, which may affect corn and soybean yields throughout the Midwestern United States. In Iowa, the spring of 2012 was exceptionally warm, and the summer was very hot and dry. Researching this period presents an opportunity to understand how cropping systems with rye may react under extreme dryness, which may become more and more common with climate change. As such, the objective of this paper is to determine how a rye cover crop affects soil water content and soil water storage during the spring as a living land cover and during the early summer as a mulch in plots planted to corn and soybeans in a corn-soybean rotation during a drought year.

Materials and Methods

Research sites

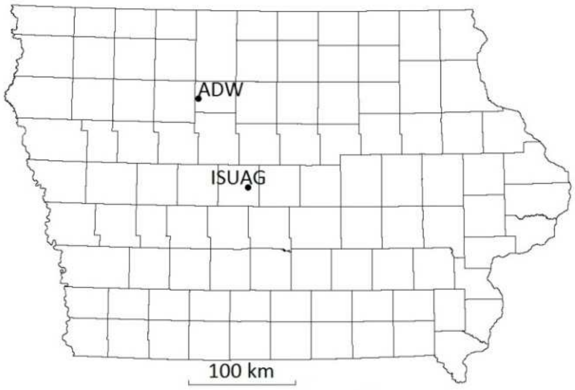

Figure 4.1. Location of ADW and ISUAG sites in Iowa.

The field study was performed at two sites in Iowa: the Agricultural Drainage Water Research Site (ADW) and the Iowa State University Agronomy and Agricultural Engineering Research Farm (ISUAG) (Fig. 4.1). Two sites were used in order to compare results where climate and, therefore, rye growth would be different. ADW is located in northwest Iowa near Gilmore City in Pocahontas County (42°74’77” N, 94°49’52” W). The most ubiquitous soils are Nicollet (fine-loamy, mixed, superactive, mesic Aquic Hapludoll) and Webster and Canisteo (fine-loamy, mixed, superactive, mesic Typic Endoaqualls) clay loams with 3% to 5% organic matter, having an average slope of 0.5% to 1.5%. They are naturally poorly to naturally somewhat poorly drained glacial till soils. The total research area is 4.5 ha, of which 3.8 ha are used as experimental plots. There are seventy-eight 0.05 ha plots (15 x 38 m), each containing subsurface tile drainage. An automatic on-site meteorological station monitored weather conditions, including rainfall. Rainfall patterns at the site were compared to long-term averages (30 years from 1971-2000) determined from readings at the National Climate Data Center station Pocahontas (IA6719) located 19 km west of the research site.

ISUAG is located in central Iowa near Boone in Boone County (42°00’94” N, 93°78’06” W). The most ubiquitous soils are Clarion loam (fine-loamy, mixed, superactive, mesic Typic Hapludoll) with an average slope of 2% to 5%, Nicollet loam (fine-loamy, mixed, superactive, mesic Aquic Hapludoll) with an average slope of 1% to 3%, and Webster silty clay loam (fine-loamy, mixed, superactive, mesic Typic Endoaquoll) with an average slope of 0% to 2%. These soils are naturally poorly to naturally moderately well drained glacial till soils. The total research area is 0.9 ha, divided into 0.009 ha (6 x 15.2 m) plots. The amount and placement of subsurface drainage at ISUAG is unknown, as the site was previously used as an agricultural field. An automatic on-site meteorological station monitored weather conditions. This station ([A130209] Ames) is a part of the Iowa Environmental Mesonet, Iowa State University Agricultural Climate series. Rainfall patterns at the site were compared to long-term averages (30 years from 1971-2000) determined from readings at the National Climate Data Center station AMES-8-WSW (IA0200) located approximately 5 km northwest of the research site.

