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Monitoring and modeling of subsurface drainage and nitrate leaching under various land covers

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Monitoring and modeling of subsurface drainage and nitrate leaching under various land covers

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

This dissertation includes the study of hydrologic cycling and nitrogen dynamics under various land covers for the subsurface drained agriculture in Iowa through field investigation and modeling approaches. Land covers included conventional corn-soybean rotation, winter rye cover crop in corn-soybean rotation, kura clover as a living mulch for corn, and perennial forage. Field experiments consisted of two parts: one was conducted in a crop field at a plot-scale including all the land covers near Gilmore City, Iowa from 2006 to 2008 and the other was conducted in non-weighing lysimeters with winter rye cover crop and bare soil during 2006-2008. The RZWQM-DSSAT model was tested against the measured data from the plot-scale study and the evaluated model was subsequently used to simulate the long-term impacts of winter rye cover crop on hydrologic cycling and nitrogen dynamics. Overall, the results suggest that subsurface drainage water quality in terms of NO_3-N contamination can be effectively improved by converting conventional corn-soybean rotation into perennial forage, but at present there would be little economic return for the grasses and it may also alter the local hydrologic cycle. Planting corn in established kura clover living mulch also reduced the annual flow-weighted NO_3-N concentration and NO_3-N loss in the subsurface drainage flow, but the corn yield in kura clover treatment was significantly reduced. Although not significantly impacting total NO_3-N loss in the plot-scale study, rye significantly reduced the NO_3-N concentration in soil water within the soil profile, and showed a potential in reducing subsurface drainage and NO_3-N loss in the non-weighing lysimeter and the long-term simulation studies. Therefore, rye cover crop has the potential to be an excellent cropping option under an integrated concern for the environment and economy.

CHAPTER 1. GENERAL INTRODUCTION

1.1 Introduction

Nitrate-nitrogen (NO_3-N) has been deemed a main source of pollution for both shallow groundwater and surface water bodies. NO_3-N loading from the Mississippi River is suspected to be a main contributor to the hypoxic zone in the Gulf of Mexico (Rabalais et al., 2001). The main source of NO_3-N in the Mississippi River Basin (MRB) is linked to tile drainage (Lowrance, 1992; Keeney and DeLuca, 1993; David et al., 1997; Zucker and Brown, 1998). In Iowa specifically, approximately 25% of agricultural land is estimated to be artificially drained (Baker et al., 2004) with multiple studies reporting the high NO_3-N loading from these drained lands. Schilling and Zhang (2004) reported that while Iowa accounts for 5% of the area of the MRB it contributes approximately 25% of NO_3-N load. The mass of NO_3-N loss is closely related to subsurface drainage volume (Baker et al., 1975; Cambardella et al., 1999). In Iowa, the majority of subsurface drainage and NO_3-N loading occurs in April, May and June when the crops are not planted or just establishing (Helmers et al., 2005). To aid in reducing NO_3-N loss, annual cover crops, perennial living mulches, and perennial forage are being investigated in the Midwest.

An annual cover crop is any living ground cover that is planted into or after a main crop and then commonly killed before the next crop is planted (Hartwig and Ammon, 2002). Annual winter cover crops were historically added into the corn-soybean rotation to achieve soil and water conservation benefits in the Midwest (Unger and Vigil, 1998; Kaspar et al., 2001). Rye is one of the main annual winter cover crops; it is a cereal crop that has excellent weather hardiness and the ability to grow on soils with marginal fertility (Bushuk, 2001). Field investigation on the reduction of subsurface drainage and NO_3-N loss by winter rye cover crop, however, was limited in the Midwest (Strock et al., 2004; Kasper et al., 2007). The winter rye cover cropping system could exert impacts on the infiltration and evaportranspiration processes. Dabney (1998) and Unger and Vigil (1998) reviewed the mechanism by which winter cover crops affect the hydrological processes and found they can increase infiltration by trapping snow and exert influence on soil evaporation by altering net radiation, wind speed, vapor pressure deficit, and soil surface temperature. Because evaportranspiration of rye cover crop may offset the increased infiltration, the soil water storage had a similar pattern in a rye cover field compared to a no rye cover field (Islam et al., 2006). Moreover, transpirational water consumption by rye may adversely affect the soil moisture that could lead to water stress for the following main crop (Munawar et al., 1990).

Living mulches are cover crops planted either before or with a main crop and maintained as a living ground cover throughout the growing season (Hartwig and Ammon, 2002). Living mulches can reduce erosion, suppress weeds, and in the case of legumes benefit N cycling. Italian ryegrass, alfalfa, and kura clover are examples of living mulches. Perennial leys, including lucerne and grasses, had considerably less drainage volumes and NO_3-N loss than the treatments with annual barley (Bergstrom, 1987). Corn in Italian ryegrass was unable to establish a competitive root system thus its growth and yield were reduced in a study in Switzerland (Liedgens et al., 2004). With suppression and careful management, kura clover in corn did not reduce the whole-plant biomass, grain yield (Zemenchik et al., 2000) or corn root density (Eleki, 2003) in North Central USA, especially if herbicide-resistant corn was planted (Affeldt et al., 2004). However, there is very limited information concerning the effect of kura clover-corn system on drainage and NO_3-N leaching in the Midwest. Soil moisture effect of kura clover as a living mulch for corn was not consistent in related studies. (Kurtz et al., 1952 ; Pendleton et al., 1957 ; Ewing et al., 1991; Eberlein et al., 1992; Zemenchik et al., 2000).

Perennial forage grassland serves as the most effective nitrogen loss reduction approach because no fertilization is necessary and it has a longer growing period than winter cover crop, although at present there is little economic market for the product. Fields with alfalfa showed lower NO_3-N concentration and less NO_3-N export than row crop fields (Baker and Melvin, 1994; Kanwar et al., 2005). However, there is very limited information on the impact of orchard grass mixed with clovers as perennial forage cover on subsurface drainage and NO_3-N leaching in the Midwest. Converting a perennial forage field into a corn or soybean cropland could increase soil water storage because of the shallow rooting depth and short growing season of row crops. Intensive studies on soil water dynamics under deep-rooted pasture and annual corps have been conducted in this Australia because of the argument about which species use more water (Nulsen, 1984; Farrington et al., 1992; Scott and Sudmeyer, 1993; Crawford and Macfarlane, 1995; Ridley et al., 1997; Dolling, 2001). There is little literature specifically discussing soil water dynamics of perennial forage or pasture in the Midwest of the USA. Related studies showed that deep-rooted savanna, woodland and pasture extracted more water from the deeper soil profile than the annual corn crop (Proffitt et al., 1985; Asbjornsen et al., 2007).

Besides field investigations, agricultural systems models are promising tools for evaluating the effects of emerging agricultural practices on the local hydrologic cycle and water environment. The Root Zone Water Quality Model (RZWQM, Ahuja et al., 2000) describes the physical, biological, and chemical processes in the agricultural crop root zone and from this simulates plant growth, water movement, and fate of nutrient and pesticides.

RZWQM has been widely used to simulate the response of subsurface drainage and water quality, as well as crop production, to the change in agricultural management, fertilization rate, tillage, and cropping systems. RZWQM was evaluated by field measured data from MESA sites across the Midwestern United States (Hanson et al., 1999; Jaynes and Miller, 1999; Wu et al., 1999; Ghidey et al., 1999) and the strength of its hydrologic and nutrient cycling algorithms under various climatic conditions was recognized by model users.

In Iowa, RZWQM has been intensively tested and successfully used as a tool to evaluate the effect of potential agricultural management on water balance and drainage water quality (Singh, 1994; Azevedo, 1997; Kumar et al., 1998; Bakhsh et al., 2001; Bakhsh et al., 2004). The model has been successfully used to simulate the long-term effect of crop rotation, tillage, controlled drainage, and N application rate on crop production, water balance, and nitrate loss in northeast Iowa (Malone et al., 2007; Ma et al., 2007).

CERES and CROPGRO models were recently coupled with RZWQM (Ma et al., 2005; 2006), generating RZWQM-DSSAT model. Saseendran et al. (2007) reported that this hybrid model showed no advantages over the previous generic crop growth module within RZWQM at the Nashua site in Iowa, but could be potentially improved by obtaining site-specific weather data and reducing the uncertainty of input parameters. Based on more detailed site specific data and parameters from previous RZWQM modeling studies conducted in Iowa, Thorp et al. (2007) found that RZWQM-DSSAT reasonably quantified hydrology, corn yield, and nitrogen dynamics for a corn-soybean rotation field near Story City, IA. The calibrated hybrid model was subsequently adopted by Li et al. (2008) and successfully used to simulate nitrate leaching under winter rye cover crop at a site in Boone County, IA. However, there has been no study investigating the long-term effects of adding winter rye cover crop to the corn-soybean rotation on hydrologic and nitrogen cycling. With the increased concern related to water quality in Iowa, there is a need to investigate the long-term effectiveness of introducing winter rye cover crop on subsurface drainage and nitrate loss reduction.

The overall goal of this dissertation is to investigate the effects of various land cover systems on hydrologic cycling and NO_3-N loss. A field experiment at the plot-scale, a field experiment using non-weighing lysimeters, and computer modeling using RZWQM-DSSAT were conducted to achieve the general goal. Data collected from the 3-year experiment using non-weighing lysimeters was used to study soil water dynamics and subsurface drainage as affected by winter rye cover crop on a small-scale. The field experiment at the plot-scale was conducted to investigate the effect of winter rye cover crop, kura clover as a living much for corn, and perennial forage on subsurface drainage, biomass and yield, NO3-N loss, and soil water storage during 2006-2008. The RZWQM-DSSAT model were tested using measured data from the plot-scale field study and subsequently was used to estimate the long-term (40 years) effects of winter rye cover crop on hydrologic cycling and nitrogen balance.

1.2 Dissertation Overview

This dissertation is organized as a compilation of four articles that are currently in different stages of the review process as referred publications. Chapter 2 includes a paper entitled " Soil water dynamics under winter rye cover crop in central Iowa" which describes the impacts of winter rye cover crop on subsurface drainage and soil water dynamics in a field study using non-weighing lysimeters over a 3-year period. Chapter 3 contains a paper entitled "Nitrogen uptake and nitrate-nitrogen loss under various land covers in an Iowa subsurface drained crop field". This paper described the effects various land covers, including conventional corn-soybean rotation, winter rye cover crop in corn-soybean rotation, kura clover as a living mulch for corn, and perennial forage, on subsurface drainage, crop biomass accumulation, and NO_3-N leaching based on a 3-year field study at the plot-scale. Chapter 4 contains a paper entitled "Soil water dynamics under various land covers in Iowa", which analyzed the differences of soil water storage among the land covers from the field study in Chapter 3. Chapter 5 contains a paper entitled "Simulating long-term impacts of winter cover crop on hydrological cycling and nitrogen dynamics using the RZWQM-DSSAT model." In this paper, the hydrology, crop growth, and nitrogen components of RZWQM-DSSAT model was tested against field measured data from the winter rye cover crop in corn-soybean rotation treatment. The tested RZWQM-DSSAT model was used with a 49-year weather and management data set to study long-term impacts of a cover cropping system on hydrologic cycling and nitrogen dynamics.

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CHAPTER 2. SOIL WATER DYNAMICS UNDER WINTER RYE COVER CROP IN CENTRAL IOWA

A paper published in Vadose Zone Journal

Zhiming Qi and Matthew J. Helmers

2.1 Abstract

Utilization of cereal rye as a winter cover crop has potential benefits for subsurface drainage and nitrate loss reduction. The objective of this study was to quantify the soil water balance components and impacts of a rye cover crop on subsurface drainage in central Iowa. Rye was planted in lysimeters in mid-October and terminated in early-June in three years and lysimeters were left fallow during the summer months. Subsurface drainage water was generally pumped out weekly along with taking soil moisture measurements; however, multiple appreciable rain events in a given week required more frequent pumping. During May through July of the three years, monthly subsurface drainage was significantly reduced by 21% when comparing the rye system to bare soil ($p<0.1$). Drainage of individual pumping events was significantly lower in the rye lysimeters than bare lysimeters when averaged across three years ($p<0.05$). Soil water storage in the rye treatment was also significantly lower than the bare treatment ($p<0.05$) in all three years. The winter cover crop effectively reduced the subsurface drainage which would then be expected to decrease nitrate load, which is essential to water quality improvement. During the main growing month, May, estimated evapotranspiration of rye was 2.4 mm day^{-1}, significantly higher than the evaporation of the bare treatment (1.5 mm day^{-1}, $p<0.1$). The soil water depletion by rye in May could reduce drainage volume and may also help facilitate trafficability but in dry years it is still unknown what impact there may be on crop production.

2.2 Introduction

Inadequate drainage reduces seed germination, root growth, and crop yield and grain quality (Evans and Fausey, 1999). With the installation of artificial drainage systems, the prairies and swampy areas in the U.S.A were converted to productive farm lands (Wheaton, 1977). About 9.7 million ha of Iowa's 14.6 million ha farmland is planted with row crops and 3.6 million ha has been artificially drained (Baker et al., 2004). Drainage water is a major source of nutrients, nitrate in particular. The mass of nitrate loss from subsurface drain tile was found to be related to the quantity of drainage water flow volume in Walnut Creek watershed, Iowa (Cambardella et al., 1999). Kanwar et al. (2005) observed a strong linear relationship between annual NO_3-N leaching and drainage flow volume (r^2=0.99) in northeastern Iowa. In the upper Midwest, the period from April through June is the main season for drainage and nitrate loss (Helmers et al., 2005; Randall and Vetsch, 2005), when the row crops have not established. Applying crops that can grow in this period is a promising approach to reduce subsurface drainage volume thereby decreasing nitrate loss. In addition, crops can assimilate nitrogen from the soil profile during the main drainage season, which would be expected to decrease the NO_3-N concentration in the soil water.

Cover crops, which have historically been added into corn-soybean rotation to achieve soil and water conservation benefits in Midwest (Kaspar et al., 2001; Unger and Vigil, 1998), are being studied for assessing their potential in reducing subsurface drainage and nitrate concentration in the drain flow thereby decreasing the nitrate loss from the soil. A cover crop is any living ground cover that is planted into or after a main crop and then commonly killed before the next crop is planted (Hartwig and Ammon, 2002). Cover crops would be expected to use soil water and nitrogen during the main drainage period from April through June. As one of the main annual winter cover crops, rye is a cereal crop with extreme weather hardiness and ability to grow on soils with marginal fertility (Bushuk, 2001). Rye requires less heat than wheat and it can germinate at temperatures slightly above 0 ºC. Appreciable growth of rye ceases when mean temperatures drop below 5 ºC but it will continue to grow when the temperatures rise above 5 ºC (Leonard and Martin, 1963). It can survive under temperatures of -25 to -35 ºC even with limited snow cover (Stoskopof, 1985), and can overwinter in North Dakota and Montana in the northern United States (Leonard and Martin, 1963). In North America, some rye is grown at the northern limit of the Canadian grain belt and rye is the last crop to stop growing in the fall and the first to start in the spring (Buskuk, 2001).

Some research has been done recently to investigate the biomass accumulation, nitrogen uptake and leaching, subsurface drainage, and the effect on corn and soybean yield by winter rye cover crop in the Upper Mississippi River Basin states (Andraski and Bundy, 2005; Singer and Kohler, 2005; Kaspar et al., 2007; McDonald et al., 2008; De Bruin et al., 2005; Strock et al., 2004). There are some differences in the effect of rye on subsurface drainage volume. Strock et al. (2004) found that drainage was significantly reduced by rye while the difference was not significant between cumulative drainage in rye and control treatments in Kaspar et al. (2007), which might be attributed to varying field conditions. An indoor lysimeter experiment which was conducted by Logsdon et al. (2002) strengthened the findings of Strock et al. (2004) that subsurface drainage was reduced by a winter rye cover crop. However, there has been no lysimeter experiment exposed to natural weather conditions in this region to quantify the soil water dynamics under a winter rye cover crop. Since nitrate loss has been reported to be proportional to subsurface drainage in a corn-soybean system (Cambardella et al., 1999; Kanwar et al., 2005), it is important to investigate strategies that have the potential to reduce subsurface drainage volumes. As a result, there is a need to quantify the effectiveness of winter rye on hydrological cycling due to the increased need for water quality improvement in this region. The objective of this study is to quantify the subsurface drainage volume, soil water storage change, and evapotranspiration with winter rye under central Iowa field conditions.

2.3 Materials and Methods

2.3.1 Non-weighing Lysimeters

This study was conducted using non-weighing lysimeters at the Iowa State University Agronomy and Agricultural Engineering Research Center near Ames, Iowa, U.S.A (42°01′17″ N, 93°46′26″ N) from October 2005 through October 2008. Construction of these sixteen lysimeters was completed in 1982 with the help of a grave-digging machine, which allowed for the soil to be separated by horizons. A 1.1-mm thick impermeable liner was placed in the pit to form a sealed volume except for the top surface. A perforated drainage pipe (10 cm outer diameter) is laid at the center bottom with a vertical tube through which the drainage water can be pumped out (Figure 2.1). The original layers of soil were repacked to their initial depths. A metal border was inserted into the ground with 20 cm above the soil surface to prevent surface water interaction. Detailed construction procedure was given by Cook and Baker (2001). The dominant soil type is Nicollet (fine-loamy, mixed, superactive, mesic Aquic Hapludoll) with sand, silt, and clay percentage of 33%, 39%, and 28%, respectively (ISPAID, 2004). Each lysimeter is 2.29 m long and 0.97 m wide with a depth of 1.37 m. A fiberglass access tube was vertically installed in October 2005 in the center of each lysimeter to measure water content in the soil profile with a PR2 capacitance probe (Delta-T Services, UK).

2.3.2 Treatment and Agronomic Management

Ten lysimeters were selected for the study utilizing a completely randomized design: five with rye (Rye) and five without rye (Bare). Rye was planted on October 13, 2005, October 12, 2006, and October 13, 2007, and was removed by cutting on June 2, 2006, June 5, 2007, and June 14, 2008 without any following row crop. Even though rye was killed late in this lysimeter study, it was not much later than killing before soybean at some field study sites (Strock et al., 2004; Qi, et al., 2008). Biomass growing in each rye treatment lysimeter was dried at 60 ºC for a week to determine the above ground dry matter. In 2006 and 2007, the leaf area index (LAI) of rye was measured at a 10-day interval by a PAR ceptometer (ICT International), and the plant height was monitored by a meter stick in 2007. In each lysimeter, 10 rye shoots were randomly selected to measure the plant height and LAI was measured at three random locations. The nitrogen content in the soil profile of the lysimeters was suspected to be lower than the routinely cultivated farmland since the lysimeters were not used for several years, therefore prior to this study, in each year before rye planting every lysimeter was tilled by a shovel to 15 cm and urea-ammonium-nitrate (UAN) was applied at 26.8 kg N ha^{-1} to help the rye establish. The rye was hand planted with a seed rate of 22.4 kg ha^{-1} and a row spacing of 19 cm. After the rye was removed, all the lysimeters were left fallow in summer and herbicide was sprayed periodically for weed control from April through October when the weeds are normally growing in Iowa. Row crops were not planted to ensure that the investigation on soil water dynamics was restricted to solely the rye factor.

2.3.3 Temperature and Rainfall Measurement

Daily mean temperature and daily rainfall were monitored by an automatic meteorological station mounted at the Iowa State University Agronomy and Agricultural Engineering Research Center, approximately 2 km away from the non-weighing lysimeter experimental site. To get a more precise monthly rainfall at the experimental site, a cylinder rain gauge was installed in the middle of the experimental site and was checked weekly prior to drainage and soil moisture measurements. Thirty-year averages on daily temperature and precipitation from 1971 to 2000 for the Iowa State University Agronomy and Agricultural Engineering Research Center (NCDC, 2002) was considered the long-term norm and provided a base for temperature and precipitation comparisons.

2.3.4 Soil Moisture Measurement

A Theta probe and a PR2 Profile probe (Delta-T Services, UK) were used to measure the soil permittivity from April through October. The measurement was not conducted in the winter because the soil was frozen and the PR2 probe was not capable of monitoring soil moisture in frozen soils. The permittivity of the top soil (0-5 cm) was measured five times around each access tube with the Theta probe to provide adequate replication. The permittivity output of the Theta probe was converted into volumetric water content by the equation calibrated by Kaleita et al. (2005) using field data collected on Des Moines Lobe soils. The PR2 Profile probe was inserted into the fiberglass access tubes to measure the soil permittivity at 6 depths of 10, 20, 30, 40, 60 and 100 cm. The PR2 probe was calibrated by in-situ soil sampling in one of the bare non-weighing lysimeters in May, July, and October 2008. The influence diameter of the PR2 profile probe is 10 cm, however, to avoid soil destruction within the PR2 influence volume, soil samples were extracted 60 cm away from the access tube to gain gravimetric water content immediately after the permittivity measurement. One soil sample was taken at each of the six depths at which the PR2 probe measured permittivity. Soil bulk density cores were obtained by inserting three Shelby tubes, 45 cm long each with an inner diameter of 7.32 mm, into the lysimeter soil using a Giddings probe (#25-SCS Model HDGSRPS, Giddings Machine Company Inc, CO). The soil cores were cut into 10 cm long segments by a band saw and were oven dried at 105 °C for 7 days subsequently to determine the soil bulk densities. The gravimetric soil water content was multiplied by the bulk density to compute what was considered the observed volumetric soil water content. A linear equation was fit between the observed volumetric soil water content and the permittivity following the instructions on the field calibration of PR2 probe (Delta-T Devices). This calibrated equation was applied to convert the permittivity into volumetric water content for the PR2 probe. The calibration equation for the Theta probe was adopted from the field calibration by Kaleita et al. (2005) for Nicollet, Clarion, and Webster soils in central Iowa.

The Theta and PR2 measurements were taken once a week from April through October in 2006-2008 prior to the drainage volume monitoring. The soil water storage (SWS) was calculated by volumetric soil water content multiplied by the depth range for each layer. Because the soil water content at 100 cm would be largely influenced by the high water table, SWS was calculated in the soil layers from 0 through 60 cm below ground. The soil water content measured by PR2 probe at 10, 20, 30, 40, and 60 cm were assumed to be representative of soil depths at 5-10, 10-20, 20-30, 30-45, 45-60 cm, respectively, and the soil moisture in the top 0-5 cm layer was calculated by the Theta probe readings.

2.3.5 Subsurface Drainage Monitoring

The subsurface drainage water in the perforated pipe at the bottom of the lysimeters was pumped weekly from April through October in 2006-2008 and additional pumping was conducted after heavy rain events in the wet spring period. In the upper Midwest, the ground is frozen from late November to late March limiting drainage in this period (Randall, 2004). Vacuum was generated by a portable electric vacuum pump in a hand graduated 20-L glass carboy. Water in the drainage pipe flowed into the carboy driven by the negative pressure. The water volumes pumped from lysimeters were recorded manually.

2.3.6 Evapotranspiration and Statistical Methods

Evapotranspiration (ET) of the rye lysimeters and evaporation (E) of the bare lysimeters were estimated by the water balance computation in a certain period:

$$ET \quad or \quad E = R - D - \Delta SWS$$

where ET is the evapotranspiration of the rye lysimeters (mm); E is the evaporation of the bare lysimeters (mm); R is the rainfall (mm), D is the subsurface drainage volume (mm), and ΔSWS is the soil water storage change by subtracting soil water storage at the calculation beginning date from the soil water storage at the ending date (mm). Daily reference evapotranspiration (ET_0) for the experimental site, computed by Penman-Monteith equation, was retrieved from Iowa Agriculture Climate Network (Iowa Environmental Mesonet). Daily reference evapotranspiration is the evapotranspiration of a hypothetical grass reference crop with abundant water supply. The experiment followed a completely randomized design with 5 replications. Data were analyzed for each individual year separately, and the 3-year data was also combined to test the significance of difference between treatments across years. Differences in monthly and annual drainage, and ET and E were analyzed using the PROC MIXED procedure (SAS Institute Inc., 1999) at the 0.05 and

0.1 probability levels. Treatment effect on drainage at each pumping event and soil water storage monitored weekly were analyzed by PROC MIXED using the monitoring date as a repeated measure at 0.05 probability level.

2.4 Results and Discussion

2.4.1 Weather and Biomass Accumulation

Daily mean temperature and daily precipitation from October 2005 through October 2008 are presented in Figure 2.2. Temperature and rainfall in fall 2005 were included because rye was first planted on October 13, 2005 and the weather condition in the fall and winter would affect germination and root establishment of the rye. Precipitation data was not available from November to March due to the potential freezing impairment of rain gauges. Temperatures during the rye growing season, from October to May, were the highest in 2006 and the lowest in 2008. The average daily temperatures during the rye growing season were 4.3, 3.8, and 2.4 ˚C for 2006, 2007, and 2008 respectively, while the 30-year long-term average daily temperature from October to May at this location was 3.3 ˚C. The long-term average monthly temperatures in February, March, April, and May were -4.0, 2.8, 9.9, and 16.3 ˚C; however, in 2008 the temperatures for these four months were -8.2, 0.4, 7.8, and 14.6 ˚C, consistently lower than the long-term averages. In comparison, the four months average temperatures were -4.2, 2.2, 12.0, and 16.2 ºC for 2006, and -8.7, 5.7, 8.3, and 18.3 ºC for 2007.

The 30-year long-term annual precipitation of the experimental site is 865 mm of which 696 mm normally occurs in the period from April through October. The daily precipitation recorded by the meteorological station in this season is included in Figure 2.2.

The wettest year was 2008 and the driest year was 2006. Table 2.1 lists the monthly precipitation from April to October in the three years measured by the cylinder rain gauge located at the lysimeter experiment area. In 2006, most monthly rainfall amounts were lower than the long-term average but the rainfall in September was twice as much as the corresponding long-term average. In 2007 it was dry in June but the rainfall in April, May, August, and October were greater than the long-term average. The elevated rainfall in June and July of 2008 was twice as much as the long-term average. The observed rainfall amounts for the season from April through October were 542, 830, and 888 mm in 2006, 2007, and 2008, respectively. During the growing season of rye, the total amounts of rainfall in April and May were 145, 309, and 202 mm for 2006, 2007, and 2008, respectively, and the sum of long-term precipitation in April and May was 199 mm.

The rye cover crop had the greatest above ground biomass in 2007 and least in 2006 without statistically significant differences among years. The above ground dry matter yields at termination were 2.2, 3.1, and 2.9 Mg ha^{-1} for 2006, 2007, and 2008, respectively, with 2.7 Mg ha^{-1} on average across the three years for rye growth in the 5 lysimeters. The biomass productions were comparable to the biomass of rye (2.3 Mg ha^{-1}) burned down in late May before soybean in a plot-scale experiment that was conducted in northwestern Iowa (Qi et al., 2008). Rainfall and temperature affected the growth of rye interactively. Temperatures were above the norms in early 2006 but the rainfall was below average which might have resulted in plant water stress; conversely, the rainfall was abundant in spring 2008 but the temperatures were much lower than the normal values (Figure 2.2). In 2007 the rye produced the highest biomass with average temperatures close to normal values in the spring and an above average amount of rainfall. May was the main growing month for rye in this study.

The peak leaf area index (LAI) was observed on May 19, 2006 and May 26, 2007 with values of 1.77 and 1.78, respectively. The rye plant reached its maximum height of 89.1 cm on June 5, 2007, which is three times higher than that on April 28, 2007. Although there were severe freezing conditions from April 4 through April 7, 2007 (-3.6 ˚C on average) which permanently killed about 1/6 of the rye shoots, it recovered quickly and accumulated the highest amount of above ground dry matter of the three years. This is likely due to the highest temperature in May (18.3 ˚C on average) for the 3-year study period.

2.4.2 Subsurface Drainage

The differences of average annual drainage discharge, for both five rye lysimeters and five bare lysimeters, were significant among years due to the variability of yearly weather conditions ($p<0.05$). The quantity of rainfall that exited from the drain tile during April through October was proportional to the total rainfall amount during the same period. The total drainage across the treatments during April through October was 228 mm in 2006, 460 mm in 2007, and 523 mm in 2008. The relationship between the annual drainage and precipitation was strongly linear: $D = 0.837R - 227.2$ (r^2=0.997), where D is the total drainage volume during April through October (mm), and R is the total rainfall observed during the same period (mm). Moreover, the percentage of rainfall that was drained fluctuated in accordance with the total rainfall. Drainage volume represented 38% of the total rainfall observed in 2006, 53% in 2007, and 58% in 2008 for rye lysimeters; and 46% in 2006, 58% in 2007, and 61% in 2008 for bare lysimeters. This indicates that in a drier year the total drainage is less, and the ratio of total drainage to total rainfall is lower.

Table 2.1 gives the information on monthly observed rainfall and drainage averaged over five lysimeters of each treatment. That the drainage in April was higher than the monthly rainfall amount is attributed to snow melt in late March. In May through July, the total drainage averaged over 3 years was significantly reduced in the rye treatment. The average 3-month drainage, May through July, was 161 mm for rye, 21% (42 mm) lower than 203 mm for bare treatment across 3 years ($p<0.1$). May was the month that rye accumulated the most biomass based on visual observation. The difference of drainage volume between rye and bare treatments in May was 25 mm when averaged over the three years, which represented 28% of the drainage from the bare lysimeters. The drainage reduction by rye was 8 mm for June and July, respectively when averaged over the 3 study years. The monthly drainage from rye and bare lysimeters were very similar in other months, namely April, August, September, and October. The differences of monthly drainage volume between rye and bare treatments in these 4 months were 3, 4, 2, and 8 mm, respectively, which were below 5% of the corresponding monthly drainage from bare plots. In 2006, which was a dry year, the total drainage from rye lysimeters in May through July was reduced by 58% when compared to bare lysimeters ($p<0.05$). This suggests that rye is more effective in drainage reduction in a year with rainfall below the average. There was no statistically significant difference between annual drainage of rye and bare treatments averaged over 2006-2008 or in each year. However, in all three years the annual cumulative subsurface drainage from the lysimeters with rye cover crop was consistently lower than that from the bare lysimeters (Figure 2.2). The annual cumulative drainage volume of the rye lysimeters averaged 387 mm across 3 years, which accounted for 51% of the total rainfall observed during the same period and was 9% (37 mm) lower than the average drainage from bare lysimeters (424 mm). The percentage of drainage reduction by rye in this study may have been larger if corn or soybean had been planted following winter rye cover crop, because the total amount of drainage would be much less in the summer and fall due to the existence of corn or soybean.

Note that rye was terminated no later than June 14, but it showed an extended influence on drainage volume in late June and July. Drainage volume at each pumping event was plotted in Figure 2.3. The drainage volume at each pumping was lower in rye treatment from May through July in these three years but very close in other months. This trend was more evident in 2006 than in the other two years. The average drainage of each pumping event was listed in Table 2.2. Pumping was conducted 42 times in 2006, 71 times in 2007, and 69 times in 2008. Statistical test on repeated drainage measurement indicated significant differences between the mean drainage of rye and bare treatment at each event across three years ($p<0.05$). In individual years, the mean drainage for each pumping event was significantly reduced by rye ($p<0.05$) in all years except for 2008. The impact of rye on drainage was likely minimized by extremely high precipitation in May through July of 2008.

2.4.3 Soil Water Storage

The field calibration result of the PR2 probe is shown in Figure 2.4. The slope is steeper and the y axis intercept is lower than the default equation provided by the manufacturer indicating an overestimation of soil moisture at high permittivity but an underestimation at low permittivity using the default equation. This calibration trend is similar to the field calibration equation presented in Huang et al. (2004).

Soil permittivity of the soil profile was measured 37 times in 2006, 43 times in 2007, and 36 times in 2008 for each of the 10 lysimeters. Soil water storage (SWS) in the soil layers from 0 to 60 cm was calculated from the volumetric water content converted by applying permittivity measured by sensors to calibrated equations. Statistics on repeated soil water storage measurement indicated significantly lower soil water storage for the rye treatment than the bare treatment ($p<0.05$) across the 3-year study period and in each individual year (Table 2.2). For rye lysimeters, the soil water storage over 3 years averaged 148 mm which was 7% lower than the bare lysimeters. The soil water storage difference between the two treatments was the highest in 2006 and 1owest in 2008. This suggested that in a drier year, rye had a greater impact on soil moisture.

To illustrate how soil moisture changed according to the weather conditions and land cover, Figure 2.5 shows the soil water storage of the soil profile from 0 to 60 cm in the rye and bare treatments and associated daily rainfall. The temporal pattern of soil water storage suggested a high water depletion rate by rye in May of each of the three years. The overall difference between the soil water storage of rye treatment and bare treatment was 11 mm for all the measuring months, while the difference in May was 19 mm which was 76% higher than the annual average difference. The soil water depletion by rye in May 2007 showed the largest amount in the three years even with a higher precipitation which was likely a reflection of the highest biomass accumulation. Since rye dried the soil out in May, soil water storage remained lower in June and July, extending the impact of the rye crop after removal. In all three years, August through October showed a lower difference in soil water storage between rye and bare lysimeters than May. During August through October soil water storage between bare lysimeters was 9 mm higher than rye lysimeters.

2.4.4 Daily ET and E Estimation

May was the main growing month for rye in this study. A water balance approach was adopted to compute the estimated daily evapotranspiration (ET) of rye and the daily evaporation (E) of the bare lysimeters in May (Table 2.3). The ET in May averaged 2.4 mm day^{-1} for rye lysimeters over the three years, which was 60% higher than the E for bare lysimeters (1.5 mm day^{-1}) with a statistical significance at $p<0.1$ across 3 years. The ET in the rye treatment was consistently higher than the E in the bare treatment by 55%, 90%, and 57% in 2006, 2007, and 2008, respectively, which was not statistically significant due to high deviation in a given year. The average daily reference ET_0 was 5.6 mm day^{-1} at the study area in May of the three study years. The ratio of the average daily ET or E to ET_0 is defined as the crop coefficient. This ratio for the five rye lysimeters in May was 0.43 in contrast to 0.27 for the five bare lysimeters. The Basal crop coefficient for the crop at the initial stage when the soil is nearly bare is 0.25 (USDA, 1993), which is comparable to the ratio of E to ET_0. The 20 cm above ground section of the lysimeters could have blocked the wind and generated a shade over the soil surface. This could cause discrepancies in ET and E when compared to field situations and might be a factor to consider in designing lysimeter such as used for this type of study.

2.5 Summary

Rye growth was impacted by both the rainfall amount and the temperature during the growing season from October through May. Without water stress, rye established the highest amount of above ground biomass as a result of higher temperature in May. Averaged across three years, utilizing rye as a winter cover crop led to an annual subsurface drainage volume reduction of 9% (37 mm). Rye cover crop significantly reduced the total monthly drainage by 21% (42 mm) from May through July compared to the bare treatment ($p<0.1$). The average drainage of each individual pumping event was significantly lower in lysimeters with rye than those bare lysimeters ($p<0.05$). Soil water storage monitored on weekly basis was significantly lower in the rye treatment than the bare treatment in all three years of the experiment ($p<0.05$). The evapotranspiration of the rye treatment in May, which was calculated to be 2.4 mm day^{-1}, was 60% higher than the evaporation of the bare treatment. Since the mass of nitrate loading to surface water bodies is related to the amount of water drained through the tile lines in Iowa, it is expected that the effectiveness of rye in reducing drainage in May through July would be of benefit in reducing NO_3-N loss because May and June are two of the three main months for subsurface drainage in Iowa. The influence of rye on soil moisture was evident in May which indicated a potential benefit to field traffic but in dry years it is still unknown what impact this might have on crop production. To validate the findings in this study, a field-scale experiment parallel to this non-weighing lysimeter study is being conducted in Iowa to investigate the impact of rye cover crop on soil water dynamics and nitrate leaching.

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Table 2.1. Monthly rainfall and subsurface drainage from rye and bare treatments during April through October in 2006, 2007, and 2008 (unit in mm)

Month	30-yr average rainfall	2006			2007			2008			3-year average		
		rainfall	drainage		rainfall	drainage		rainfall	drainage		rainfall	drainage	
			rye	bare		rye	bare		rye	bare		rye	bare
April	89	34	58	53	143	192	190	102	100	104	93	117	116
May	110	111	36 *	64 *	166	88	128	100	66	71	126	63	88
June	127	9	0 **	9 **	55	37	38	269	149	163	111	62	70
July	113	103	7 **	30 **	109	6	5	197	94	98	136	36	44
August	110	81	28	27	175	38	35	56	33	32	104	33	31
September	78	160	50	46	50	13	12	64	24	28	91	29	29
October	68	44	27	20	131	68	69	100	49	48	92	48	45
May, June, &July	350	223	43**	103**	331	131	171	566	308	332	373	161*	203*
Total	695	542	205	250	830	442	478	888	514	544	753	387	424

Note: Significance was test within rows.
* significantly different at $p<0.1$;
** significantly different at $p<0.05$;

Table 2.2. Mean drainage and soil water storage (SWS) at each measuring event in 2006, 2007, and 2008.

Year	No. pumping	Drainage (mm)			No. soil moisture	SWS in 0-60cm depth (mm)		
		rye	bare	difference†		rye	bare	difference
2006	42	4.9	5.9	-1.0 **	37	136	154	-18 **
2007	71	6.2	6.7	-0.5 **	43	147	158	-11 **
2008	69	7.4	7.8	-0.4 ns‡	36	162	166	-4 **
Average	61	6.3	6.9	-0.6 **	39	148	159	-11 **

Note: † difference = rye – bare;
‡ not significantly different at $p<0.1$;
** significantly different at $p<0.05$.

Table 2.3. Evapotranspiration and evaporation of the rye and bare treatment calculated by the soil water balance components in May (unit mm)

Year	Beginning date	Ending date	ET_0† (mm/d)	ΔSWS (mm)‡		ET or E (mm/d) §		ET-E mm/d
				rye	bare	rye (ET)	bare (E)	
2006	May 01	May 30	6.1	-14	-12	3.1	2.0	1.1 ns¶
2007	May 01	May 31	5.8	20	8	1.9	1.0	0.9 ns
2008	April 29	May 27	4.9	-27	-11	2.2	1.4	0.8 ns
Average			5.6	-7	-5	2.4	1.5	0.9 *

Note: † ET_0: reference evapotranspiration by Penman-Monteith Equation;
‡ ΔSWS: soil water storage change;
§ drainage and rainfall for ET or E calculation was included in Table 2.1;
¶ not significantly different at $p<0.1$;
* significantly different at $p<0.1$.

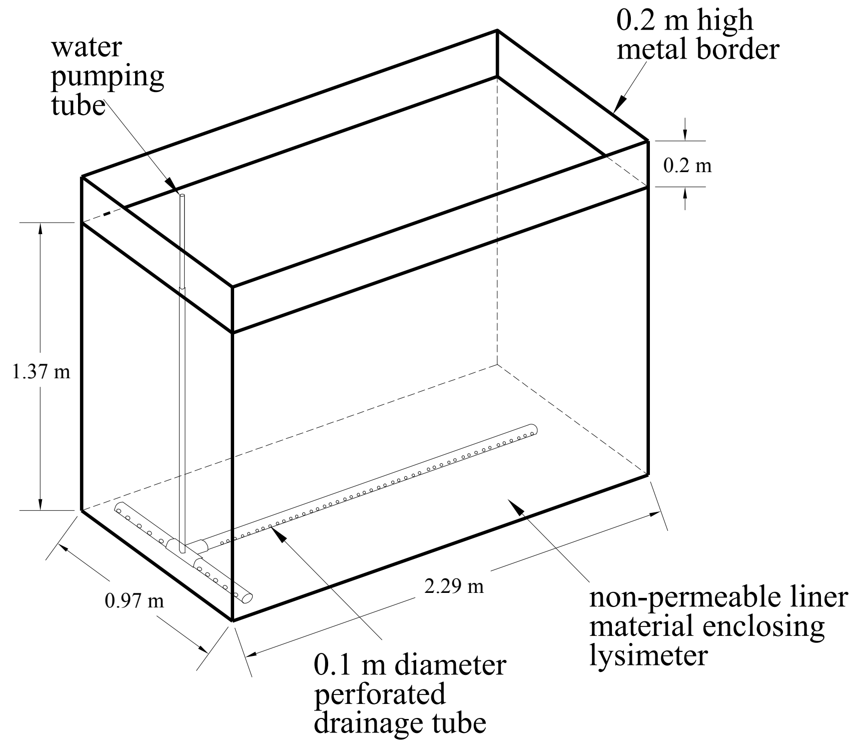

Figure 2.1 Schematic of non-weighing lysimeter and drainage tube set-up (adapted from Cook and Baker, 2001).

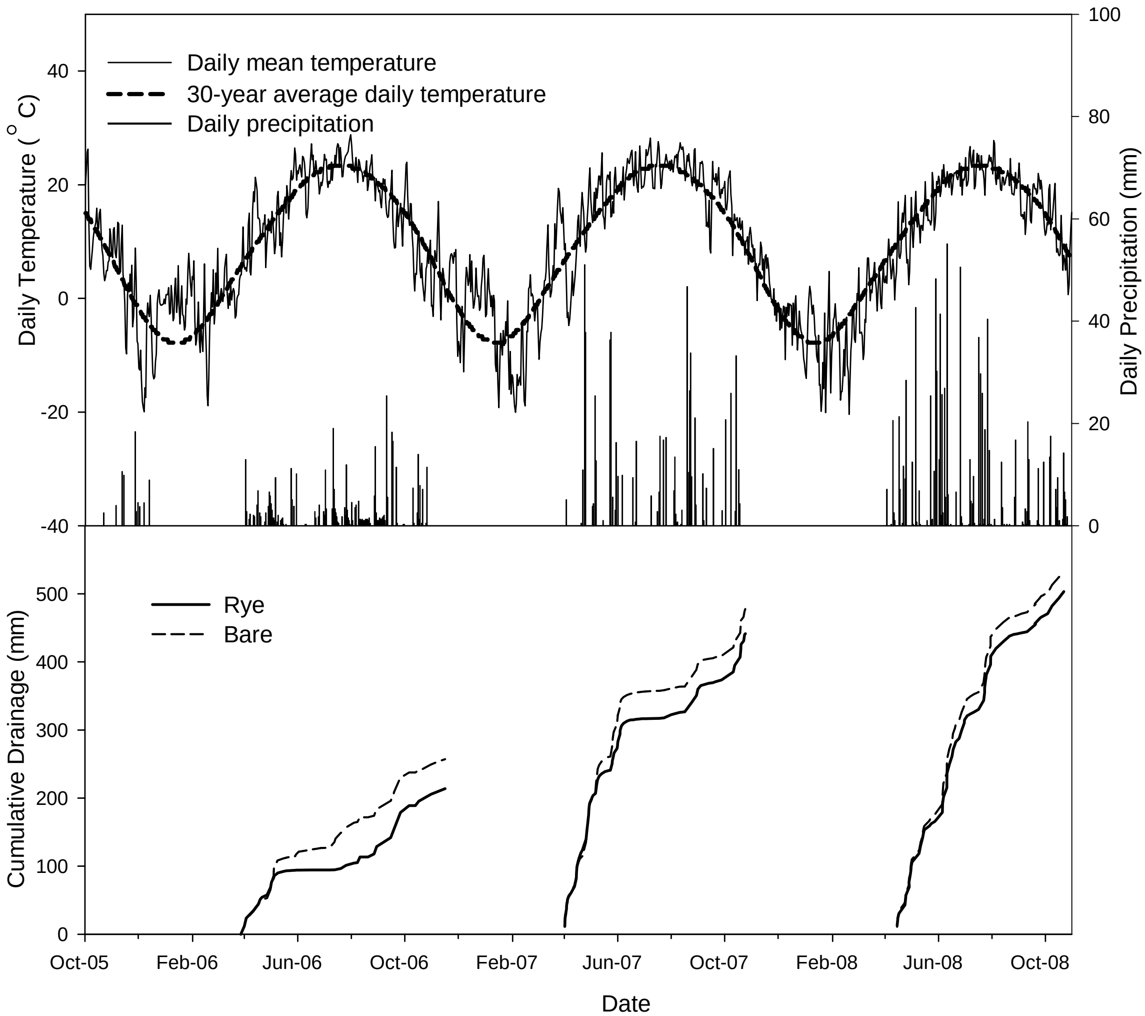

Figure 2.2. Daily mean temperature, daily rainfall, and cumulative subsurface drainage volume in rye and bare treatments in October, 2005 through October, 2008.