Soil characteristics

In each plot, 15-20 soil samples for texture analysis were taken to a depth of 60 cm using a 2.5 cm diameter metal push probe. The percentages of sand, silt, and clay for depth increments 0-10 cm, 10-20 cm, 20-40 cm, and 40-60 cm were determined. To determine the bulk density of the soils, a hand core system with soil core rings with a height and diameter of 7.6 cm were used. In the spring of 2011, in each plot, three replicates of each of the following depths were sampled: 0-10 cm, 10-20 cm, 20-40 cm, and 40-60 cm. Samples were taken at the quarter row position (out of machinery wheel tracks) in corn plots and in the same position in soybean plots. The bulk density of each soil core was determined by drying the soil at 105°C for 48 hrs in a soil oven and dividing the dry soil weight by the volume of field sampled soil.

Soils at the two sites are generally loamy soils (Table 4.1). Textures found, in order of decreasing predominance, are clay loam, loam, sandy clay loam, and sandy clay. The most ubiquitous soil texture throughout both sites is clay loam, but at ISUAG, soils tend to be a bit loamier, while at ADW, soils tend to be more clayey. In general, the bulk density of soils increases with depth throughout soil profiles, and the bulk density of soils at ADW increases to a greater degree through the profile than those at ISUAG. Texture and bulk density properties of soils can affect how precipitation infiltrates and how it is retained and moves within a soil profile. Using ANOVA (α = 0.05) to test whether texture varied significantly among treatments in the same field within a depth, only silt content at a depth of 20 cm in corn plots at ADW varied significantly compared to other treatments.

Table 4.1. Soil characteristics at ADW and ISUAG.

Site	Treatment	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Bulk Density (g/cm^3)
ADW	C	0 - 10	46	20	34	0.95
		10 - 20	46	19	35	-[a]
		20 - 40	45	23	32	1.45
		40 - 60	44	25	31	1.59
	rC	0 - 10	39	32	29	0.91
		10 - 20	36	32	32	-[a]
		20 - 40	36	32	32	1.45
		40 - 60	36	32	32	1.56
	S	0 - 10	37	34	30	0.96
		10 - 20	37	33	31	1.41
		20 - 40	34	36	31	1.37
		40 - 60	37	33	31	1.50
	rS	0 - 10	37	34	30	0.92
		10 - 20	34	35	32	1.37
		20 - 40	34	34	33	1.39
		40 - 60	33	35	33	1.49
ISUAG	C	0 - 10	45	35	20	1.24
		10 - 20	44	30	26	1.56
		20 - 40	47	31	23	1.56
		40 - 60	48	29	22	1.65
	rC	0 - 10	38	40	21	1.39
		10 - 20	38	36	25	1.52
		20 - 40	37	37	26	1.48
		40 - 60	41	33	26	1.59
	S	0 - 10	34	41	25	1.23
		10 - 20	31	41	28	1.47
		20 - 40	30	41	29	1.45
		40 - 60	28	42	30	1.50
	rS	0 - 10	31	41	27	1.24
		10 - 20	32	41	27	1.44
		20 - 40	28	43	29	1.43
		40 - 60	28	42	30	1.52

[a] Data not available.

Study design, field management, and rye sampling

The study period was March 1 through July 10 of 2012. This was split into two periods. The first was the “rye growth period”, which began with the start of appreciable rye growth (March 1) until planting of the main crop (corn or soybean). The second period was the “main crop growth period”, which began one week after main crop planting and ended July 10. A one week gap in between the two periods was allowed for germination, and because soil temperatures were unseasonably warm, it is likely that main crops began growing quickly. For the study, 16 plots were chosen, eight each at ADW and ISUAG. A randomized complete block design was used. At each site, there were two replicates of the following four treatments: corn without rye (C), corn with rye (rC), soybeans without rye (S), and soybeans with rye (rS). In each plot, corn and soybeans were planted in rotation, and so the main crop in each treatment name refers to the crop that would be planted following rye growth and termination in the spring of 2012. At ADW, rye was drilled in following corn and soybean harvest on October 12 at a rate of 100 kg/ha. On the day of termination, in each plot, rye was sampled with hand grass clippers along a 30 cm long length of three adjacent rows at three randomly selected locations, dried, and weighed for biomass determination. At ISUAG, rye was drilled in following corn and soybean harvest on October 3 at a rate of 63 kg/ha. On the day of termination, rye was sampled using a square with 0.3 m long edges; rye within the square was cut with a hand grass clippers, dried, and weighed for biomass determination. Rye was terminated with glyphosate herbicide in the spring (Table 4.2).