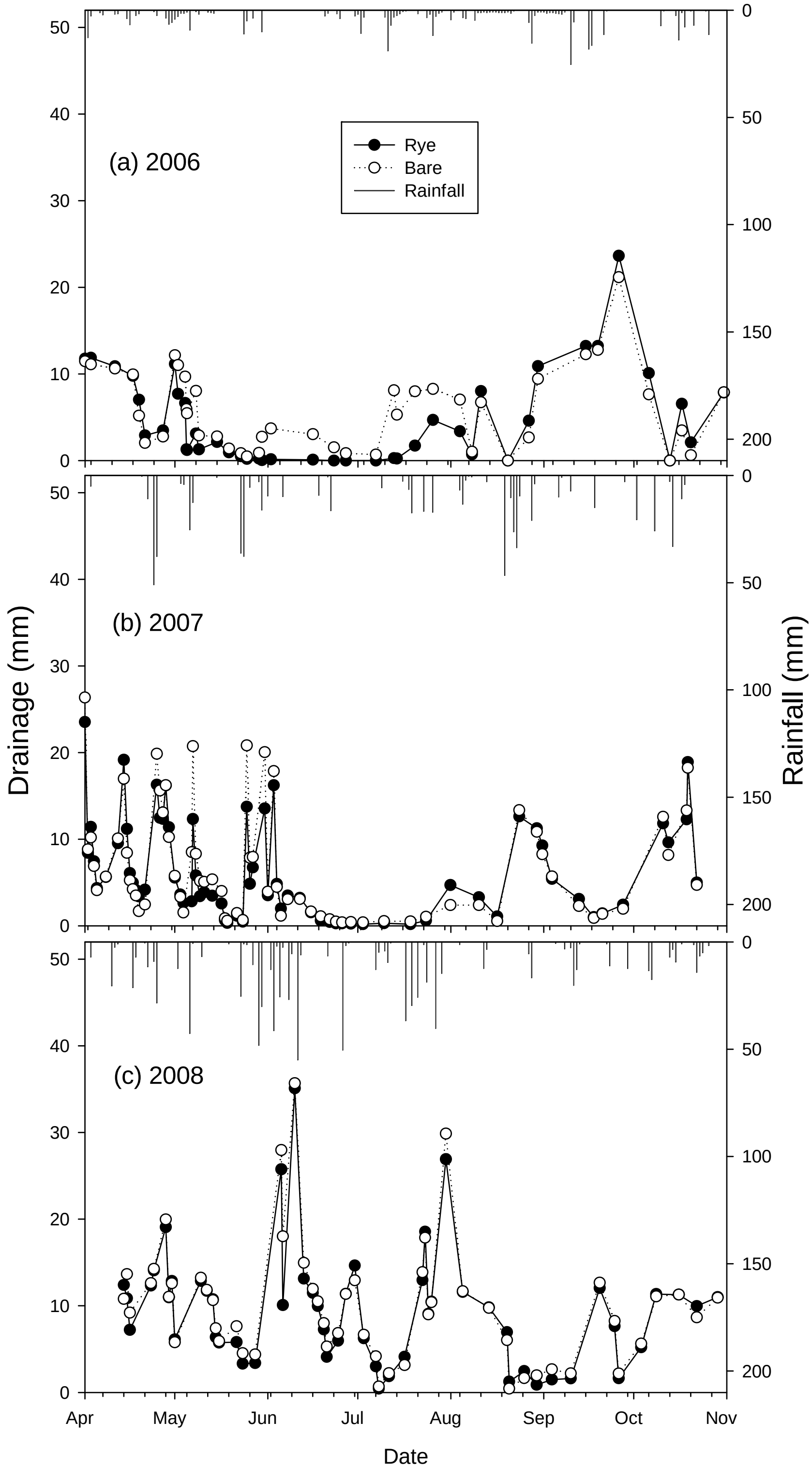

Figure 2.3. Subsurface drainage volume of each pumping event and daily rainfall in April through October of (a) 2006, (b) 2007, and (c) 2008.

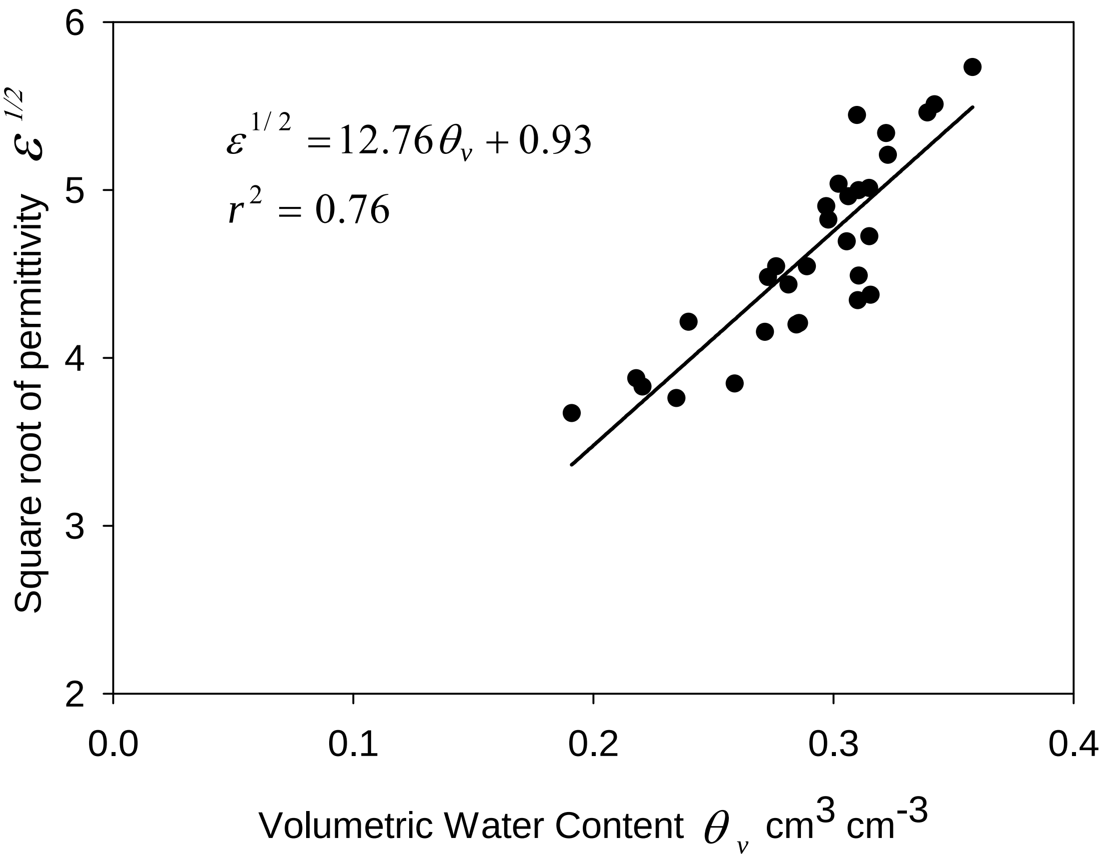

Figure 2.4. Field relationship between the square root of permittivity ($\varepsilon^{1/2}$) as measured by the PR2 probe and observed volumetric water content (θ_v) computed by gravimetric water content and bulk density.

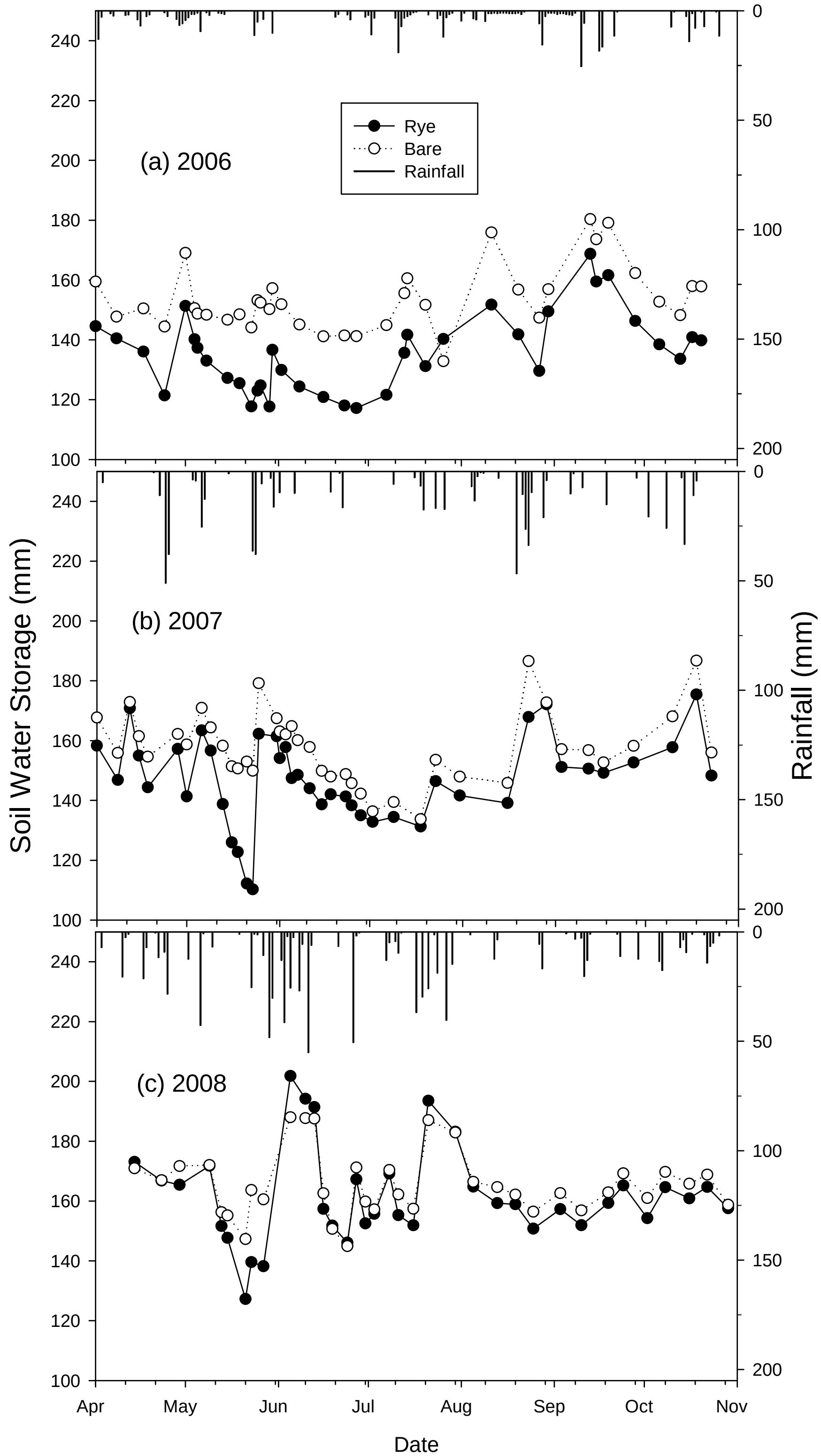

Figure 2.5. Soil water storage of rye and bare treatment in the soil layer of 0-60 cm and daily rainfall in April through October in (a) 2006, (b) 2007, and (c) 2008.

CHAPTER 3. CROP UPTAKE OF NITROGEN AND NITRATE-NITROGEN LOSSES FOR VARIOUS LAND COVERS IN SUBSURFACE DRAINED FIELDS

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3.1 Abstract

Nitrate-nitrogen (NO_3-N) loading from subsurface drainage is an environmental concern in the Midwest. In Iowa, the majority of NO_3-N loading occurs in April, May and June when little to no plant growth in the field. Changing the cropping scheme to a perennial forage or introducing cover crops that grow prior to main crop establishment in the spring could potentially decrease NO_3-N loss. In this 3-year field study, various land covers were investigated and compared in terms of biomass accumulation, nitrogen (N) uptake, subsurface drainage, NO_3-N leaching and NO_3-N concentration in the soil profile. Land cover treatments included: 1) conventional corn-soybean rotation fallowed in winter and early spring (fC and fS), 2) winter rye cover crop prior to corn-soybean rotation (rC and rS), 3) corn with established kura clover as a living mulch (kC); and 4) orchard grass as a perennial forage cover (PF). The objectives of this study were to: i) quantify nitrogen (N) uptake by various land covers; ii) evaluate the impact of different land covers on NO_3-N loss in subsurface drainage flow under recommended crop fertilization; and iii) investigate NO_3-N concentrations in the soil water within the vadose zone under different land covers. The above ground maximum N uptake by rye in rC, rye in rS, kura clover in kC and orchard grass in PF was 16.2 (sampled in late-April to early-May), 34.2 (mid- to late-May), 97.0 (early-June), and 48.1 (early-June) kg N ha^{-1}, respectively. The alternative cropping system of rC and rS showed no yield disadvantage on subsequent corn and soybean, but the corn yield was

reduced by kC treatments. For all plots, the average subsurface drainage was equivalent to about 45% of the total rainfall during the drainage season and 63% of the annual drainage occurred in April through June. Effect of land covers on subsurface drainage volume was not significant. The annual flow-weighted average NO_3-N concentration (FWANC) from the drainage tile was significantly lower for kC (6.8 mg L^{-1}) and PF (5.3 mg L^{-1}) treatments than conventional fC (14.0 mg L^{-1}) and fS (13.3 mg L^{-1}) treatments ($p<0.05$). The rC and rS treatments did not significantly reduce the annual FWANC when comparing to the fC and fS treatments. Average monthly FWANC was significantly reduced by rC and rS treatments ($p<0.05$) when compared with fC and fS treatments. NO_3-N loss through the tile drainage was significantly reduced by 45% and 64% in kC and PF treatments, respectively, when compared to fC plots ($p<0.05$). NO_3-N concentrations in the soil water solution in rS and PF treatments were significantly lower than in the conventional fC and fS treatments. This study suggests that winter rye cover crop, kura clover as a living mulch, and perennial forage land covers have potential for reducing NO_3-N loss in Iowa.

3.2 Introduction

Nitrate-nitrogen (NO_3-N) has been deemed a main source of pollution for both shallow groundwater and surface water bodies. Groundwater serves as drinking water supply for more than 50% of the population in the United States (Nolan and Hitt, 2006). NO_3-N has been found to be an important contaminant in drinking water because it appears widely in groundwater with a median value of 2.9 mg N L^{-1} in agricultural areas and 1.5 mg N L^{-1} in urban areas (Nolan, 2004). USGS assessed the water quality of more than 60% of the Nation's drinking water and water supplies for irrigation and industry during 1991-2001 as part of the The National Water-Quality Assessment (NAWQA). Twenty percent of the sampled shallow wells in agricultural areas exceeded the drinking water standard of 10 mg N L^{-1} for NO_3-N (USGS, 2004). A state-wide rural well water survey in Iowa that was conducted in 1988 and 1989 showed that 18% of Iowa's private rural drinking wells exceeded the EPA Maximum Contaminant Level (MCL) for NO_3-N of 10 mg L^{-1} (Kross et al., 1990).

In addition to contaminating groundwater, NO_3-N impairs surface water bodies. NO_3-N loading from the Mississippi River is suspected to be a main contributor to the hypoxic zone in the Gulf of Mexico (Rabalais et al., 2001). The main source of NO_3-N in the Mississippi River Basin (MRB) is linked to tile drainage (Lowrance, 1992; Keeney and DeLuca, 1993; David et al., 1997; Zucker and Brown, 1998). Approximately 25% of agricultural land is artificially drained in Iowa (Baker et al., 2004) with multiple studies reporting the high NO_3-N loading from the drainage systems. Schilling and Zhang (2004) reported that while Iowa accounts for 5% of the area of the MRB it contributed approximately 25% of the NO_3-N load (26 kg N ha^{-1} $year^{-1}$) over a 28-year period from 1972 to 2000. From 1980 to 1996, the annual average total N yields were 2750, 2290, 2020, 3090 and 1850 kg N km^{-2} $year^{-1}$ from the Cedar, Iowa, Skunk, Raccoon, and Des Moines Rivers in the state of Iowa, respectively (Goolsby et al., 2001). Plot-scale experiments measured NO_3-N loss of 26 to 55 kg N ha^{-1} $year^{-1}$ in northeast Iowa (Weed and Kanwar, 1996), 27 to 31 kg N ha^{-1} $year^{-1}$ in central Iowa (Baker et al., 1975; Baker and Johnson, 1981; Kanwar et al., 1983) and 45 to 68 kg N ha^{-1} $year^{-1}$ in north-central Iowa (Lawlor, et al., 2008).

The mass of NO_3-N loss is closely related to subsurface drainage volume (Baker et al., 1975; Cambardella et al., 1999). Hatfield et al. (1998) documented that the NO_3-N loading had the same pattern as the subsurface drainage discharge in the Walnut Creek watershed in central Iowa. Kanwar et al. (2005) observed a linear relationship between annual NO_3-N loss and drainage flow volume (r^2=0.99) in northeastern Iowa under different land covers. Bakhsh et al. (2002) also found a strong linear relationship between drainage and precipitation, and between NO_3-N loss and drainage. April, May and June has been found to be the main subsurface drainage period in Iowa. During these 3 months, nearly 70% of the drainage occurred in north-central Iowa (Helmers et al., 2005).

To aid in reducing NO_3-N loss, annual cover crops, perennial living mulches, and perennial forage are being investigated in the Midwest. An annual cover crop is any living ground cover that is planted into or after a main crop and then commonly killed before the next crop is planted (Hartwig and Ammon, 2002). Annual winter cover crops were historically added into corn-soybean rotation to achieve soil and water conservation benefits in the Midwest (Unger and Vigil, 1998; Kaspar et al., 2001). Rye is one of the main annual winter cover crops; it is a cereal crop that has excellent weather hardiness and the ability to grow on soils with marginal fertility (Bushuk, 2001). Rye requires less heat than wheat and it can germinate at temperatures slightly above 0 ºC. Appreciable growth of rye ceases when the mean temperature drops below 5 ºC but growth resumes when the temperatures rise (Leonard and Martin, 1963). It can survive under temperatures of -35 to -25 ºC even with limited snow cover (Stoskopof, 1985), and has been observed to grow well during the cold winters in North Dakota and Montana (Leonard and Martin, 1963). In North America, some rye is grown at the northern limit of the Canadian grain belt. Overall, rye is the last crop to stop growing in the fall and the first to start in the spring (Buskuk, 2001).

Nitrogen uptake by winter rye cover crop has been widely reported from field experiments conducted in the Midwest. N uptake by rye was reported to be 42-48 kg N ha^{-1} in Nebraska, 21-74 kg N ha^{-1} in Minnesota, 9-34 kg N ha^{-1} in Wisconsin, and 35-51 kg N ha^{-1} in Illinois (Kessavalou and Walters, 1999; Ruffo et al., 2004; Andraski and Bundy, 2005; De Bruin et al., 2005). In Iowa, Kaspar et al. (2007) reported rye N uptake of 48 kg N ha^{-1} with rye harvested in late April and early May. McDonald et al. (2008) reported average self-seeded rye nitrogen uptake of 5 kg N ha^{-1} in Iowa when rye was chemically desiccated in April. The literature reveals conflicting results on the impact of cover crop on following main crop yield, with some researchers finding a reduction of 5 to 22% (MacDonald et al., 2008), some an increased corn yield (Andrski and Bundy, 2005), and most no significant difference (Ritter et al., 1998; Strock et al., 2004; De Bruin et al., 2005).

Investigation on the reduction of subsurface drainage and NO_3-N loss by winter rye cover crop, however, is limited in the Midwest. Under a controlled indoor environment, Logsdon et al. (2002) and Parkin et al. (2006) demonstrated reduction of drainage and NO_3-N leaching by winter rye cover crop. Reduction of drainage and soil water content in rye was also observed in a field study using confined nonweighing lysimeters (Qi and Helmers, 2009). In field studies on a plot-scale, Strock et al. (2004) found that drainage and NO_3-N loss in rye treatment was reduced by 11% and 13%, respectively. Kasper et al. (2007) reported that the difference was not significant between cumulative drainage in rye and control treatments, but the rye cover crop decreased the flow-weighted average NO_3-N concentration by 59% and NO_3-N loss by 61%. Of note from this study is that N application rates to corn were 235 and 246 kg N ha^{-1} which are above the Iowa recommended N application rates of 112 to 165 kg N ha^{-1} to corn in a corn-soybean rotation (Blackmer, et al., 1997)

Living mulches are cover crops planted either before or with a main crop and maintained as a living ground cover throughout the growing season (Hartwig and Ammon, 2002). Living mulches can reduce erosion, suppress weeds, and in the case of legumes benefit N cycling. Italian ryegrass, alfalfa, and kura clover are examples of living mulches. Perennial leys, including lucerne and grasses, had considerably less drainage volumes and NO_3-N loss than the treatments with annual barley (Bergstrom, 1987). Corn in Italian ryegrass was unable to establish a competitive root system thus its growth and yield were reduced in a study in Switzerland (Liedgens et al., 2004). With suppression and careful management, kura clover in corn did not reduce the whole-plant biomass, grain yield (Zemenchik et al., 2000) or corn root density (Eleki, 2003) in North Central USA, especially if herbicide-resistant corn was planted (Affeldt et al., 2004). However, there is very limited information concerning the effect of kura clover-corn system on drainage and NO_3-N leaching in the Midwest.

Perennial forage grassland has the potential to serve as the most effective nitrogen loss reduction approach because no fertilization is necessary and it has a longer growing period than winter cover crop, although at present there is little economic market for the product. Randall et al. (1997) reported that row crop systems showed 1.6 times higher drainage flow and about 35 times higher NO_3-N loss than alfalfa treatment and Conservation Reserve Program (grass based) system over a 6-year study in southwestern Minnesota. In Iowa, large-scale prairie restoration in row crop field showed less NO_3-N export in a paired watershed study (Schilling, 2002). In field studies, Baker and Melvin (1994) documented that the NO_3-N concentration in tile drainage from alfalfa was much lower than that from corn or soybean. Kanwar et al. (2005) reported that reduction of flow-weighted average NO_3-N was significant in alfalfa and strip inner cropping systems in comparison to conventional corn-soybean rotation, but the reduction of NO_3-N loading mass was offset by elevated drainage flow volume. However, there is very limited investigation on the impact of orchard grass mixed with clovers as perennial forage cover on subsurface drainage and NO_3-N leaching in the Midwest.

To gain a better understanding on the effects of land covers on NO_3-N loss, a field experiment was conducted in north-central Iowa with winter rye cover crop in corn-soybean rotation, kura clover as a living mulch for corn and a perennial forage land cover. The objectives of this study were to: 1) quantify the spring N uptake and crop production under different land covers; 2) evaluate the impact of a different land covers on NO_3-N concentration and loss in subsurface drainage under a recommended crop fertilization; and 3) investigate NO_3-N concentrations in the soil profiles under different land covers.

3.3 Materials and Methods

3.3.1 Site description

The field study was conducted at the Agricultural Drainage Water Quality – Research and Demonstration Site (ADWQ-RDS, former Agricultural Drainage Well Site) near Gilmore City in Pocahontas County, north-central Iowa. Rainfall and temperature were recorded by an automatic meteorological station at the site. Precipitation and air temperature norms for Pocahontas and Humboldt, located 19 km west and east of the research site, respectively, were averaged to represent the long-term precipitation at the site. A 30-year average from 1971 to 2000 provided by National Climatic Data Center (NCDC) for Pocahontas (Station No. 125) and Humboldt (Station No. 070) was considered the long-term norm. The size of each plot was 38 m in length and 15.2 m in width. The plots were established in 1989 after the installation of corrugated plastic drain tiles through the center and both boundaries parallel to the long dimension (7.6 m spacing) at a depth of 1.06 m. Drainage water from each center line is collected in an aluminum culvert with automatic pumping, volume monitoring and water sampling systems. All water exited from the border lines flowed directly into one of two large sumps and pumped into a nearby wetland without volume measurement. Detailed descriptions of the water pumping and sampling systems can be found in Helmers et al. (2005), Singh et al. (2006) and Lawlor et al. (2008).

The field experiment was initiated in the fall 2004 with a completely randomized block design, but research presented in this study covered the data from 2006 through 2008, since 2005 was considered a transition year. Land cover treatments were: 1) conventional corn-soybean rotation fallowed in winter and spring (fC and fS), 2) winter rye cover crop prior to corn-soybean rotation (rC and rS), 3) corn with established kura clover as a living mulch (kC); and 4) perennial forage treatment (PF) (Table 3.1). The plots were blocked by drainage characteristics based on the long-term drainage performance. The four blocks were high (H), medium high (MH), medium low (ML) and low (L) drainage. One plot in each block was randomly assigned to each treatment (6 treatments×4 blocks×1 replication) in this study. The fC and fS treatments were rotated every year and as well the rC and rS treatments, resulting four cropping scenarios as fCfSfC, fSfCfS, rCrSrC, and rSrCrS during the three years of study. Forage plots were mowed and baled once or twice a year but were not grazed by animals.

3.3.2 Agronomic management

Agronomic field activities were completed in a timely manner prior to and during the crop season beginning in October 2004 with plot tillage and rye seeding. For the fC and fS plots, corn residue was chopped and chisel plowed in the fall followed by disking and field cultivation prior to corn planting in the spring, and soybean residue was disked and field cultivated in the spring prior to soybean planting. For the plots with rye (rC and rS), tillage operations were conducted in the fall prior to rye planting. Corn residue in rC treatment was chopped, disked twice and smoothed with a field cultivator, and soybean residue was disked once and field cultivated. 'Rhymin' rye (Secale cereale) was drill seeded at a rate of 100 kg ha^{-1} in 19 cm rows with a skip row every 76 cm for subsequent corn or soybean planting. Tillage for seedbed preparation for kura clover and forage was completed in the spring just prior to planting on April 18, 2005. 'Endura' kura clover (Trifolium ambiguum) was hand seeded at a rate of 13 kg ha^{-1}, the perennial forage plots were hand seeded with 'Duration' red (Trifolium retense), and 'Pinnacle' ladino (Trifolium repens) clovers with 'Extend' orchardgrass (Dactylis glomerata) at 9, 0.6, and 4.5 kg ha^{-1}, respectively.

In the spring, glyphosate was applied at a rate of 239 mL ha^{-1} in rC and rS plots to terminate rye growth. Glyphosate resistant corn (Zea maize) and soybean (Glycine max) were used and planting dates were dictated by field conditions. Seeding rates were 77,000 seed ha^{-1} for corn and 439,750 seed ha^{-1} for soybean. Corn planting in the kura clover plots started in 2007, giving a two-year (2005 and 2006) period for kura clover to establish according to recommended management. After corn planting, the entire kura clover plots were suppressed by glyphosate in 2007 and the plots were band sprayed in 2008. Commercial-grade 28% aqueous ammonia-nitrogen (N) was applied at 140 kg N ha^{-1} in the spring closely following corn emergence to corn plots only. This application is within the recommended rates of 112 to 168 kg N ha^{-1} (Blackmer et al., 1997). N fertilizer was applied mid-row to corn with a conventional knife applicator. For weed control in all corn and soybean plots, glyphosate was subsequently applied two more times during the growing season, as dictated by weed pressure. Similar operations were followed in all years and agronomic timing details are included in Table 3.2.

3.3.3 Biomass and soil residual NO_3-N

Above ground rye shoots were sampled weekly from early spring until chemically desiccated with glyphosate. Weekly sampling of kura clover and forage shoots coincided with rye sampling and continued until late June. From July until early October, corn, soybean, kura clover and forage were sampled once every three weeks. Rye, corn, and soybean were sampled along a 30-cm long section at four randomly selected locations; kura clover and forage were sampled using a 30×30 cm^2 area randomly selected at three locations in each plot. Samples were dried at 60 ºC for a week for dry biomass determination. Total nitrogen content was analyzed on all sampling periods for corn and soybean plots, two occasions for kura clover and forage, and two occasions for corn soybean plots. The total nitrogen analysis was conducted in the Soil Plant Analysis Laboratory at Iowa State University by the dry combustion method using a TruSpec CN (LECO Corp., MI). In 2007 and 2008, soil cores with 2 cm in diameter were sampled for residual soil NO_3-N analysis at three times: before rye or spring cover re-growth in early spring (ES), before corn fertilizing in late spring (LS), and after corn or soybean harvest in late fall (LF). In each plot, soil cores were extracted by a JMC soil sampler (Clements Associations Inc., Newton, IA) at four evenly distributed locations along the plot diagonal of three depths (0-15, 15-30, and 30-60 cm). The four samples from the same depth were combined to form one for each plot. NO_3-N was extracted from soil samples by water saturated with a calcium solution and was analyzed by the cadmium reduction procedure with a flow injection analyzer (Ward Laboratories, Inc., NE).

3.3.4 Subsurface drainage and NO_3-N loss

For each plot, a flow meter was used to measure the subsurface drainage flow volume and the meter reading was manually recorded on a weekly or biweekly basis. Starting in April 2006, the flow meter was switched to a magnetic one which was connected to an HOBO data logger, facilitating the measurement of drainage flow volume in increments of 14 L (0.5 cubic foot) which represented a drainage flow depth of 0.005 cm. A fraction of the drainage flow was directed to a 20 L carboy through a plated orifice nozzle. Subsamples of the drainage water were collected after approximately every 1.3 cm of drainage flow, and thereafter were stored in a cooler at 4 ºC until analyzed. NO_3-N concentration was analyzed in the Wetland Research Laboratory, Iowa State University through the second-derivative spectroscopy technique (Crumpton et al., 1992). Drainage water pumping and water sampling system is well documented in Lawlor et al. (2008). NO_3-N concentration was multiplied by the representative drainage volume to calculate NO_3-N loss.

3.3.5 Nitrogen mass balance

The nitrogen mass balance was computed following the method provided by Gentry et al. (2009). Nitrogen input includes atmospheric deposition, fertilizer and N fixation by legumes, and N output includes N removal by grain harvest, N loss through drainage, and denitrification. The atmospheric deposit of nitrogen at the ADWQ-RDS site in 2006, 2007, and 2008 were estimated by linear interpolation of the N deposition maps provided by the National Atmospheric Deposition Program/National Trends Network site (NADP, 2009). The N_2 fixation by soybean was estimated to be 60% of the total N in the above ground biomass of soybean according to Iowa State University Extension (2009). This percentage is close to the measured values of 77% and 48% in Minnesota (Vasilas and Ham, 1984), and 58%, 60%, and 77% in Illinois (Gentry et al., 2001; 2009). The N in the above ground biomass of clovers derived from N_2 fixation was considered to be 155 kg N ha^{-1} according to Seguin et al. (2000). For the N output components, Nitrogen removal by grain harvest and N loss through drainage were site specifically monitored, and the N loss through deep seepage and denitrification was estimated by the RZWQM model (Qi et al., unpublished data).

3.3.6 Soil water solution sampling

Soil water solution was sampled using two suction lysimeters (1 m apart) installed along the median line between the center and boundary lines at depths of 30 and 60 cm in each of the medium high, medium low and low flow block plots in 2007 and 2008. The suction lysimeter consisted of a porous ceramic cup, connected to a sealed section of 3.8 cm PVC pipe. Two sections of hard plastic tubing penetrated inside the PVC pipe, one for vacuum application and the other for solution sampling. Tubing extended 10 cm outside the pipe with a sealable top. To install the suction lysimeter, a soil core was removed vertically by a truck mounted Gidding's probe (#25-SCS Model HDGSRPS, Giddings Machine Company Inc, CO). Fine silica sand was placed in the bottom of the hole to ensure a good contact between the ceramic cup and the soil wall. The gap above the ceramic cup was filled with soil and the gap on the soil surface was sealed with granular bentonite. A vacuum of -75 kPa was applied to the suction lysimeters every week and any available soil water solution sample was collected every three to four days. NO_3-N concentration of the soil water solution from the suction lysimeters soil water solution samples were analyzed in the Agricultural and Biosystems Engineering Water Quality Laboratory, Iowa State University using a

Quickchem 2000 Automated Ion Analyzer flow injection system (Lachet Instruments, Milwaukee, WI).

3.3.7 Statistical analysis

The corn-soybean rotation treatments were separately analyzed in the corn or soybean phase. Six types of land covers, fC, rC, fS, rS, kC and PF, were considered the treatment factor in this study. Subsurface drainage volume, flow-weighted NO_3-N concentration and NO_3-N loss in the subsurface drainage, and NO_3-N concentration in the suction lysimeter were analyzed as a completely randomized block design using the PROC MIXED procedure in SAS9.1 software (Littell et al., 2006). Because subsurface drainage may not occur in all plots during the same period, the NO_3-N concentration data were unbalanced. The MIXED procedure has advantages in analyzing unbalanced data compared to PROC GLM. Repeated measures analysis was used in the PROC MIXED procedure to test the significance of differences among monthly averaged NO_3-N concentration in the subsurface drainage and suction lysimeter soil water solution. Means were grouped using a least significant difference test at p=0.05 ($LSD_{0.05}$).

3.4 Results and Discussion

3.4.1 Precipitation and temperature

Daily precipitation and temperature for the study period are presented in Figure 3.1. The annual precipitation for 2006, 2007, and 2008 was 626, 1050, and 926 mm respectively, with 550, 935 and 827 mm in the drainage season from March to November, respectively. The average long-term normal annual rainfall for Pocahontas and Humboldt, Iowa, is 821 mm, of which 753 mm occurs in the drainage season. The annual precipitation for 2006 was well below the long-term average. However, the rainfall during the winter cover crop growing season from March to May for 2006 was 207 mm, which was near to the long-term total rainfall of 236 mm during the same period. Rainfall during April, May and June, which is the main drainage period in the spring, were 162, 241 and 408 mm, accounting for 30%, 26% and 49% of the precipitation during the drainage seasons in 2006, 2007, and 2008, respectively. The year of 2007 was much wetter in August and October when 367 and 119 mm rainfall occurred, which was 3 and 2 times as much as the long term normal rainfall in these two months, respectively. However, both 2006 and 2007 experienced a dry period in June and July. In these two months, total rainfall was 57 mm for 2006 and 85 mm for 2007, while the long-term average was 226 mm at the study site.

The long-term monthly average temperatures during the rye growing season in March, April, and May are 1.0, 8.6 and 15.6 °C. The temperatures during these three months in 2006 were 1.3, 11.7 and 15.8 °C which were higher than the long term average. In 2007, the average temperatures in March and May were 3.8 and 18.1 °C which were higher than the average, but in April the average temperature was 7.4 °C, lower than the long-term average. Cold weather was observed in early April of 2007 with an average temperature of -0.9 °C in the first 10 days of April and -5.1 °C on average from April 4 through April 7, 2007 with the lowest temperature of -10.0 °C observed on April 7. In 2008, averaged daily temperatures on a monthly basis were consistently lower than the long-term average. In March, April, and May of 2008, the monthly temperature was lower than the long-term norms by 1.0, 3.8, and 2.1 °C, respectively.

3.4.2 Biomass and N uptake of spring land covers

The maximum average above ground dry biomass produced in the spring was 1.04, 3.82, and 3.06 Mg ha^{-1} when averaged across three years for rye, kura clover and forage grass, respectively. Biomass accumulation on spring land covers was influenced by the weather conditions apparent in Figure 3.2a where accumulation was limited in abnormally cold years (2007 and 2008). Biomass of each spring land cover for 2006 was significantly higher than those for 2007 and 2008 ($p<0.05$). The difference between 2007 and 2008 was not statistically significant for each land cover at a level of $p=0.05$, except that the kura clover biomass in 2008 was significantly higher than that in 2007. However, if the statistical significance level was set as $p=0.1$, rye in both rC and rS plots for 2007 was significantly higher than 2008. The rainfall and temperature conditions during early spring of 2006 were favorable for establishing spring land covers. Due to the short term extreme low temperature in April 2007 and long period of cold weather in 2008, the growth of land covers in spring was affected to different extents. Calculated growing degree days (GDD) during the period from beginning of the year to the harvest date by setting the base temperature to 5.5 °C were 167, 210, and 114 for rye in the rC plots in 2006, 2007, and 2008, respectively. For rye in the rS treatment, which had approximately 20 days longer growing period, the GDD were 297 in 2006, 504 in 2007, and 224 in 2008. Although the GDD for rye in 2007 was higher than that in 2006, the rye growth was seriously impacted by the cold weather in early April of 2007. Setting the base temperature for kura clover growth to 10 °C, the GDD from January to the latest sampling date (between June 5 and June 9) for 2006, 2007, and 2008 were 280, 408, and 233, respectively. Although for kura clover the GDD during this period in 2007 was 71% higher than the GDD in 2006, growth was seriously impacted by the short term freezing weather in early April of 2007 and kura clover recovered slowly in the subsequent warm days. Besides weather conditions, the agronomic management exerted a negative impact on kura clover growth since herbicide was applied in 2007 and 2008 to suppress kura clover for the planting and establishment of corn in late May. Although all spring land crops experienced colder than normal conditions in April of 2007, the rye and orchard grass recovered more quickly than kura clover.

Biomass of various vegetation species in the spring was significantly different when averaged over the observational years ($p<0.05$, Figure 3.2a). Kura clover produced the highest biomass amount of 3.82 Mg ha^{-1} in late spring, which was comparable to the forage orchard grass of 3.06 Mg ha^{-1}. The biomass of rye in rS treatment was 1.67 Mg ha^{-1}, significantly higher than that of rye in rC treatment with biomass yield of 0.46 Mg ha^{-1}($p<0.05$); moreover, rye biomass in both rS and rC plot was significantly lower compared with the forage and kura plots ($p<0.05$). Winter rye cover crop growing in the rS treatment was chemically desiccated in the middle to late May and the rye in the rC treatment was killed in late April with a difference around 20 days. Within the 20 days after the rye followed by corn was killed, rye followed by soybean accumulated 72% of the total observed biomass when averaged across 3 years.

Nitrogen (N) uptake by spring land covers was statistically different among years ($p<0.05$) (Figure 3.2b). N uptake in 2007 was significantly lower than 2006 ($p<0.05$), but not statistically different from 2008 for all land cover treatments. For the rS treatment, N uptake by rye was 61.6 kg N $ha^{-1}$for 2006, significantly higher than the N uptake of 31.8 and 18.1 kg N $ha^{-1}$for 2007 and 2008, respectively ($p<0.05$). N uptake of rye in rC was 31.1 kg N $ha^{-1}$for 2006, significantly higher than the N uptake of 11.3 kg N ha^{-1} for 2007 and 6.2 kg N $ha^{-1}$for 2008 ($p<0.05$). In the spring, kura clover extracted N of 43.9 kg N ha^{-1} in 2007 and 95.2 kg

N ha^{-1} in 2008, significantly lower than that in the spring of 2006 by 71.1% and 37.3%, respectively ($p<0.05$). Perennial forage (PF) assimilated 103.8 kg N ha^{-1} in 2006, 2.8 times higher than in 2007 and 3.0 times higher than in 2008. Overall, annual differences are attributed to the impact of different weather conditions on the biomass accumulation in the spring.

Similar to biomass accumulation, different land cover species showed significant differences in total N uptake in the spring of all the three study years ($p<0.05$) (Figure 3.2b). When averaged across 3 years, kura clover assimilated 97.0 kg ha^{-1} of nitrogen in the above ground biomass, significantly higher than the PF orchard grass with a nitrogen uptake of 48.1 kg ha^{-1} ($p<0.05$). Nitrogen extracted by rye in the rS treatment averaged 34.2 kg ha^{-1} across 3 years, significantly higher than the rye in rC treatment of 16.2 kg ha^{-1} ($p<0.05$). Total nitrogen (TN) content in the dry biomass of the spring land covers was higher in early spring and decreased with plant growth. Total N content in the rye shoot was measured as high as 6% in late March, and as low as 2% in late May. Between April 26 and April 30, the nitrogen content was 4.1% and 3.7% for the kura clover and forage orchard grass, respectively, when averaged across 3 years; while the N content decreased to 2.6% and 1.9% for kura clover and orchard grass when the plant shoot was sampled between June 5 to June 9 in the 3 years.

3.4.3 Corn soybean yield and N uptake

Corn and soybean in the plots with rye as a winter cover (rC and rS) did not show grain yield disadvantage compared with the conventional spring fallowed plots (fC and fS), however, corn that grew with kura clover as living mulch (kC) was significantly affected ($p<0.05$) in terms of biomass accumulation and grain production (Table 3). On average, the corn yield was 8.7 and 8.3 Mg ha^{-1} for fC and rC treatment, but was 2.5 Mg ha^{-1} for the kC treatment. The corn yield in kC plots was 1.0 Mg ha^{-1} in 2007 and 4.2 Mg ha^{-1} in 2008, respectively. Soil moisture, nutrient, and sunlight competition could be responsible for the poor corn establishment and low grain production in the kC plots. Soil moisture in the top 15 cm in the kura clover treatment was 17% lower than in the fallow plots at corn planting on May 14, 2007. The soil moisture content in the kC plots was nearly always lower than other corn or soybean plots from late April to late July in the three observed years due to the water use of kura clover during this period (Data not presented). Another reason could also be the hard soil surface because of reduced tillage and root mass of the kura clover in kC plots. Average soybean grain yield for rS was 2.7 Mg ha^{-1} which was lower than the yield of 3.1 Mg ha^{-1} for fS but this was not statistically significant.