Table 4.2. Timeline of research and field management at ADW and ISUAG sites.

	Site			
Timeline	ADW		ISUAG	
	Before corn	Before soybean	Before corn	Before soybean
Rye seeding	12 Oct 2011	12 Oct 2011	3 Oct 2011	6 Oct 2011
Period 1: Rye growth period	1 Mar 2012 – 10 May 2012	1 Mar 2012 – 16 May 2012	1 Mar 2012 – 26 Apr 2012	1 Mar 2012 – 11 May 2012
Termination of rye	12 Apr 2012	9 May 2012	6 Apr 2012	25 Apr 2012
Planting of main crop	10 May 2012	16 May 2012	26 Apr 2012	11 May 2012
Period 2: Main crop growth period	17 May 2012 - 10 July 2012	23 May 2012 - 10 July 2012	3 May 2012 – 10 July 2012	18 May 2012 - 10 July 2012

Soil water measurements

In order to obtain soil water content data, a Decagon Em50 Data Logger was used in conjunction with five soil water content sensors (Decagon Devices, Inc., Pullman, WA), installed at depths of 10, 20, 40, 60, and 100 cm below the soil surface at quarter-row position in each plot. A 5TE sensor was installed at the 10 cm depth, recording soil temperature, volumetric water content, and electrical conductivity (EC), while 5TM sensors were used for the remaining depths, measuring only soil temperature and volumetric water content. A trench 60 cm deep and 20 cm wide was dug, and the top 4 soil sensors were installed parallel to the soil surface into the side wall of the trench. For the deepest soil sensor, a smaller hole (40 cm deep and roughly 5 cm wide) was dug at the bottom of the larger trench, and the soil probe at 100 cm was installed at the bottom, perpendicular to the soil surface. At ADW, measurements at all five depths were recorded in hourly increments from March 1 to March 20, and then sensors were turned off for field management; sensors were reactivated March 27, and data was recorded in increments of 5 minutes from then until July 10, the end of the study period. At ISUAG, soil measurements at all five depths were recorded in hourly increments from March 1 to April 2, and then in increments of 5 minutes until July 10. At both sites and all depths, daily average soil water content was calculated for analysis.

Data analysis

To determine differences in soil water contents and soil water storage (SWS) among a corn-soybean rotation with and without a winter rye cover crop, soil water content and SWS were analyzed using a mixed model repeated measure analysis of variance (RPM-ANOVA) with day of year as the repeated factor. Statistical analyses were performed separately among the two field locations, two depths, and two time periods. Covariate structure selection was based on smallest value of AICC and BIC fit statistics; an ARMA (1,1) covariate structure was used for all analyses. All statistics were performed in SAS (version 9.3, SAS Institute, Inc, Cary, NC) and means were separated at the 0.05 level.

Results and Discussion

Weather

Air temperatures at both ADW and ISUAG were much above normal throughout the study period, most notably during March when maximum daily temperatures were 10.3° warmer than normal at ADW and 9.2° warmer than normal at ISUAG (Table 4.3). During March, daily minimum temperatures were 7.9° warmer than normal at ADW and 7.4° warmer than normal at ISUAG; at both sites, this shifted average minimum temperatures from below to above freezing. Throughout the rest of the study period, the warm trend continued, but temperatures were nearer to normal. Temperatures during the month of June were closest to normal. The average high temperature from July 1-10 at both sites exceeded 30° C. Over the entire research period, precipitation was much below normal (Table. 4.3). For the research period, observed precipitation was 80% and 54% of normal at ADW and ISUAG, respectively. During the months of March and April (roughly the rye growth period), observed precipitation was much closer to normal, 113% and 86% of normal at ADW and ISUAG, respectively. From May 1 – July 10 (roughly the main crop growing period), observed precipitation was only 63% and 38% of normal at ADW and ISUAG, respectively. Conditions were generally wetter at ADW with some periods of above average precipitation in late April and May, while precipitation was below normal for the entire research period at

ISUAG (Fig. 4.2). At both sites, however, a very dry period began around the second week of May and persisted until mid-June. After a short period of rainfall, a very dry period began at the end of June and persisted through the end of the study period. By the end of the research period, the U.S. Drought Monitor indicated that both sites were under Moderate Drought (D1) conditions; drought conditions worsened throughout the summer, and by mid-September, when main crops were harvested, both sites experienced Extreme Drought (D3) conditions (2012).

Table 4.3. Air temperature and precipitation normals vs. observed weather at ADW and ISUAG sites during the study period. Pocahontas is 19 km west of ADW, and AMES-8-WSW is 5 km northwest of ISUAG.

	Max. Temp. (°C)	Min. Temp. (°C)	Daily Avg. Temp. (°C)	Precip. (mm)	Max. Temp. (°C)	Min. Temp. (°C)	Daily Avg. Temp. (°C)	Precip. (mm)
Pocahontas Normal[a]					**AMES-8-WSW Normal**[b]			
March	6.2	-4.8	0.7	52.6	8.2	-2.6	2.8	53.6
April	14.9	1.8	8.3	85.1	16.4	3.4	9.9	94.5
May	21.8	9.2	15.5	104.1	22.8	10.1	16.5	122.2
June	27.3	14.8	21.1	124.5	27.5	15.5	21.5	125.9
July 1-10	29.4	16.7	23.1	39.1	29.4	17.7	23.3	41.2
Total				405.3				437.4
ADW 2012					**ISUAG 2012**			
March	16.5	3.1	9.4	52.8	17.4	4.8	11.0	43.4
April	18.0	4.3	10.8	102.6	17.9	5.8	11.8	84.3
May	25.3	11.2	18.3	68.1	25.3	12.6	19.1	49.8
June	28.1	15.2	21.9	98.0	28.6	16.4	22.7	56.4
July 1-10	31.9	19.3	25.7	1.8	33.2	20.5	26.8	2.8
Total				323.3				236.7

[a] Source: Climatological Data for Iowa, National Climate Data Center for Pocahontas, IA, 1971-2000.
[b] Source: Climatological Data for Iowa, National Climate Data Center for AMES-8-WSW, 1971-2000.

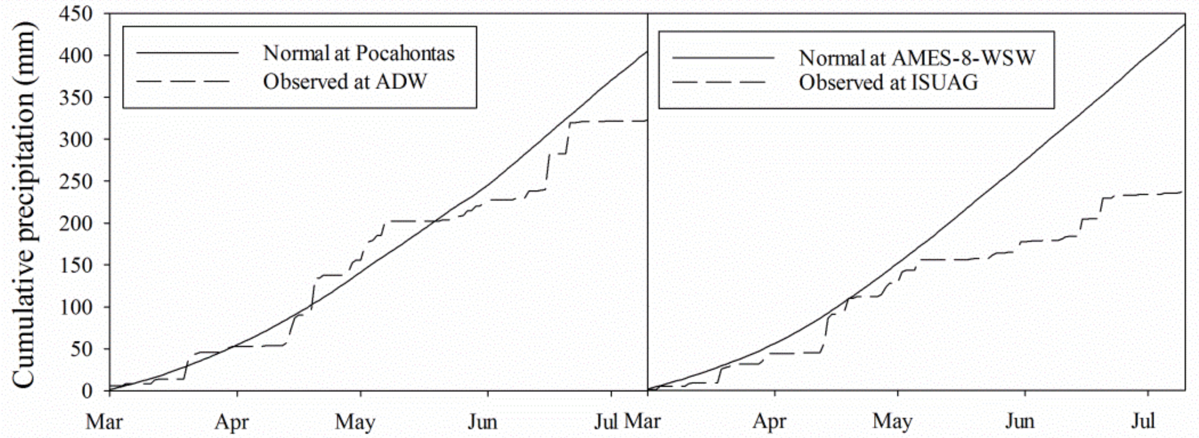

Figure 4.2. Normal cumulative precipitation vs. observed cumulative precipitation at the research sites during the study period (March 1 – July 10). Source for normals: Climatological Data for Iowa, National Climate Data Center for Pocahontas and AMES-8-WSW, 1971-2000.