Yield for corn and soybean varied over years due to the impact of weather conditions. Although the total rainfall during the 2006 growing season of corn and soybean from May through September was 47.0% less than that in 2008 (300 mm vs 566 mm), the yield of corn or soybean in 2006 was similar to the yields in 2008 for corn and soybean for the fS, rS, fC, and fS treatments. However, although the total rainfall during the 2007 growing season (640 mm) was the highest among the 3 years, the corn grain yield in 2007 was significantly reduced by 22% when compared to average corn yield in 2006 and 2008 for fC and rC treatments ($p<0.05$).

Winter rye cover crop did not exert negative impact on total N uptake of subsequent corn and soybean based on statistical analysis, but corn planted in kura clover as a living much was affected in terms of N uptake. The total nitrogen uptake by corn biomass was 197, 201, and 89 kg N ha^{-1} for fC, rC, and kC treatments, respectively. Soybean assimilated 187 and 153 kg N ha^{-1} for fS and rS treatments, respectively. Total above ground biomass of corn, including stover and grain, in fC and rC were significantly greater than soybean in fS and rS ($p<0.05$), but total N uptake by the biomass in fC and rC were not significantly greater than soybean in fS and rS treatments (Table 3.3). Although the grain yield, the above ground biomass, and the total N uptake of corn in kC were less than corn in fC and rC plots ($p<0.05$), the nitrogen content in corn stalk of kura clover plots, which was analyzed to be 1.40%, was significantly higher than corn stalk nitrogen content of fC and rC treatments by 26% and 47%, respectively ($p<0.05$). However, the N content in the corn grain from kC treatment was not significantly higher than from fC and rC treatments. Corn or soybean residue was left in the field, thus only the nitrogen that was contained in the grain was removed from the field. The average N export by the grain was 102 kg N ha^{-1} for soybean, 103 kg N ha^{-1} for corn in fC and rC, but was 35 kg N ha^{-1} for corn in kC due to lower grain yield.

3.4.4 Residual Soil NO_3-N

To investigate the residual soil NO_3-N, soils were sampled to 60 cm three times a year: before rye or spring cover re-growth in early spring (ES), before corn fertilizing in late spring (LS), and after corn or soybean harvest in late fall (LF) for 2007 and 2008. There was no yearly effect on the residual soil NO_3-N but it varied within individual year (Table 3.4). The residual NO_3-N in late spring was higher than early spring and late fall which might be caused by mineralization during the spring period as temperatures rise.

The impact of land cover treatment on residual soil NO_3-N was evident when averaged over sampling years 2007 and 2008. Soil with the PF treatment, as a result of no fertilization, showed the lowest NO_3-N residual among all the treatments (11.6 kg N ha^{-1}) compared with an average of 52.8 kg N ha^{-1} over all other treatments ($p<0.05$). Residual soil NO_3-N in most treatments increased from early to late spring, but the magnitude of increase were significantly different (Table 3.4). Soil under kura clover increased with the highest amount of soil residual NO_3-N during the spring period in 2008 while the increase of soil residual NO_3-N under rye in rS treatment in 2007 and 2008 and the in PF treatment in 2008 were significantly lower than other treatments ($p<0.05$). Moreover, residual soil NO_3-N in the rS treatment decreased in spite of the impact of increased temperature in the spring of 2008. This provides an indication that rye in rS plots assimilates the available NO_3-N in the soil profile and significantly reduced the soil mineral N accumulation in the spring.

3.4.5 Subsurface drainage

Subsurface tile drainage typically initiated in late March, and continued to late fall depending on the rainfall pattern (Table 3.5). The volume of subsurface drainage varied due to precipitation, and showed large variability from plot to plot. Statistical tests showed that treatment did not independently influence annual or monthly drainage flow volume, except that the drainage of kC and rS in May 2007 was significantly lower than fC and fS treatments, respectively ($p<0.05$). Overall, the effect of block and treatment × block was evident ($p<0.05$). The annual discharge for the 24 plots ranged from 30 to 240 mm in 2006, 104 to 1010 mm in 2007, and 89 to 1053 mm in 2008. Of note is that the monitored center line was assumed to drain 50% of the plot area, however, the actual drainage area of the center line may vary with topography and hydrogeologic conditions. High drainage volume that exceeded or was close to the annual precipitation could be attributed to larger actual drainage area; smaller actual drainage area and lateral flow loss could similarly lead to an unexpected low flow from the monitored center lines. The average annual drainage of all land cover treatments was 350 mm during the three-year study, which represented 45% of the rainfall during the drainage season. The total drainage in April, May and June was 222 mm which accounted for 63% of the annual drainage when averaged over the three years. This percentage was much higher in 2006 and 2008 with values greater than 90%. However, the percentage of annual drainage occurring in April through June of 2007 was 31% due to wetter weather in late summer and fall period.

3.4.6 NO_3-N concentration in tile drainage

Impacts of land cover treatment on NO_3-N concentration in the subsurface drainage flow were investigated both yearly and monthly. Table 3.6 includes annual flow-weighted average NO_3-N concentration (FWANC) for each treatment. When averaged over three years, annual FWANC in drainage flow from kC and PF treatments were significantly lower than that from all other plots ($p<0.05$). Average annual FWANC in kC and PF treatments were 6.8 and 5.3 mg N L^{-1}, below the MCL value of 10 mg N L^{-1}. Reduction of annual FWANC by rye cover crop was 8.5% for rC and 13.5% for rS when compared with their checks, but were not statistically significant. In each individual year, kC and PF treatments generally revealed significantly lower annual FWANC than all other land cover treatments ($p<0.05$), and the effect of rye on annual FWANC reduction was not evident. Because there had been no fertilizer applied to PF plots since 2004, it was not unexpected to detect average annual NO_3-N concentration as low as 5.3 mg L^{-1}; however, for the kC plots, although fertilizer was applied at a rate of 140 kg N ha^{-1} in early summer in both 2007 and 2008, the low NO_3-N concentration in the tile effluent could be attributed to the large amount of N uptake by the living mulch land cover. The annual flow-weighted NO_3-N concentration from the rC and rS treatments was reduced by14.8% and 26.3% compared with fallow controls in 2007, but that was not significantly different. Additionally the annual flow-weighted NO_3-N concentration of rS treatment in 2007 was below the MCL of 10 mg N L^{-1}.

Although the annual FWANC in rC and rS treatments were not significantly different from fC and fS treatments, significant differences were shown when investigating monthly FWANC (Table 3.7). When averaged over all 16 months in which subsurface drainage was observed in from 2006 to 2008, introducing rye as a winter cover crop significantly reduced the average monthly FWANC by 1.6 and 2.1 mg N L^{-1} in rC and rS treatments when compared to fC and fS, respectively ($p<0.05$). That the differences between monthly FWANC in rye treatments and in their controls were significant but not the annual FWANC was attributed mainly to the largely reduced standard error of monthly FWANC. Reduced standard error was a result of increased number of samples for monthly FWANC because the variances of monthly and annual FWANC were not different. For example, standard error of monthly FWANC for rC treatment was 0.36 mg N L^{-1}, 59.5% lower than that of annual FWANC (0.89 mg N L^{-1}). However, the standard deviation of monthly FWANC compared with annual FWANC was 2.67 versus 3.08 mg N L^{-1} for rC treatment.

The monthly FWANC in April, May and June consistently exceeded the MCL of 10 mg N L^{-1} for the corn-soybean rotation plots regardless of winter rye as a cover crop. NO_3-N concentrations in the soybean phase were slightly lower than in the corn phase with the same spring land cover situation but not significantly different, which is consistent with other studies (Randall and Vetsch, 2005). The monthly FWANC for rS and rC were lower than fS and fC, respectively, for most cases in 2006 and 2007 but not in 2008 (Table 3.7). This could be a result of low biomass establishment of rye in 2008 (Figure 3.2a). Although significant monthly FWANC reduction by rye was only observed in rS for the year of 2006, the reduction of monthly FWANC was observed in most cases during April, May and June. In 2007, the monthly FWANC in the rC treatment was significantly lower than in the fC treatment in April and May; monthly FWANC in the rS plots was significantly lower than in the fS plots in May ($p<0.05$). The monthly FWANC were generally below 10 mg N L^{-1} in the kC and PF treatments. Before N fertilizer application to the corn in the kC plots on June 26, 2007, NO_3-N concentration was lower than in the PF plots, which was an indicator of more nitrogen uptake by kura clover than orchard grass. The increased NO_3-N concentration in the drainage flow from the kC plots in August 2007 may be attributed to the fertilizer application and low nitrogen uptake by corn in kC plots.

3.4.7 NO_3-N loss in tile drainage

Annual NO_3-N loss was substantially affected by the land covers and drainage season precipitation (Table 3.8). When averaged across three years, fC and fS treatments released 43.7 and 41.4 kg ha^{-1} NO_3-N into the downstream water bodies via the subsurface drainage pipes. However, the annual NO_3-N loading was 24.2 and 15.9 kg N ha^{-1} for kC and PF treatments, respectively. The kC and PF land cover treatments significantly reduced annual NO_3-N loss by 42% and 62% compared with the average NO_3-N loss of conventional fC and fS treatments, respectively ($p<0.05$). Winter rye followed by soybean (rS) slightly reduced annual NO_3-N loss by 4.5 kg N ha^{-1} but not significantly. Annual effects on NO_3-N loss were evident during the 3-year study. When averaged across treatments, the annual NO_3-N loss in 2006 was 13.0 kg N ha^{-1}, which was 73% and 67% less than in 2007 and 2008, respectively ($p<0.05$). The average annual drainage in 2006 was 78% and 76% less than that in 2007 and 2008. Overall, lack of difference in NO_3-N loss is not unexpected due to variability in flow volume among plots.

Monthly NO_3-N loss in the three observational years is also listed in Table 3.8. Total NO_3-N loss in April through June was significantly reduced by the kC and PF treatments

($p<0.05$) due to lower NO_3-N concentrations in those plots. Monthly NO_3-N loss varied over a wide range depending on the precipitation, with the average NO_3-N loss in April through June being 21.6 kg N ha^{-1}, accounting for 63% of the annual NO_3-N loading when averaged across all treatments. This percentage was higher than 90% in 2006 and 2008 when late season drainage was not significant. NO_3-N loss in these three months was 27.7 kg N ha^{-1} for fC treatment and 28.3 kg N ha^{-1} for fS treatment. Compared with fC treatment, NO_3-N reduction in these three months was 56% by kC treatment and 63% by PF treatment ($p<0.05$). Rye followed by soybean (rS) slightly reduced NO_3-N loading by 19% which was not significant. Monthly NO_3-N loss from rS was observed to be significantly lower than the fS treatment in May 2007 ($p<0.05$).

3.4.8 Nitrogen balance

Nitrogen balance estimation suggested a risk of soil fertility degradation under the corn-soybean rotation system and a benefit of introducing kura clover as a living mulch for corn (Table 3.9). In this study, the annual average fertilizer application was 70 kg N ha^{-1} $year^{-1}$ (140 kg N ha^{-1} to corn phase every other year), while the annual NO_3-N loss through subsurface drainage systems was 43 kg N ha^{-1} $year^{-1}$ for the conventional corn-soybean rotation, representing about 61% of the chemical fertilizer. Nitrogen deficit was estimated to be 30 kg N ha^{-1} $year^{-1}$ for the conventional corn-soybean rotation and 36 kg N ha^{-1} $year^{-1}$ for corn-soybean rotation with winter rye cover crop. For the PF treatment, nitrogen deficit was estimated to be 38 kg N ha^{-1} $year^{-1}$ due to biomass removal, drainage and seepage NO_3-N loss, and denitrification. Cultivating corn in a kura clover living mulch benefitted the nitrogen budget for Iowa soils due to the high N fixation. In the soil profile of kC plots, the average N accumulation was 223 kg N ha^{-1} $year^{-1}$. This number might have decreased if the grain yield of corn reached a normal level.

3.4.9 NO_3-N concentration in suction lysimeters

Although efforts were made weekly to extract soil solution, the number of samples that we could be obtained depended on the soil moisture conditions. About 25 sets of soil solution samples were obtained from the weekly sampling in the growing season for 2007 and 2008. The variability of NO_3-N concentration in soil water solution extracted by suction lysimeters was higher than that in tile line drainage flow. The NO_3-N concentration in suction lysimeters ranged from no-detection to 77.6 mg N L^{-1} in 2007 and no-detection to 48.1 mg N L^{-1} in 2008. The high NO_3-N concentrations in 2007 were obtained from one of the kC plot with an average of 45.2 and 67.1 mg N L^{-1} at 30 and 60 cm depth, respectively, in four samples collected from August 23 to September 30, 2007. However, the average NO_3-N concentration in other plots of kC treatment ranged from 7.8 to 23.7 mg N L^{-1}. There was no annual effect on the NO_3-N concentration in the soil water. Statistics also showed that the NO_3-N concentration in the soil water at a depth of 30 cm was 10.5 mg N L^{-1}, not significantly different from the concentration of 10.1 mg N L^{-1} at the 60 cm depth.

The average NO_3-N concentrations for each treatment are included in Table 3.10. When averaged over all samples obtained at two depths in two years, the NO_3-N concentration in the soil profile from 0-60 cm was 7.9 N L^{-1} for rS and 0.5 mg N L^{-1} for PF treatment, which was 38% and 96% lower than the fC plots, respectively ($p<0.05$). Monthly averaged NO_3-N concentration was reduced by rye followed by soybean treatment in most spring and early summer months. Monthly averaged NO_3-N concentrations in the soil water solution extracted from the rS plots were consistently lower than from the fS treatment during April through July in the two observational years. In May, June, and July of 2007, as well as May and June of 2008, the NO_3-N concentration at 30 cm depth of the soybean phase was significantly reduced by the winter rye cover crop relative to winter-fallow treatment ($p<0.05$). Combining these observations with the findings that the increase of the residual soil NO_3-N in the rS treatment was significantly lower than in the fS and fC treatments during the rye growing season, it is evident that rye planted prior to soybean phase has the potential to effectively reduce the NO_3-N concentration in the soil profile. However, the monthly average NO_3-N concentrations within the soil profile in the rC treatment were not significantly different from fC treatment in most cases over the two years.

The average monthly NO_3-N concentration in PF treatment was 0.5 mg N L^{-1}, well below the MCL level in 2007 and 2008 (Table 3.8). The NO_3-N concentration in the soil water solution from PF plots was 0.04 mg N L^{-1} in 2008. Sixty-five samples were gathered in 2008 for PF treatment, from which 43 samples were no-detection and others were slightly above zero when testing the NO_3-N concentration in the soil water solution. Kura clover-Corn (kC) showed lower NO_3-N concentrations in the soil profile than PF treatment before the fertilization application to corn on June 26, 2007. The NO_3-N after this fertilizer application reached a peak as high as 25.0 mg N L^{-1} at 30 cm deep and 36.8 mg N L^{-1} at 60 cm depth in August 2007. This peak was also found in July 2008 after fertilizer injection on June 20, 2008, but the magnitude of the peak was not as large as in 2007. This could in part be due to the better corn establishment in 2008. However, the monthly flow-weighted NO_3-N concentration was 11.1 mg N L^{-1} in August 2008, and lower than 10 mg N L^{-1} in the following September and October 2008.

3.5 Conclusions

Winter rye as a cover crop for corn-soybean rotation, kura clover as a living mulch for corn, and perennial forage grass are three alternative land covers that may have potential for reducing NO3-N loss to downstream water bodies in Iowa's subsurface drained landscape when compared the conventional corn-soybean rotation. A three-year experiment was conducted on a plot-scale to investigate the effectiveness of these land covers on subsurface drainage and NO_3-N loss reduction. The main findings are:

1) The growth of the land covers in spring was substantially related to the weather conditions in early spring period. Specifically, the growth of these species in spring was mainly determined by the temperature rather than by the rainfall. In the spring, the maximum nitrogen uptake by rye prior to corn (rC), rye prior to soybean (rS), kura clover, and forage orchard grass was 16.2, 34.2, 48.1, and 97.0 kg N ha^{-1}, respectively.
2) The cropping systems with rye cover crop prior to corn (rC) and soybean (rS) showed no grain yield disadvantage for the subsequent corn or soybean crops. However, the grain yield of corn with kura clover as a living mulch (kC) was significantly reduced. When averaged over 3 years, the corn yield in rC compared with fC was 8.3 versus 8.7 Mg ha^{-1}; soybean yield was 2.7 Mg ha^{-1} for rS and 3.1 for fS treatment. Total N removed by grain harvesting was 104, 101, and 32 kg N ha^{-1} for corn in fC, rC, and kC treatments, respectively, and 104 and 90 kg N ha^{-1} for soybean in fS and rS treatments, respectively.
3) Soil residual NO_3-N content was found to be the highest in early June among the three sampling times in each year of 2007 and 2008. The NO_3-N content in the soil

generally increased in the spring likely due to nitrogen mineralization driven by the increased temperature. The amount of NO_3-N increase in rS was significantly lower than the fS treatment which could be attributed to nitrogen uptake by the winter rye.

4) The average annual drainage volume was 350 mm in the three years, which was 45% of the total rainfall during the drainage season from March through November. Sixty-three percent of annual subsurface drainage occurred in April, May, and June. Impact on annual or spring subsurface drainage due to land cover treatments was not evident.

5) Annual flow-weighted NO_3-N concentration (FWANC) in the subsurface drainage was higher in a dry year and lower in a wet year. The annual FWANC in the tile drainage was significantly reduced to 6.8 mg N L^{-1} by the kC treatment and 5.3 mg N L^{-1} by the PF treatment. However, the annual flow-weighted NO_3-N concentration averaged 13.7 mg N L^{-1} for the conventional fC and fS treatments, consistently above the MCL level set by USEPA in the three-year study. Rye slightly reduced, although not significantly, the annual FWANC by 1.2 to 1.8 mg N L^{-1}. However, investigating monthly FWANC reduction due to rye cover showed a significant decrease.

6) NO_3-N loss through subsurface drainage was significantly lower in the kC and PF treatments than in fC treatment by 45% and 64%, respectively.

7) NO_3-N concentration of the soil water solution was lower in the rS and PF treatments than in the conventional fC treatment, 38% and 96% lower, respectively. However, average soil water NO_3-N concentration in kC treatment was close to fC treatment due to fertilizer application. Average NO_3-N concentration in the soil profile of rS and PF was 7.9 and 0.5 mg N L^{-1}, below the MCL value, while the NO_3-N concentration exceeded this limit for all other treatments.

Subsurface drainage water quality in terms of NO_3-N contamination can be effectively improved by converting conventional corn-soybean rotation into perennial forage, but at present there would be little economic value for the grasses. NO_3-N concentration in the perennial forage treatment was reduced to 3.0 mg N L^{-1} for drainage effluent and 0.5 mg N L^{-1} for the soil water solution in the soil profile after four years of operation. Planting corn in established kura clover living mulch also reduced the annual flow-weighted NO_3-N concentration in the subsurface drainage flow below the NO_3-N MCL for drinking water set by USEPA, but corn yield in the kura clover treatment was significantly reduced in this study. Although having not significantly impacted total NO_3-N loss, rye as a winter cover crop significantly reduced the NO_3-N concentration in soil water within the soil profile, and when cultivated prior to the soybean phase of the crop rotation, rye significantly reduced the residual soil NO_3-N in the spring. Overall, the rye cover crop has the best potential as a cropping option under an integrated concern for the environment and economics of crop returns.

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Table 3.1. Land cover treatments.

Treatment	Spring	Summer
fC	fallow	Corn
rC	rye	Corn
fS	fallow	Soybean
rS	rye	Soybean
kC	kura clover	Kura clover+Corn *
PF	perennial forage	Perennial Forage

* Corn was planted in kura clover plots 2007 and 2008, not in 2006

Table 3.2. Agronomic field activity timing.

Management	2005	2006	2007	2008
Termination of rye followed by corn	30-Apr	24-Apr	30-Apr	6-May
Corn planting	10-May	4-May	14-May	15-May
Soybean planting	18-May	10-May	17-May	23-May
Termination of rye followed by soybean	20-May	16-May	23-May	26-May
Suppression of kura clover for corn establishment	- *	-	29-May	26-May
Fertilization to corn	25-May	18-May	5-Jun	20-Jun
Soybean harvest	10-Oct	3-Oct	15-Oct	11-Oct
Corn harvesting	10-Oct	7-Oct	22-Oct	28-Oct
Rye seeding	11-Oct	12-Oct	25-Oct	21-Oct

*kura clover was not suppressed in 2005 and 2006 when corn was not planted in it.