Rye yields

Rye yields at both sites were slightly over 2x higher in plots with rye followed by soybean as with those followed by corn (Table 4.4). At ADW, rye followed by soybean was allowed to grow 4.5 weeks longer than rye followed by corn, and at ISUAG, it was allowed 5.5 weeks more. This time period was during the warmer interval in late April and May, when rye growth rate was most likely higher than in March and early April. Overall, rye yields at ISUAG were about 7x higher than at ADW. ISUAG saw less precipitation than normal and had less precipitation than ADW in 2012, but nighttime lows during April and May were about 1°C higher at ISUAG than at ADW, and in general, temperatures at ISUAG were higher, both of which could have assisted rye growth.

Table 4.4. Average rye yields for 2012 at ADW and ISUAG sites.

Site and treatment	Rye yield (kg/ha)
ADW rC	136
ADW rS	322
ISUAG rC	1039
ISUAG rS	2207

Soil water

At ADW, neither the main crop (corn or soybean) nor the presence of rye had any significant effects on soil water content or SWS during the rye growth or main crop growth periods (Table 4.5). The small amount of rye growth (Table 4.4) at ADW most likely did not significantly affect infiltration or evaporation during the rye growth period, and during the main crop growth period, there was most likely not enough of a rye mulch cover to significantly aid in conserving soil water. Although there were no significant differences in soil water content at ADW, in the 10-20 cm depth during the rye growth period, and in both depths during the main crop period, there was a smaller amount of water present in plots with rye, although SWS was greater in plots with rye during both periods. It is possible that the small amount of rye growth was not able to decrease evaporation, and that this growth depleted water in the top soil layers through transpiration.

At ISUAG, during the rye growth period, the main crop (corn or soybean) and rye both significantly affected soil water content in the 0-10 cm depth and SWS. During the rye growth period, soil water content was 2.9% higher in rye plots in the 0-10 cm depth, and SWS was greater by 1.9 cm. This trend continued during the main crop growth period; in rye plots, soil water content was 4.1% and 3.3% higher in 0-10 cm and 10-20 cm depths, respectively. SWS was not significantly different, but it was 2.7 cm greater in plots with rye. Even though the main crop growth period was quite dry at ISUAG (Fig. 4.2), rye was able to help conserve soil water. Greater rye growth at ISUAG as compared to ADW did not decrease soil water during its growth period, and as a mulch, rye was able to assist soil

Table 4.5. Repeated measures [ARMA (1,1)] analysis of variance summary of soil water content and storage under corn-soybean rotation with and without winter rye cover crop.

	ADW						ISUAG					
	Rye growth period			Main crop growth period			Rye growth period			Main crop growth period		
	0-10 cm	10-20 cm	SWS[a]	0-10 cm	10-20 cm	SWS	0-10 cm	10-20 cm	SWS	0-10 cm	10-20 cm	SWS
Source	*p*-values											
Block	0.03	0.76	0.07	< 0.01	0.35	0.03	0.75	0.13	0.25	0.58	0.4	0.89
Date	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Main crop	0.16	0.52	0.18	0.31	0.19	0.17	0.03	0.31	0.01	0.35	0.11	0.09
Rye	0.99	0.26	--	0.32	0.31	--	0.02	0.14	0.03	< 0.01	0.05	0.09
Crop*Rye[b]	0.95	0.15	--	< 0.01	0.17	--	0.14	0.13	0.66	0.04	0.14	0.42
	Contributed variance (%)											
Block	1.7	< 0.1	3.4	1.1	0.2	4.3	< 0.1	0.5	0.1	0.1	0.1	< 0.1
Date	97.8	99.6	94.4	97.2	98.5	94.9	97.0	98.4	97.8	95.6	98.1	95.9
Main crop	0.4	< 0.1	0.1	0.1	0.5	0.9	1.2	0.2	1.3	0.2	0.5	2.1
Rye	< 0.1	0.1	--	0.1	0.2	--	1.4	0.5	0.8	3.1	0.9	2.1
Crop*Rye	< 0.1	0.3	--	1.5	0.5	--	0.5	0.5	< 0.1	1.1	0.4	0.2
Main crop	Means											
C	0.245	0.277	--	0.252	0.279	--	0.269 a[c]	0.284	17.4 b	0.252	0.266	16.8
S	0.261	0.289	17.7	0.260	0.317	19.4	0.242 b	0.300	19.9 a	0.242	0.301	20.1
Rye	Means											
Yes	0.253	0.272	18.1	0.252	0.284	19.7	0.270 a	0.300	19.6 a	0.267 a	0.300 a	19.8
No	0.253	0.293	17.4	0.260	0.312	19.0	0.241 b	0.280	17.7 b	0.226 b	0.267 b	17.1

[a] SWS = soil water storage from 0-80 cm.

[b] * indicates test of interaction.

[c] Different letters indicate significant differences at the 0.05 level.

in retaining water. Because rye had been established 5 years previous in 2008, it is possible that rye rooting had altered the soil structure in the top soil layers, compounding its effects on soil water conservation.

Extreme dryness characterized the rest of the main crop growth season after the end (July 10) of the study period, but soil water results are not available for this time period. Around mid-July, it is likely that corn was entering its silking stage; during the silking stage, severe water stress can lead to poor pollination because of desiccated silks and pollen grains (Kranz et al. 2008). Water stress during the silking stage has the greatest potential to decrease corn yields (Kranz et al. 2008), and because rye at ISUAG assisted in conserving water in the upper soil layers during this stage, these potential corn yield decreases were most likely avoided. Also, rye’s ability to conserve soil water in the upper soil layers is important, as corn generally extracts 40% of the water it uses in ET from the top 25% of its rooting depth (Kranz et al. 2008). At ADW, the very small amount of rye biomass produced no significant decrease in soil water content or SWS, as was expected, so rye may not have had any negative effects on corn yield during the study period.

Conclusions

At ISUAG, a rye cover crop was able to conserve soil water and increase SWS preceding the main crop in a corn-soybean rotation. At ADW, rye did not have a significant effect on soil water content or SWS in either period included in the study. Adequate spring precipitation and rye growth at ISUAG may have contributed to increased infiltration during the rye growth period and decreased evaporation during the main crop period, when rye was a mulch. Because of increased soil water at ISUAG, and no significant change in soil water at ADW due to rye, it is possible that, given an adequately wet spring, rye may not deplete soil water, even during a drought year. More research on long-term rye plots should be undertaken; understanding rye rooting patterns and the mechanisms by which these roots may alter soil structure and water holding capacity is an important portion of research that should be pursued, as well.

Acknowledgements

Thanks go out to Aaron Daigh for undertaking complex statistical analysis. This research is part of a regional collaborative project supported by the USDA-NIFA, Award No. 2011-68002-30190, “Cropping Systems Coordinated Agricultural Project: Climate Change, Mitigation, and Adaptation in Corn-based Cropping Systems.” Project Web site: sustainablecorn.org.

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CHAPTER 5. GENERAL CONCLUSIONS