Table 3.3. Total Biomass, grain yield, total biomass N uptake, and grain N uptake

Crop	Total Biomass Mg ha^{-1}*				Grain Yield Mg ha^{-1}				Total Biomass N Uptake kg ha^{-1} *				Grain N Uptake kg ha^{-1}			
(Treatment)	2006	2007	2008	Avg	2006	2007	2008	Avg	2006	2007	2008	Avg	2006	2007	2008	Avg
Corn (fC)	19.9 b	13.3 a	18.0 a	17.1 a	9.1 a	7.4 a	9.6 a	8.7 a	234 ab	145 b	211 a	197 a	113 a	86 a	113 a	104 a
Corn (rC)	21.8 a	11.6 b	18.4 a	17.3 a	7.9 a	6.9 a	10.1 a	8.3 a	261 ab	135 b	207 ab	201 a	97 a	90 a	121 a	103 a
Corn (kC)	-	3.1 d	10.3 b	6.7 b	-	1.0 c	4.1 b	2.5 b	-	42 c	135 b	89 b	-	13 b	51 b	32 b
Soybean (fS)	5.6 c	5.1 c	5.2 c	5.3 b	3.3 b	3.0 b	3.0 b	3.1 b	201 b	185 a	174 ab	187 a	118 a	108 a	101 a	109 a
Soybean (rS)	5.6 c	3.3 d	4.2 c	4.4 b	3.0 b	2.4 b	2.8 b	2.7 b	200 b	119 b	140 ab	153 a	107 a	87 a	93 a	96 a

Mean within years and on average (i.e., within column) followed the same letter are not significantly different at p=0.05.
* Biomass listed in this table was sampled in the late season between late August and late September. Corn was not planted in kC plots in 2006.

Table 3.4: Residual soil nitrate in 0 to 60 cm soil layer for early spring (ES), late spring (LS), and late fall (LF) of 2007 and 2008.

Treatment	2007					2008				
	ES	LS	LF	Δ(LS-ES)		ES	LS	LF	Δ(LS-ES)	
	---------- kg N ha^{-1} ----------									
fC (fallowCorn)	42	68	49	25	a	42	70	31	28	ab
rC (ryeCorn)	31	61	53	30	a	48	80	86	32	ab
fS (fallowSoy)	57	87	43	30	a	44	82	41	37	ab
rS (ryeSoy)	46	53	38	7	b	55	53	52	-1	c
kC (kuraCorn)	-	-	-	-		26	72	38	47	a
PF (Forage)	-	-	-	-		8	21	6	13	c

ES: early spring (Apr 9 in 2007 and Apr 16 in 2008); LS: late spring (Jun 4 in both 2007 and 2008); LF: late fall (Oct 31 in 2007 and Nov 18 in 2008); Δ(LS-ES): difference between LS and ES; -: not sampled.

Mean within column followed the same letter are not significantly different at p=0.05.

Table 3.5. Monthly and annual drainage in 2006, 2007, and 2008.

Treatment	Drainage (mm)																					
	2006					2007									2008							
	Apr	May	Jul	Total		Mar	Apr	May	Jun	Aug	Sep	Oct	Total		Apr	May	Jun	Jul	Oct	Nov	Total	
fC	71	40	8	119	a	7	118	38	9	182	5	129	488	a	85	70	177	8	20	28	387	a
rC	47	32	19	98	a	6	132	43	5	183	4	172	545	a	129	106	257	3	10	11	516	a
fS	67	45	12	124	a	5	94	38	3	119	4	119	383	a	97	106	227	10	26	27	492	a
rS	71	36	9	116	a	12	112	17	2	260	0	175	577	a	86	78	172	1	5	10	352	a
kC	66	21	4	91	a	16	143	11	2	238	2	125	538	a	121	73	236	0	18	19	467	a
PF	81	23	3	108	a	9	111	30	4	175	8	98	437	a	127	117	221	13	26	31	534	a

Mean within years (i.e., within column) followed the same letter are not significantly different at p=0.05.

Table 3.6. Annual flow-weighted average NO3-N concentration in 2006, 2007, and 2008.

Treatment	Annual flow-weighted average NO_3-N concentration (mg N L^{-1})							
	2006		2007		2008		Average	
fC	15.1	a	13.9	a	13.0	a	14.0	a
rC	15.2	a	11.8	ab	11.4	a	12.8	ab
fS	14.9	a	12.9	ab	12.1	a	13.3	ab
rS	12.3	ab	9.9	bc	12.3	a	11.5	b
kC	6.9	c	7.4	dc	6.1	b	6.8	c
PF	8.4	c	4.4	d	3.0	b	5.3	c

Mean within years and on average (i.e., within column) followed the same letter are not significantly different at p=0.05.

Table 3.7. Monthly flow-weighted average NO3-N concentration in 2006, 2007, and 2008.

Treat-ment	Nitrate-nitrogen concentration in drainage (mg N L^{-1})																			
	2006				2007								2008							16-month
	Apr	May	Jul	Average	Mar	Apr	May	Jun	Aug	Sep	Oct	Average	Apr	May	Jun	Jul	Oct	Nov	Average	average
fC	14.3 a	16.6 a	15.3 a	15.4 a	13.0 a	14.5 a	16.9 a	17.7 a	11.9 a	11.0 a	13.5 a	14.1 a	13.8 a	12.7 a	12.6 a	11.7 a	10.3 ab	11.8 a	12.2 a	13.6 a
rC	13.2 a	13.1 a	16.8 a	14.4 ab	11.4 a	11.6 b	13.3 b	13.3 ab	10.2 a	9.1 a	13.2 a	11.7 b	11.5 a	11.4 a	11.4 a	10.4 a	11.5 ab	10.6 a	11.1 a	12.0 b
fS	14.3 a	15.8 a	14.9 a	15.0 a	11.9 a	13.2 ab	16.8 a	14.5 ab	12.5 a	13.5 a	12.0 ab	13.5 a	13.2 a	12.3 a	11.5 a	8.6 a	12.5 ab	12.1 a	11.7 a	13.1 a
rS	12.7 a	12.3 a	8.9 ab	11.3 b	9.6 a	10.8 b	13.0 b	12.0 b	9.3 a	5.8 a	9.7 b	10.0 b	13.7 a	11.6 a	12.0 a	11.5 a	11.3 ab	9.6 a	11.6 a	10.9 b
kC	7.3 b	5.3 b	4.4 b	5.7 c	2.7 b	2.6 c	2.5 c	3.9 c	10.9 a	7.6 a	6.1 c	5.2 c	6.7 b	6.4 b	5.8 b	-	4.4 b	4.5 b	5.6 b	5.4 c
PF	8.5 b	7.9 b	-	8.2 c	4.3 b	4.1 c	3.9 c	-	3.7 b	-	3.1 c	3.8 c	3.8 b	2.8 b	2.0 c	-	3.7 b	1.1 b	2.7 c	4.1 c

Mean within years and on average (i.e., within column) followed the same letter are not significantly different at p=0.05.

Table 3.8. Monthly and annual NO3-N loss in 2006, 2007, and 2008.

Treatment	Nitrate-nitrogen Loss (kg ha^{-1})																						
	2006					2007									2008								annual average	
	Apr	May	Jul	Total		Mar	Apr	May	Jun	Aug	Sep	Oct	Total		Apr	May	Jun	Jul	Oct	Nov	Total			
fC	8	6	1	16	ab	1	17	6	2	22	1	17	66	a	12	8	24	1	2	3	49	ab	44	a
rC	6	4	4	15	ab	1	15	6	1	17	0	22	62	a	14	12	28	0	1	1	56	a	44	a
fS	10	7	2	19	a	1	12	6	0	15	0	14	50	ab	11	12	26	1	3	3	56	a	41	a
rS	9	4	1	15	ab	1	12	2	0	23	0	16	55	ab	12	8	20	0	1	1	42	ab	37	ab
kC	5	1	0	6	b	0	4	0	0	26	0	7	39	ab	8	5	13	0	1	1	28	ab	24	bc
PF	7	2	0	9	ab	1	6	1	0	9	0	4	21	b	6	4	6	0	1	1	18	b	16	c

Mean within years and on average (i.e., within column) followed the same letter are not significantly different at p=0.05.

Table 3.9. Nitrogen balance in the three years of study.

Treatment	N input ($kg\ ha^{-1}\ year^{-1}$)			N output ($kg\ ha^{-1}\ year^{-1}$)				N balance ($kg\ ha^{-1}\ year^{-1}$)
	atmospheric deposit	fertilization	N fixation [1]	harvest	tile drainage	deep seepage	denitrification	N output - N input
conventional Corn-Soybean	6	70	56	107	43	8	4	-30
Corn-Soybean with rye cover	6	70	46	99	41	9	9	-36
Corn with kura clover [2]	6	140	155 [3]	32	34	8	4	223
perennial forage	6	0	32	47	16	8	4	-38

1. soybean N fixation = total N in biomass × 60% (Iowa State University Extension, 2009);
2. corn with kura clover was averaged over two years (2007 and 2008);
3. kura clover N fixation = 155 $kg\ ha^{-1}\ yr^{-1}$ by Seguin et. al.(2000);
4. N fixation estimated from red and ladino clover;
5. N removal by mowing and baling.

Table 3.10. NO_3-N concentration in suction lysimeters.

Treat-ment	30-cm depth (mg N L^{-1})											60-cm depth (mg N L^{-1})											Average over all samples	
	2007						2008					2007						2008						
	Apr	May	Jun	Jul	Aug	Sep	May	Jun	Jul	Sep	Oct	Apr	May	Jun	Jul	Aug	Sep	May	Jun	Jul	Sep	Oct		
fC	21.4	11.4	12.2	13.6	8.4	16.0	15.2	7.9	18.7	17.4	1.7	19.8	17.2	15.1	13.4	5.2	8.7	13.2	9.5	14.8	10.7	13.4	12.9	a
rC	14.8	13.0	17.7	11.0	3.4	7.5	17.7	14.2	20.0	11.8	12.5	7.3	11.7	10.4	10.0	4.9	12.4	13.1	12.8	10.1	13.6	5.8	12.0	a
fS	25.1	15.2	16.6	17.9	2.8	6.7	12.6	12.1	21.4	10.4	18.6	30.8	26.6	27.6	21.4	8.1	7.1	12.2	12.3	15.8	20.2	10.4	15.1	a
rS	10.7	8.0	4.1	7.8	3.9	5.6	6.9	3.2	18.3	25.3	24.2	19.3	12.2	4.7	4.7	3.2	4.5	10.6	3.1	9.4	11.2	10.6	7.9	b
kC	8.5	2.5	4.3	-	25.0	23.2	10.9	5.8	14.6	8.3	11.9	-	2.6	2.1	0.6	23.2	36.8	11.1	8.0	12.6	5.6	2.3	12.9	a
PF	-	1.0	5.0	-	0.2	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.2	3.1	0.0	1.0	0.1	0.2	0.0	0.0	0.0	0.0	0.5	c

- no soil water solution sample was obtained.

Average over all samples for each treatment (within column) followed the same letter are not significantly different at $p=0.05$.

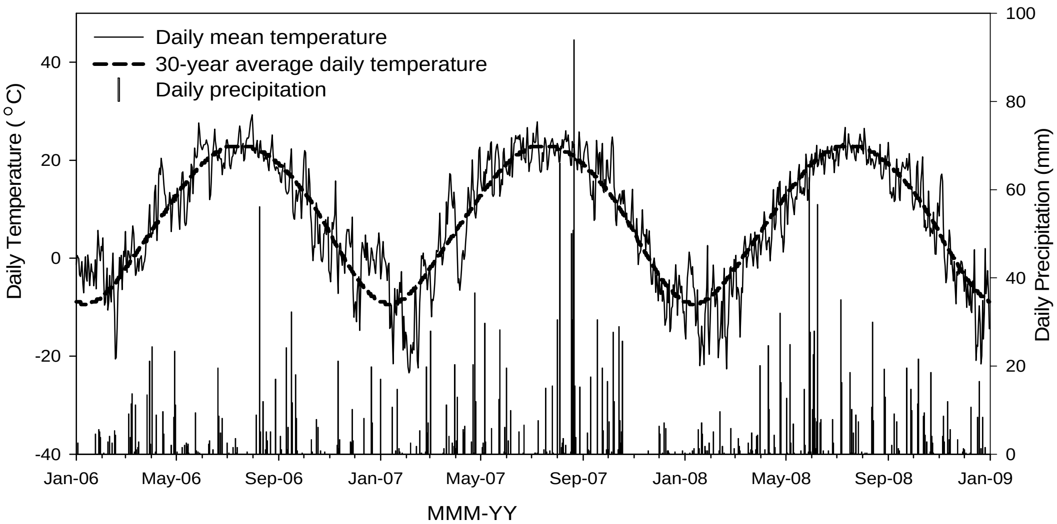

Figure 3.1. Daily precipitation and temperature of the experimental site.

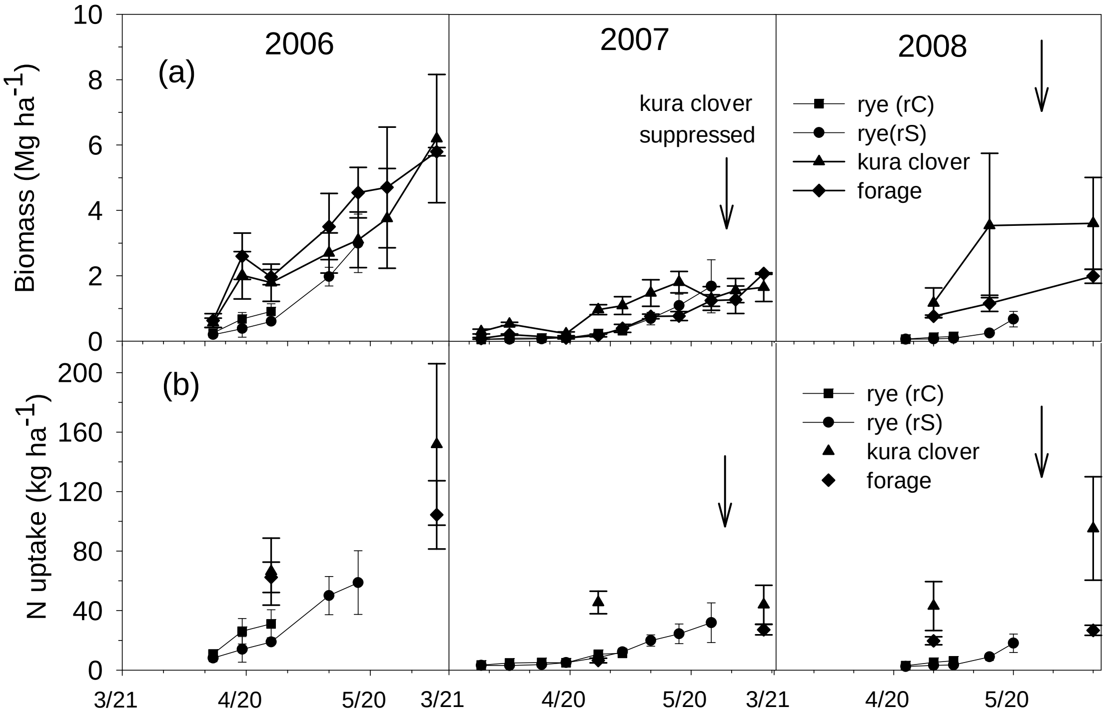

Figure 3.2. Biomass (a) and nitrogen uptake (b) of land covers in spring of 2006, 2007, and 2008.

CHAPTER 4. SOIL WATER DYNAMICS UNDER VARIOUS LAND COVERS IN IOWA

A paper to be submitted to Agriculture, Ecosystems & Environment

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4.1 Abstract

Soil water is essential to crop growth and effects agricultural effluent in fertilized agricultural systems with intensive drainage. Alternative land covers to conventional corn-soybean rotation are being studied in Iowa due to increased concern of surface water quality and quantity connected with agriculture. The objective of this study was to investigate soil water dynamics under various land covers in Iowa. Land covers including winter rye-Corn (rC), winter rye-Soybean (rS), kura clover as a living mulch for Corn (kC), and perennial forage (PF), as well as conventional Corn (fC, fallow in the spring) and Soybean (fS), were grown in subsurface drained plots in north-central Iowa. From 2006 through 2008, Soil water content was monitored on a weekly basis during the growing season to the depth of 100 cm, and soil water storage (SWS) was examined in the 0-60 cm soil layer for this study. Results showed that SWS was significantly affected by land cover treatments, particularly in the summer ($p<0.05$). Treatments of rC and rS typically maintained higher SWS than fC and fS, respectively, during the three years of this study. SWS in the kC treatment was significantly lower than rC and rS treatments ($p<0.05$) across three years. The PF treatment had the lowest SWS among all treatments in each individual year ($p<0.05$). During the cover crop growing season in spring, during a ten- to fifteen-day period when the rainfall was less than 11 mm, SWS in plots with rye, kura clover, and forage grass decreased at a significantly higher rate than the fC and fS plots which were bared during this time period. The results of this study

indicate that planting winter rye as a cover crop has benefits for water conservation in Iowa without a disadvantage on main crop yield. Kura clover growing with corn as a living mulch needs further studies to establish a feasible agronomic management to reduce water competition for corn. Low soil water storage under perennial forage suggests that the hydrologic cycle may be altered by converting conventional corn soybean rotation into perennial cover.

4.2 Introduction

Nutrient loss through subsurface drainage systems in the Midwest of the United States has been an increasing concern as a result of hypoxia in the Gulf of Mexico. Approximately 70 percent of subsurface drainage flow, as well as nitrate-nitrogen (NO_3-N) loss, occurred in spring when the main crops have not established (Helmers et al., 2005; Randall and Vetsch, 2005). Land covers that can grow in the spring are promising approaches for reducing subsurface drainage volume thereby decreasing nitrate loss from row cropped fields in the Midwest region of the United States. Studies have shown that annual cover crop, perennial living mulch and perennial forage grassland have the potential to reduce NO_3-N leaching in the Midwest (Baker and Melvin, 1994; Kassavalou and Walters, 1999; Zemenchik et al, 2000; Eleki, 2003; Affeldt, et al. 2004; Strock et al., 2004; Kaspar et al., 2007; Heggenstaller et al., 2008).

However, these alternative cropping systems could exert beneficial and/or detrimental impacts on the local hydrologic circle by altering infiltration and evaportranspiration processes. Dabney (1998) and Unger and Vigil (1998) reviewed the mechanism by which winter cover crops affect hydrological processes and found they can increase infiltration by trapping snow and can influence soil evaporation by altering net radiation, wind speed, vapor pressure deficit, and soil surface temperature. Unger and Vigil (1998) also found that runoff can be reduced by increased surface roughness and rainfall interception due to the existence of the cover crop. Soil water storage can be affected by increasing the infiltration rate and water consumption by transpiration, and by a modification of soil matrix porosity structure. Macropore geometry can be changed by a cover crop both directly through root extension and indirectly by changing populations and activity of worms. Moschler et al. (1967) demonstrated elevated soil water content with winter rye cover crop in soil layers from 0 to 60 cm. In British Columbia, Canada, Odhiambo and Bomke (2007) compared gravimetric soil moisture in winter cover crops with that in bare plots in the early spring and found that soil water content in rye treatment was significantly higher for top soil (0-20 cm) possibly due to reduced soil evaporation and increased infiltrability in the cover cropfield. Because evapotranspiration of rye cover crop may offset the increased infiltration, the soil water storage had a similar pattern in a rye cover field compared to a no rye cover field (Islam et al., 2006). Moreover, transpirational water consumption by rye may adversely affect the soil moisture that could lead to water stress for the following main crop. Munawar et al. (1990) compared the soil moisture between early killed (3 weeks before corn planting) and later killed (on the corn planting day) winter rye cover crop and documented that soil moisture in late killed plots was significantly lower than that in early killed plots due to more soil moisture depletion.

The effect of kura clover as a living mulch for corn on soil moisture was not consistent in related studies. Gravimetric soil moisture in corn growing with kura clover showed no difference between the treatment of solely kura clover and corn with killed kura clover which could be attributed to successive water supply (Zemenchik et al., 2000). However, in other studies, available soil water could be the most limiting factor for the main crop growth in the north central United States (Eberlein et al., 1992) and in the U.S. Coastal Plain when the precipitation was below the long-term average (Ewing et al., 1991). Kurtz et al. (1952) and Pendleton et al. (1957) observed grain yield loss of corn which was grown in an interseeded legume due to soil water deficit conditions.

Converting perennial forage, pasture or native prairie into corn or soybean cropland could increase soil water storage because of the shallow rooting depth and short growing season of corn and soybean. In Western Australia, the replacement of deep-rooted native prairie with annual crops, which consume less water, has led to the rise of water tables (George et al., 1997). Soil water dynamics under pasture and annual crops have been intensively studied in this area because of the argument about which species use more water. Some studies indicated that perennial pasture used more water than annual crop and reduced drainage (Crawford and Macfarlane, 1995; Ridley et al., 1997; Dolling, 2001), while other studies concluded that pasture used less water than annual crops (Nulsen, 1984; Farrington et al., 1992; Scott and Sudmeyer, 1993). There is little literature specifically discussing soil water dynamics of perennial forage or pasture in the Midwest of the USA. However, related studies showed that deep-rooted savanna, woodland and prairie extracted more water from the deeper soil profile than the annual corn crop in this region (Proffitt et al., 1985; Asbjornsen et al., 2007).

In Iowa, studies have suggested that changes in land uses and vegetative cover affected water uptake patterns which may ultimately impact the hydrologic balance on a large scale (Asbjornsen et al., 2007). Linear regression modeling indicates that land cover and soil properties largely govern the base flow for rivers in Iowa (Schilling and Wolter, 2005). However, there is little information addressing the soil water impacts of introducing alternative land covers into a conventional corn-soybean rotation system. With the increased concern about biomass production, nutrient loss reduction, and soil erosion control, the use of winter cover crops, living mulches, and perennial forage have the potential to alter the conventional mono-cropping system in Iowa and the larger Corn Belt (Sulc and Tracy, 2007; McDonald et al., 2008). As a result, there is a need to investigate the effect of these alternative land covers on the hydrologic cycle. The objective of this study was to investigate the impact of alternative land covers, including a winter cover crop with corn and soybeans, corn growing with kura clover as a living mulch, and perennial forage, on soil water storage when compared to the conventional corn-soybean rotation.

4.3 Materials and Methods

4.3.1 Site description

The Agricultural Drainage Water Quality - Research and Demonstration Site (ADWQ-RDS), located in Pocahontas County in north-central Iowa, is a subsurface drained site composed of seventy-six plots administrated by the Iowa Department of Agriculture and Land Stewardship and Iowa State University. Predominant soils are Nicollet (fine-loamy, mixed, superactive, mesic Aquic Hapludoll), Webster (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls), Canisteo (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls) and Okoboji (Fine, smectitic, mesic Cumulic Vertic Endoaquolls). Each plot is 38 m in length and 15.2 m in width. The plots were established after the installation of corrugated plastic drain tiles through the center and along both boundaries parallel to the long dimension (7.6 m spacing) at a depth of 1.06 m. All subsurface drainage lines extend to separate drainage monitoring sumps where water is collected and pumped into a nearby wetland. Detailed design has been described by Helmers et al. (2005), Singh et al. (2006) and Lawlor et al. (2008). An automatic meteorological station at the site monitored rainfall, air temperature, soil temperature at 10 cm depth, solar radiation, wind speed and direction, and humidity at a fine temporal resolution. Daily reference evapotranspiration (ET_0) was computed using Penman-Monteith equation following FAO56 (Allen et al, 1998) to represent the integrated weather conditions. The long-term (1971-2000) average normal precipitation and temperature were obtained from the National Climate Data Center for the two weather stations located in Humboldt (Station No. 125) and Pocahontas (Station No. 070), IA, which are 19 km east and west from the experimental site, respectively.

The field experiment was established in a completely randomized block design. Plots were blocked by their long-term (15 years) drainage characteristics. This resulted in four blocks, high (H), medium high (MH), medium low (ML) and low (L) flow blocks. One plot in each block was randomly assigned to each of the six land cover treatments (6 treatments×4 blocks) in this study. Land cover treatments were: conventional corn-soybean rotation fallowed in spring (fC and fS), winter rye cover crop in corn-soybean rotation (rC and rS), corn with established kura clover as a living mulch (kC), and perennial forage (PF). Forage plots were mowed once or twice a year but were not grazed by animals. This experiment was initiated in October 2004 but data in this paper covers the period from 2006 through 2008. Due to previous site history, 2005 was considered a transition year.

4.3.2 Agronomic management

Agronomic field activities were completed in a timely manner prior to and during the crop season beginning in October 2004 with plot tillage and rye seeding. For the fC and fS plots, corn residue was chopped and chisel plowed in the fall followed by disking and field cultivation prior to corn planting in the spring, and soybean residue was not disked until spring and was field cultivated prior to soybean planting. For the plots with rye (rC and rS), tillage operations were conducted in the fall prior to rye planting. Corn residue in rC treatment was chopped, disked twice and smoothed with a field cultivator, and soybean residue was disked once and field cultivated. 'Rhymin' rye (*Secale cereale*) was drill seeded at a rate of 100 kg ha^{-1} in 19 cm rows with a skip row every 76 cm for subsequent corn or soybean planting. Tillage for seedbed preparation for kura clover and forage was completed in the spring just prior to planting on April 18, 2005. 'Endura' kura clover (*Trifolium ambiguum*) was hand seeded at a rate of 13 kg ha^{-1}, the perennial forage plots were hand seeded with 'Duration' red (*Trifolium retense*), and 'Pinnacle' ladino (*Trifolium repens*) clovers with 'Extend' orchardgrass (*Dactylis glomerata*) at 9, 0.6, and 4.5 kg ha^{-1}, respectively.

In the spring, glyphosate was applied at a rate of 239 mL ha^{-1} in rC and rS plots to terminate rye growth. Glyphosate resistant corn (Zea maize) and soybean (Glycine max) were used and planting dates were dictated by field conditions. Seeding rates were 77,000 seed ha^{-1} for corn and 439,750 seed ha^{-1} for soybean. Corn planting in the kura clover plots started in 2007, giving a two-year (2005 and 2006) period for kura clover to establish according to recommended management. After the corn planting, the entire kura clover plots were suppressed by glyphosate in 2007 and the plots were band sprayed in 2008. Commercial-grade 28% aqueous ammonia-nitrogen (N) was applied at 140 kg N ha^{-1} in the spring closely following corn emergence to corn plots only, within the recommended rates of 112 to 168 kg N ha^{-1} (Blackmer et al., 1997). N fertilizer was applied mid-row to corn with a conventional knife applicator. For weed control in all corn and soybean plots, glyphosate was subsequently applied two more times during the growing season, as dictated by weed pressure. Similar operations were followed in all years and agronomic timing details are included in Table 4.1.

4.3.3 Biomass sampling

Above ground rye shoots were sampled weekly from early spring until chemically desiccated with glyphosate. Weekly sampling of kura clover and forage shoots coincided with rye sampling and continued until late June. From July until early October, corn, soybean, kura clover and forage were sampled once every three weeks. Rye, corn, and soybean were sampled along a 30-cm long section at four randomly selected locations; kura clover and forage were sampled using a 30×30 cm^2 area randomly selected at three locations in each plot. Samples were dried at 60 ºC for a week for dry biomass determination.

4.3.4 Soil moisture measurement

Three of the four blocks, with exception of the high drainage block, were selected for the soil water dynamics study. A PR2 Profile probe and a Theta probe (Delta-T Services, UK) were used to measure the soil permittivity. The measurement was not conducted in the winter because the soil was frozen and the probes are not capable of monitoring soil permittivity in frozen soils. In each plot, soil dielectric permittivity was measured for the soil profiles at two locations, one each in the southeast and northwest of the plot where a fiberglass access tube was installed in fall 2005 at each location to facilitate soil permittivity measurement in the soil profile. The PR2 Profile probe was inserted into the fiberglass access tubes to measure the soil permittivity at 10, 20, 30, 40, 60 and 100 cm. The permittivity of the top soil (0-5 cm) was measured five times around each access tube with the Theta probe to provide adequate replication. The PR2 probe was calibrated by in-situ soil sampling in two consecutive years, which is documented in Qi and Helmers (2008). Permittivity measured by PR2 probe was converted to volumetric water content by these calibrated equations. The permittivity output of the Theta probe was converted into volumetric water content by the equation calibrated by Kaleita et al. (2005) using field data collected in Des Moines Lobe soils.

The Theta probe and PR2 profile probe measurements were taken on a weekly basis from April through October in 2006-2008. The soil moisture measurement date was dictated by the weather to avoid sampling on rainy days. The soil water content measured by PR2 probe at 10, 20, 30, 40, and 60 cm were assumed to be representative of soil layers at 5-10, 10-20, 20-30, 30-45, 45-60 cm, respectively, and the soil moisture in the top 0-5 cm layer was calculated by the Theta probe readings. The soil water content data were multiplied by the representative depth intervals to compute the soil water storage (SWS) for each depth, and then summed to obtain the SWS for 0-60 cm soil layer. Because the soil water content at 100 cm would be largely influenced by the high water table, soil water storage (SWS) was calculated in the soil layers from 0 through 60 cm below the ground surface.

4.3.5 Statistical method

The experiment followed a completely randomized block design with 3 replications. Data were analyzed for each individual year separately. The 3-year data was also combined to test the significance of difference between treatments across years. The MIXED model with repeated measure in SAS has been applied to analyze the differences between temporally repeatedly measured soil water storage, crop production, and nitrate loss in drainage systems (Lyon et al., 1998; Aparicio et al., 2008). In this study, differences in soil water storage (SWS) among treatments were analyzed via the MIXED procedure (SAS Institute Inc., 1999) using the monitoring date as a repeated measure. Autoregressive order 1 was selected as the covariance structure in MIXED repeated procedure because the correlation of SWS was larger between short sampling time intervals as compared to long intervals. Drainage block nested in the land cover treatments was considered a random effect in the statistical analysis.

4.4 Results and Discussion

4.4.1 Weather conditions

Monthly precipitation and temperature for the study period are presented in Table 4.2. The annual precipitation for 2006, 2007, and 2008 were 626, 1050, and 926 mm, respectively, with 550, 935 and 827 mm in the drainage season from March to November in 2006, 2007, and 2008. The long-term average annual precipitation is 821 mm for the ADWQ-RDS site. The monthly precipitation for 2006 was well below average in May, June, and July, however, the rainfall during the winter cover crop growing season from March to May was 207 mm, which was near to the long-term total rainfall of 236 mm during the same period. The year of 2007 was dry in the summer but moist in August and October with 367 and 119 mm rainfall occurred, which was 3 and 2 times as much as the long term normal rainfall in these two months, respectively. The monthly precipitation in 2008 was overall close to the long-term normal but was wetter in May, June and October.

In general, temperature in 2006 was warmer than the long-term average, but in 2008 the averaged daily temperatures on a monthly basis were consistently lower than the long-term average by 1.0 to 3.8 °C from January through October. During the spring growing season, the temperature pattern varied from year to year. The long-term monthly average temperatures during the rye growing season in March, April, and May are 1.0, 8.6 and 15.6 °C. The temperatures during these three months in 2006 were 1.3, 11.7 and 15.8 °C which were higher than the long term average. In 2007, the average temperatures in March and May were 3.8 and 18.1 °C which were higher than the average, but in April the average temperature was 7.4 °C, lower than the long-term average in April. Cold weather was observed in early April, 2007 with an average temperature of -0.9 °C in the first 10 days and -5.1 °C on average from April 4 through April 7, 2007 with the lowest temperature observed on April 7 (-10.0 °C).

Because during the main growth period of rye cover crop in Iowa from March through May, soil moisture is normally abundant for rye growth, other factors such as temperature and solar radiation determine the biomass accumulation rate. Therefore, reference evapotranspiration (ET_0) is a proper integrated indicator of weather conditions for cover crop growth. In general, weather in the spring was the most favorable for crop growth in 2006 (Figure 4.1). Total ET_0 during March through May was 647 mm for 2006, 18% and 69% higher than that for 2007 and 2008, respectively. In June 2006, low temperature and cloudy days led to a low monthly ET_0 value. Monthly ET_0 in 2008 was generally lower than in 2006 and 2007, particularly from January through May. This was likely due to relatively cool temperature, high humidity and low solar radiation in 2008.

4.4.2 Biomass and Grain Yield

The maximum above ground dry biomass that land covers produced in the spring was 1.04, 3.82, and 3.06 Mg ha^{-1} when averaged across three years for rye, kura clover and forage, respectively. Biomass accumulation of spring land covers were influenced by the weather conditions (Figure 4.2). Biomass of each spring land cover for 2006 was significantly higher than those for 2007 and 2008 ($p<0.05$). The rainfall and temperature conditions during the early spring of 2006 were conducive to establishing spring land covers. The growth of land covers in spring was negatively affected by the short term extreme low temperatures in April 2007 and the long period of cold weather in 2008. The difference between 2007 and 2008 was not statistically significant for rye and forage at a level of $p=0.05$, except that kura clover biomass in 2008 was significantly higher than that in 2007. However, if the statistical significance level was set as $p=0.1$, rye in both rC and rS plots for 2007 was significantly higher than 2008.

Biomass of various vegetation species in the spring was significantly different when averaged over the observational years ($p<0.05$). Kura clover in kC produced the highest biomass amount of 3.82 Mg ha^{-1} in late spring, which was comparable to the forage grass in PF of 3.06 Mg ha^{-1}. The biomass of rye in rS treatment was 1.67 Mg ha^{-1}, significantly higher than that of rye in rC treatment with a biomass yield of 0.46 Mg ha^{-1}($p<0.05$) ; moreover, rye biomass in both rS and rC plot was significantly lower when compared with the forage and kura plots ($p<0.05$). Winter rye cover crop growing in the rS treatment was chemically desiccated in the middle to late May and the rye in the rC treatment was killed in the late April with a difference around 20 days. Rye followed by soybean accumulated 72% of the biomass when averaged across 3 years within the 20 days after the rye followed by corn was killed.

Winter rye cover crop did not affect the biomass of the following corn and soybean (Figure 4.3). Above ground dry biomass of corn or soybean in the treatments with winter rye were not significantly different in weight from the winter fallowed corn or soybean treatments, with only one exception in June 14, 2007 when the biomass of corn in fC and soybean in fS was significantly higher than biomass of corn in rC and soybean in rS, respectively. In the three years, soybean biomass in fS treatment was consistently higher than that in rS treatment from mid-June to mid-August, but in September or October the biomass of soybean in rS was higher than that in fS. From visual observation, the maturity of soybean in the rS treatment was delayed two to three weeks when compared to the fS treatment.

Corn in kC treatment was significantly lower in terms of total biomass accumulation than in fC and rC treatments at every sampling date ($p<0.05$) in 2007 and 2008 (Figure 4.3). Corn in the kC treatment grew better in 2008 than in 2007. On September 9, 2007, the total above ground biomass of corn in the kC treatment was 5.8 Mg ha^{-1}, which was about 61% lower than the biomass amount of corn in fC and rC treatments. On September 4, 2008, the amount of corn biomass was 10.3 Mg ha^{-1} in the kC treatment, about 43% lower than that of corn in fC and rC treatments.

While corn and soybean in the plots with rye as a winter cover (rC and rS) did not show 2.5 Mg ha^{-1} for the kC treatment. The corn yield in kC plots was 1.0 Mg ha^{-1} in 2007 and 4.2 Mg ha^{-1} in 2008, respectively. Soil moisture, nutrient, and sunlight grain yield disadvantage compared with the conventional spring fallowed plots (fC and fS), corn that grew with kura clover as living mulch (kC) had significantly lower biomass accumulation and grain production ($p<0.05$, Table 4.3). On average, the corn yield was 8.7 and 8.3 Mg ha^{-1} for fC and rC treatment, but was competition could be responsible for the poor corn establishment and low grain production in the kC plots. Soil moisture in the top 15 cm in the kura clover treatment was 17% lower than in the fallow plots at corn planting on May 14,

2007. The soil moisture content in the kC plots was nearly always lower than other corn or soybean plots from late April to late July in the three observed years due to the water use of kura clover during this period. Another reason could also be decreased infiltration due to the hard soil surface because of reduced tillage and root mass of the kura clover in kC plots. Average soybean grain yield for rS was 2.7 Mg ha^{-1} which was lower than the yield of 3.1 Mg ha^{-1} for fS but without statistical significance.

Yield for corn and soybean varied over years due to the impact of weather conditions. Although the total rainfall during the 2006 growing season of corn and soybean from May through September was 47.0% less than that in 2008 (300 mm vs 566 mm), the yield of corn or soybean in 2006 was similar to the yields in 2008 for corn and soybean for fS, rS, fC, and fS treatments. However, although the total rainfall during the 2007 growing season (640 mm) was the highest among the 3 years, the corn grain yield in 2007 was significantly reduced by 22% when compared to average corn yield in 2006 and 2008 for fC and rC treatments ($p<0.05$).

4.4.3 Soil Water Dynamics

4.4.3.1 General pattern of SWS

Based on the weekly measurement, the soil water storage (SWS) in the top 60 cm was computed for the various land covers (Figure 4.5). A total of 29 Weekly SWS values were obtained in 2006, 35 in 2007, and 31 in 2008 for soils around each access tube. During periods with substantial precipitation, such as in early spring of 2008 and early fall of 2007, average SWS in the 0 to 60 cm depth soil profile for each treatment was essentially the same across various land cover treatments. Soil water storage was generally higher in early spring and late autumn but lower in the summer for all the treatments. Average SWS in April and

October over the three years was 203 and 200 mm, respectively, while the average SWS in July was 179 mm. The lowest SWS (114 mm) was observed across all the treatments on July 17, 2007, which indicated a soil water content of 0.19 cm^3 cm^{-3}, close to the average wilting point ($\theta_{1500kPa}$) of 0.21 cm^3 cm^{-3} measured in the lab for 0-60 cm depth soils in Plot No. 7-1. The highest SWS (220 mm) occurred on June 9, 2008, corresponding to a soil water content value of 0.37 cm^3 cm^{-3}. This highest soil water content was near to the lab measured field capacity (θ_{330kPa}) of 0.38 cm^3 cm^{-3} for top 60 cm soils in Plot No. 7-1.

The average weekly soil moisture varied among years due to the differences in precipitation and other weather conditions. The average weekly SWS for all the treatments was 185 mm for 2006, 196 mm for 2007, and 202 mm for 2008, significantly different from each other ($p<0.05$) (Table 4.3). Despite the fact that the amount of precipitation in 2007 was the highest among the three years, the weekly average SWS was significantly lower than in 2008 because the rainfall was more evenly distributed and lower reference ET_0 was lower in 2008 (Table 4.2). Excess rainfall beyond the maximum soil water capacity exited through the drainage pipe, percolated into the groundwater or ran off the soil surface. For each treatment, average soil water storage in a year was significantly different from other years ($p<0.05$), but for the rC and PF treatment, SWS in 2007 was not statistically different from SWS in 2008.

Land cover treatment significantly affected the repeatedly measured SWS ($p<0.05$, Table 4.3). Perennial forage (PF) showed the lowest average weekly SWS (181 mm) among all the land cover treatments, significantly lower than fC, rC, fS, rS, and kC treatments ($p<0.05$). In the kC treatment, mean SWS was significantly lower than rC and rS treatments ($p<0.05$). In the corn soybean rotation treatments, the mean weekly SWS in rC was significantly higher than fC treatment ($p<0.05$). However, SWS in rS showed no significant difference from fS treatment when averaged over 3 years. The SWS differences were more evident in the year of 2006 and the summer of 2007 when rainfall was below average.

4.4.3.2 SWS in winter cover crop treatment

In Iowa, the growth of winter rye was not appreciable in the winter season from late-December to late-March. The effect of rye on hydrological components related to winter weather is not a main concern in Iowa. For example, based on field observation, rye may not be able to trap appreciable snow, or affect the process of soil freezing and thaw because it was very sparse and less than 5 cm tall until the snow melts. Effect of rye on runoff was not one of the major issues in the study area because the field is very flat and is intensively drained. To investigate the causes of increased SWS in treatments with rye as a winter cover crop in Iowa, attention should be paid to the impact of rye on water infiltration, soil evaporation, and rye root water uptake. Winter rye cover crop increases infiltration by adsorbing raindrop energy, hence preventing soil surface sealing, and increasing soil macroporosity (Dabney, 1998). It also reduces soil surface evaporation by blocking the wind and shading the surface, but conversely, SWS may be affected by the transpiration of rye.

Temporal patterns of SWS and the comparison between rC and fC, and rS and fS are illustrated in Figure 4.6 and 4.7, respectively. Increase of SWS by rye as a winter cover crop was consistently observed for both corn and soybean as main crops. The increased soil water retention in rC and rS plots could be attributed to both rye root growth in the soil and the coverage of rye residue on the ground. Rye root may increase soil porosity and rye residue may reduce the soil evaporation between corn or soybean rows. The average weekly SWS in rC over the three years was significantly higher than fC treatment ($p<0.05$), but SWS in rS showed no significant difference from the fS treatment (Table 4.3). The difference of SWS between rS and fS may be offset by water uptake of rye in rS in the spring (Figure 4.7).

Impact of rye on SWS was evident for rS treatment during a certain period in each year. Rye in rS plots was terminated on May 16 in 2006, May 23 in 2007, and May 26 in 2008. This study showed that rye accumulated 70% of the total biomass in rS treatment in the 20 days before termination. About 10 to 15 days before rye in the rS plots was sprayed, when the rainfall was minimal, SWS decreased drastically relative to the spring fallowed fS treatment ($p<0.05$, Table 4.4). Observed drainage in the rS plots was less than the fS plots ruling out major impacts of soil heterogeneity SWS (Data presented in Chapter 3). This leaves transpiration water use of rye causing the substantial drop in SWS. Table 4.4 shows the SWS change in rS and fS treatment prior to rye growth termination. For example, during the 15-day period from May 1 through May 16 in 2006, the decrease of soil water storage (ΔSWS) was 12 mm for rS, significantly higher than that for fS plots, 5 mm ($p<0.05$). Again, the difference of ΔSWS between rS and fS treatments, which was 8 mm, is most likely a result of transpirational water use by rye. Statistical analysis demonstrated that this type of difference was also significant for a 13-day period for 2007, and a 10-day interval in 2008 prior to rye growth termination of rS plots ($p<0.05$). The transpirational water use due to the presence of rye was averaged to be 1.0 mm d^{-1} in the three periods listed in Table 4.4. This value is comparable to the estimated rye transpiration of 0.9 mm d^{-1} in May from a non-weighing lysimeter field experiment conducted in Iowa during 2006, 2007, and 2008 (Qi and Helmers, 2009). Since the soil surface evaporation could be reduced by the rye, the transpirational water use of rye may have been higher than 1 mm d^{-1}.