General Discussion

The first study in this thesis showed that the amount of subsurface drainage through tile in a field decreased under perennial forage during the month of May. The second study detected an increase in top soil layer water storage during precipitation events in plots with rye cover crops. This study also explored the redistribution of infiltrated precipitation throughout the soil profile. Soil water redistribution behaved differently during and after a moderate rainfall event as compared to a heavy, intense rainfall event. The third study found that a rye cover crop was able to conserve soil water and increase SWS in a corn-soybean rotation in the spring and early summer during a drought year. Because different processes within the hydrological cycle in an area are interconnected, soil water and drainage are linked and affect each other. Drainage and soil water patterns are both dependent on precipitation timing and intensity and crop water demand (Lawlor et al. 2008, Wang et al. 2008). Even in years with the same amount of precipitation, drainage volumes from the same field can differ significantly (Lawlor et al. 2008), as differences in antecedent water conditions and rainfall event characteristics affect soil water conditions and redistribution patterns, and therefore drainage. The spatio-temporal variability of soil water can strongly impact other hydrological processes within the system as well (Choi and Jacobs 2007, Hupet and Vanclooster 2002).

As it is possible that the use of perennial or cover crops may decrease drainage during May, the time of year when the most NO_3-N is lost from fields due to leaching, and because the drainage to precipitation ratio was the highest during this time, these crops have the potential to reduce NO_3-N leaching, as well.

The ability of perennial and cover crops to mediate changes in hydrological and biogeochemical cycling caused by changes in land cover and management, along with their ability to conserve soil water amidst changes in climate, offer the potential for research within and improvement of the agronomic system. This research should also allow us to ask broader questions about the economic and environmental viability of the corn-based agricultural economy of the Upper Midwest. What costs will we consider as important when evaluating and re-evaluating our current system? How will this shape the policy we create? Will climate change necessitate a change in our current agricultural system? The way in which we frame and answer these questions is of utmost importance as we seek to create agricultural systems that are sustainable and resilient.

Recommendations for Future Research

In light of findings from this research and the literature cited within this thesis, it is recommended that research into perennial and cover crops be augmented in the following ways:

1. Studies including more species and cultivars of perennial and cover crops should be integrated into research. Different species, cultivars, and mixes of species will provide unique benefits and affect hydrological and biogeochemical cycles in different ways.
2. Research should include field study sites in areas across the Upper Midwest. Differences in climate across the region produce vastly different rainfall patterns and characteristics, which in turn create differences in drainage and soil water regimes.

3. Long-term studies examining linkages between different variables in the hydrological system should be run. A more complete picture of the system would be useful as all parts are interconnected.
4. Linkages between hydrological and nutrient cycling in fields should continue to be explored.
5. More research into the economic viability of integration of perennial and cover crops within the current system should be undertaken.
6. Creation of policy and assistance that encourages implementation of more diverse rotations should be researched.

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ACKNOWLEDGEMENTS

First, I would like to acknowledge the guidance of my major professor, Dr. Matt Helmers. His generosity as a professor, example as a transdisciplinary scientist and thinker, and ability to guide me to ask interesting questions has gone very far in helping me grow and succeed during my time at Iowa State.

Secondly, I thank Dr. Xiaobo Zhou for the kind and patient help he has provided in guiding me through managing massive quantities of data. Also, I thank Carl Pederson for his mechanical expertise which saved the day multiple times. Thanks to my program of study committee, Dr. Michael Castellano and Dr. Richard Cruse for their critique and suggestions. Thanks are due to Aaron Daigh, Ignacio Alvarez Castro, and Dan Fortin for their assistance in statistical analysis, as well. I thank all the undergraduate students who have helped with countless hours of data collection, entry, and analysis.

I thank my parents for their support which has so generously helped me to pursue my education. I thank all my friends and the rest of my family for supporting me, and I am so grateful for my fiancée Bobbie Quade and her willingness to move to Ames and marry a weird scientist.

This research is part of a regional collaborative project supported by the USDA-NIFA, Award No. 2011-68002-30190, “Cropping Systems Coordinated Agricultural Project: Climate Change, Mitigation, and Adaptation in Corn-based Cropping Systems.” Project Web site: sustainablecorn.org. The 11 institutions comprising the project team include the following Land Grant Universities and USDA Agricultural Research Service (ARS): Iowa State University, Lincoln University, Michigan State University, The Ohio State University, Purdue University, South Dakota State University, University of Illinois, University of

Minnesota, University of Missouri, University of Wisconsin, and USDA-ARS Columbus, Ohio.