Winter rye cover crop extended its effect on SWS even after the growth termination. In corn and soybean plots with rye growing in the spring, SWS was almost always higher than in corn and soybean plots which were fallowed in the spring. Because the rye shoot was chemically burned down but was not removed, it could mitigate raindrop impact energy and block the wind, thereby increase the infiltration and reducing soil surface evaporation. The rye stand usually collapsed in late summer, nevertheless, it continued influencing the SWS into late fall. In the fall of each of the three years, the SWS conserved by rye in corn plots was more apparent than for soybean plots (Figure 4.6 and 4.7). The soil surface of rC plots was well protected by rye in the spring and by corn canopy in the summer and fall; but in rS plots, due to late and smaller soybean canopy, the rye residue weathered at a higher rate. In the fall, the soil surface of soybean plots with or without rye in the spring was visually smooth and covered with surface crust, while the soil surface of corn plots was rougher and softer. The rough and soft ground surface in corn plots could be attributed to two reasons, one was that the soil was disturbed by fertilizer applicator knives in May, the other was that corn canopy protected the soil surface from being compacted by raindrops. Moreover, more extensive corn canopy may make rye residual more effective for corn plots in terms of water conservation than for soybean plots. It is also necessary to point out that in the plots with rye the soil moisture was increased but not to an extent where the traficability would be affected.

Effect of winter rye cover crop on SWS in this field plot study was in contrast to the non-weighing lysimeter study revealed a lower SWS in the rye treatment (Qi and Helmers, 2009). The non-weighing lysimeter was placed in a different micrometeorological situation from field plots. The 20-cm high standing board around each lysimeter blocked the wind and protected the rye in the winter and spring. The total biomass in the lysimeters was higher than that in the field plots, and the soil evaporation may have been reduced by the standing board, which may have resulted in transpirational water use dominating other hydrological components before rye growth termination. Furthermore, the drainage in the lysimeter was much more uniform than in the field plots. Due to the small-scale of the lysimeters with rye growing directly above the drain, macropores created by rye may act as a bypass through which water more rapidly reached the drain.

4.4.3.3 SWS under living mulch

In general, the kC treatment showed significantly lower SWS than rC and rS treatment across three years ($p<0.05$), but significantly lower than fC and fS treatments only in 2006 (Table 4.3). The SWS in kC during the spring had large fluctuations when compared to the fallowed treatments (Figure 4.8). The kC showed higher SWS values after a period of intensive rainfall, such as late April in 2007 and early June in 2008. This may be attributed to the increased macroporosity by the root development, which is similar to rye plots. However, the soil water depletion of kura clover was more evident than rye cover crop between two rainfall events. Comparison of SWS change and transpiration estimation during late spring periods is listed in Table 4.5. The magnitude of SWS decrease in kC treatment was found to be significantly higher than winter and spring fallowed corn plots. There was no treatment × year effect which indicated that the treatment effect was consistent in each individual year. During the periods listed in Table 4.5, the transpirational water use of kura clover was higher in 2007 and 2008, though the reference ET_0 was lower in these two years than in 2006. When compared with rye in rS, the SWS decreased more rapidly in kC treatment, which is an indicator that kura clover transpirational water use was much higher than in the rye in the three periods of late spring. The daily soil water transpired by kura clover averaged 1.95 mm d^{-1} over these three time intervals, nearly twice as much as that by rye cover crop.

Low SWS in the kC treatment may have negatively impacted corn growth, because corn above ground biomass and corn grain yield in kC was reduced when compared to fC. Nutrients, light and water are three major resources for which corn would compete with kura clover in kC treatment in the summer growing season. Soil was sampled in kC and fC treatments in 2008 and the difference of soil residual nitrate between kC and fC treatments was negligible before the corn planting and after corn harvesting (data not presented). At the early stages of corn, its establishment could be affected by light interception of kura clover. Overall, the limited growth and corn grain yield loss can most likely be attributed to water competition, particularly in the vegetative stages from emergence to silking. In other words, the available soil water stored in the soil profile could not support the simultaneous growth of corn and kura clover, especially in year with a dry summer such as 2007.

Figure 4.9 demonstrates the temporal pattern of soil water content (SWC) in 5-15 cm soil layers during the corn growing season of the three study years. Soil moisture pattern at 5-15 cm soil layer resembled the SWS trend of the 60 cm soil profile. After kura clover was suppressed by herbicide, the transpirational water use was largely reduced and SWC was maintained at a high level, but only lasted for about two weeks. In these two weeks, kura clover acted as a blanket cover of the soil surface and may have reduced soil evaporation to a large extent. For example, kura clover was suppressed on May 26, 2008, kC plots had higher SWS than fC plots in the following two weeks, but showed a rapid drop of SWS during the following period of kura clover recovery. In 2006, corn was not planted in kC treatment in which SWC was generally lower than the fC treatment in the late spring but similar in

August through September. This suggests that the amount of water depletion by kura clover was higher than corn from May to July and similar to corn in August to September. If corn could not successfully establish its canopy to suppress the growth of kura clover, the growth of corn would be affected by soil water stress. It is demonstrated in 2007 that corn established a poor canopy and experienced a long period of water stress until early August when two significant rain events occurred on August 1 (31 mm) and August 4 (66 mm). However, these rain events were too late because corn had already passed through all vegetative stages. The corn yield in kC was higher in 2008 than in 2007 possibly due to the 102 mm rainfall that occurred in July 2008. The corn grain yield of the kC treatment compared with the fC treatment was 1.03 Mg ha^{-1} versus 7.35 Mg ha^{-1} for 2007, and 4.07 Mg ha^{-1} versus 9.62 Mg ha^{-1} for 2008. As noted alone, the rainfall in June and July of 2007 was well below average. Besides effective kura clover suppression, the rainfall amount in June and July is suspected to be critical to corn growth and production. Under effective kura clover suppression management and limited competition, corn yields in the kC treatment have been shown to reach the same level as fC treatment (Zemenchik et al., 2000)

4.4.3.4 SWS under perennial forage

The SWS in PF treatment was significantly lower than any other treatments when statistical analysis for SWS was conducted over 3-year and over each individual year ($p<0.05$, Table 4.3). The PF treatment showed the lowest average weekly SWS (181 mm) among all the land cover treatments, significantly lower than the fC, rC, fS, rS, and kC ($p<0.05$). This indicates that the greatest amount of water is depleted by the PF roots during the growing seasons. The pattern of SWS in PF treatment was similar to kC in early and middle spring and late summer when the main rainfall events occurred (Figure 4.10). Lower SWS in PF treatment started in late spring and this difference continued unless the study site received high rainfall amounts. The largest difference of SWS between kC and PF (38.5 mm) was observed on July 17, 2007. Compared with conventional corn plots (fC), the maximum SWS difference between PF and fC was 40.2 mm in 2006, 51.0 mm in 2007, and 60.9 mm in 2008. The data suggests that perennial forage transpires water in 0-60 cm soil layer at greater quantities than annual crops and the kC cropping system. The differences of SWS mainly occurred in the summer when the stream flow rate and standing water level are low in Iowa. Converting corn-soybean rotation into forage grassland corn could significantly reduce the surface runoff and the subsurface drainage during and after the summer storm, which may subsequently affect the stream flow volume in the summer.

4.5 Conclusion

Soil water storage for 0 to 60 cm was monitored on a weekly basis during the growing season in three years from 2006 through 2008 under various land covers in Iowa. Applied land covers in each year were fallow-Corn, rye-Corn, fallow-Soybean, rye-Soybean, kura clover-Corn, and perennial forage. Results indicate that, though varied from year to year, soil water storage was significantly affected by the land cover treatments, particularly in the summer. Treatments rye-Corn and rye-Soybean almost consistently showed higher SWS than their controls, fallow-Corn and fallow-Soybean. In the spring of each year, during a ten- to fifteen-day period when the rainfall was minimal, soil water storage in plots with every spring land cover species, rye, kura clover, and forage grass, decreased at a significantly higher rate than the fallowed corn or soybean plots. In general, soil water stored in the top 60-cm of the soil profile under kura clover-Corn treatment was significantly less than that under rye-Corn and rye-Soybean treatments across the three years of the study. Low soil moisture in the kura clover-Corn plots likely contributed to low corn biomass and yield. The soil water storage under perennial forage was significantly lower than other treatments in each individual year.

The elevated soil water storage in the winter rye cover crop treatments may be attributed to the increased soil macroporsity by rye root and the increased rye residue coverage on the soil surface. The drastic decrease of soil water storage in rye-Soybean treatment relative to fallow-Soybean treatment during the ten- to fifteen-day period before the termination of rye growth could be explained by notable transpirational water use of rye. When considering the kura-clover treatments, the results indicate that it is challenging for corn to compete for water especially in a dry summer.

This study indicates that introducing rye as a winter cover crop is a promising alternative cropping management for Iowa farms to increase available soil water, without detrimental impacts on corn or soybean yields. Transpirational water use by rye may reduce surface runoff and subsurface drainage in the spring which is one of the major local environmental concerns. Kura clover growing with corn as a living mulch needs further study to establish a feasible agronomic management to avoid yield loss. Distinct low soil water storage under perennial forage suggests that the hydrologic cycle on subsurface drained lands in Iowa may be altered by converting the conventional corn soybean rotation into perennial vegetation.

4.6 References

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Table 4.1. Agronomic management in the three years of study.

Management	2005	2006	2007	2008
Termination of rye followed by corn		24-Apr	30-Apr	6-May
Corn planting §		4-May	14-May	15-May
Soybean planting		10-May	17-May	23-May
Termination of rye followed by soybean		16-May	23-May	26-May
Suppression of kura clover for corn establishment ¶		-	29-May	26-May
Fertilization to corn		18-May	5-Jun	20-Jun
Soybean harvest		3-Oct	15-Oct	11-Oct
Corn harvesting		7-Oct	22-Oct	28-Oct
Rye seeding	11-Oct	12-Oct	25-Oct	21-Oct

§ Corn was not planted in kC treatment in 2006.
¶ Kura clover was not suppressed in 2006.

Table 4.2. Rainfall and temperature at the study site.

Month	Precipitation (mm)				Temperature (˚C)			
	long-term*	2006	2007	2008	long-term	2006	2007	2008
January	23	22	45	27	-9.3	-1.7	-7.9	-10.3
February	19	19	42	25	-5.7	-5.7	-11.1	-9.5
March	55	92	69	45	1.0	1.3	3.8	-1.1
April	81	93	106	90	8.6	11.7	7.4	6.5
May	99	22	90	156	15.6	15.8	18.1	14.1
June	116	47	44	161	21.0	21	21.5	20.3
July	110	10	41	102	22.8	23.2	22.2	22.7
August	111	113	367	81	21.3	21	22.2	18.1
September	78	107	97	65	16.7	14.5	17.9	16.4
October	57	19	119	84	9.8	7.7	12.5	9.8
November	46	46	1	42	0.9	2.1	1.4	1.3
December	27	35	27	48	-6.6	-1.6	-8	-9.5
Total	821	626	1050	926	8.0	9.1	8.3	6.6

*long-term norms were averages of weather data over 1971-2000 for Pocahontas (Station No. 125) and Humboldt (Station No. 070), IA, 19 km west and east from the research site. Obtained from National Climatic Data Center, NOAA (http://cdo.ncdc.noaa.gov/ climate normals/ clim81/IDnorm.pdf).

Table 4.3. Average weekly soil water storage for each land cover treatment.

Treatment	Soil water storage (mm)							
	3-year average		2006		2007		2008	
fC	196	bc	187	b	198	ab	202	a
rC	202	a	197	a	203	ab	206	a
fS	196	bc	190	ab	196	b	202	a
rS	200	ab	193	ab	201	ab	206	a
kC	193	c	176	c	195	b	206	a
PF	181	d	166	d	185	c	188	b
average	195		185		196		202	

Mean within years and on average (i.e., within column) followed the same letter are not significantly different at $p=0.05$.

Annual average soil water storage is significantly different among years: 2008>2007>2006 at $p<0.05$.

Table 4.4. SWS change prior to rye growth termination in rS and fS treatments.

Year	Date		rS	fS	rS-fS	
			mm	mm	mm	
2006	1-May	SWS	205	196		
	16-May		193	191		
		ΔSWS	-12	-5	-7	**
					(0.5 mm/d)	
2007	8-May	SWS	212	206		
	21-May		187	195		
		ΔSWS	-25	-11	-14	**
					(0.9 mm/d)	
2008	12-May	SWS	222	213		
	22-May		194	199		
		ΔSWS	-28	-14	-14	**
					(1.4 mm/d)	

**: mean is significantly different from 0 at p=0.05.

Table 4.5. SWS change prior to rye growth termination in kC and PF treatments.

Year	Date		kC	PF	fC	kC-fC		PF-fC		PF-kC	
			mm	mm	mm	mm		mm		mm	
2006	1-May	SWS	201	202	195						
	16-May		177	173	193						
		ΔSWS	-23	-29	-2	-21	***	-27	***	-6	**
						(1.4 mm/d)		(1.8mm/d)		(0.4 mm/d)	
2007	8-May	SWS	211	215	208						
	21-May		168	171	197						
		ΔSWS	-43	-44	-11	-32	***	-34	***	-1	ns
						(2.5 mm/d)		(2.6 mm/d)		(0.1 mm/d)	
2008	12-May	SWS	217	218	215						
	22-May		185	175	201						
		ΔSWS	-33	-43	-13	-20	*	-30	**	-10	ns
						(2.0 mm/d)		(3.0 mm/d)		(1.0 mm/d)	

*, **, and ***: means are significantly different from 0 at p=0.1, 0.05, and 0.001, respectively. ns: means are not significantly different from 0 at p=0.1.

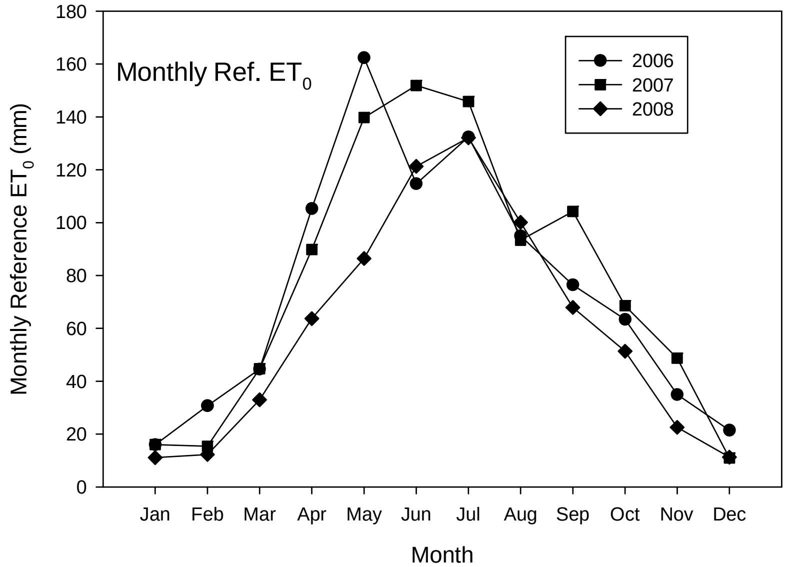

Figure 4.1. Monthly reference ET0 in the three years of study.

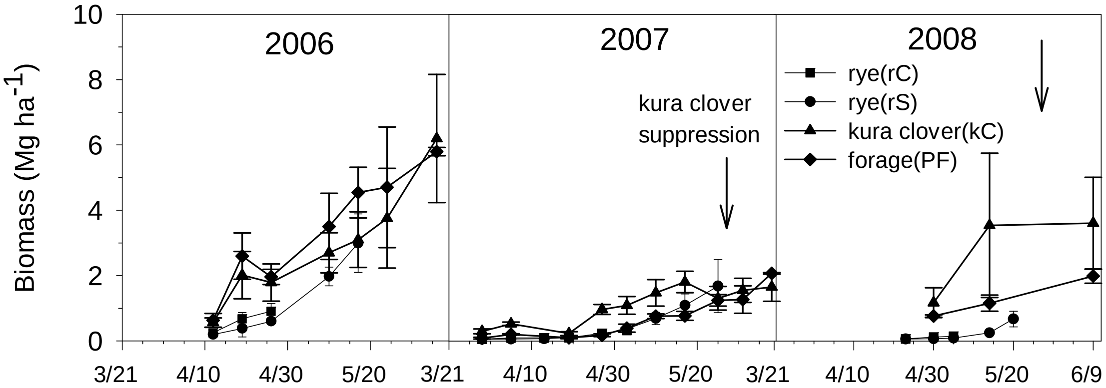

Figure 4.2. Above ground dry biomass of rye, kura clover, and forage in the three years of study (Error bar is ±1 standard deviation).

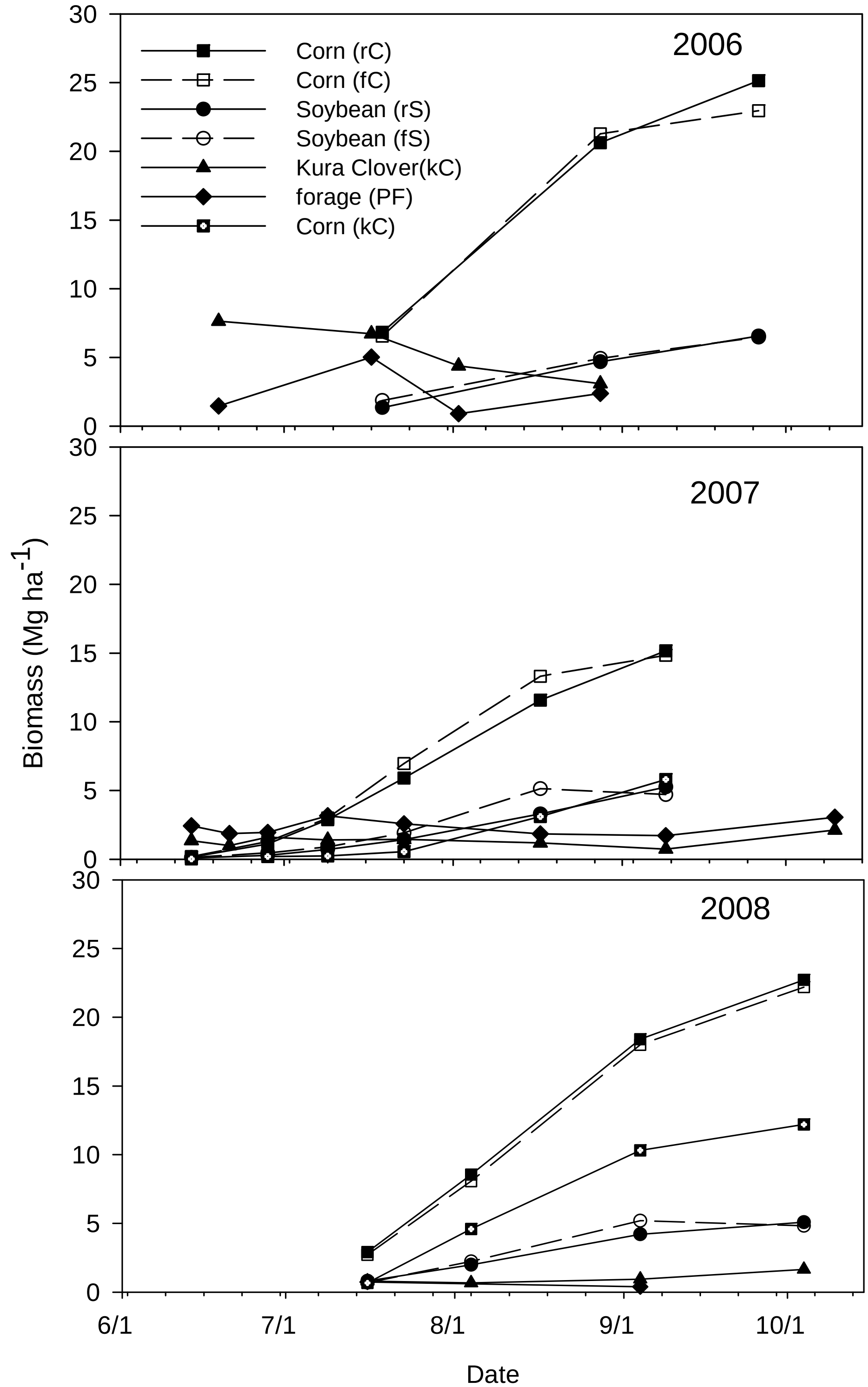

Figure 4.3. Biomass accumulation of all land covers in the three years of study.

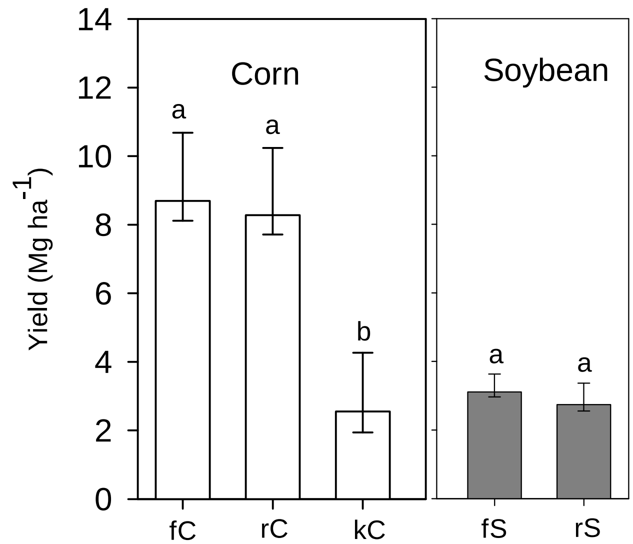

Figure 4.4. Corn and soybean grain yield averaged over the three years of study. In the kC treatment, corn was planted in 2007 and 2008 not in 2006 (Error bar is ±1 standard deviation).

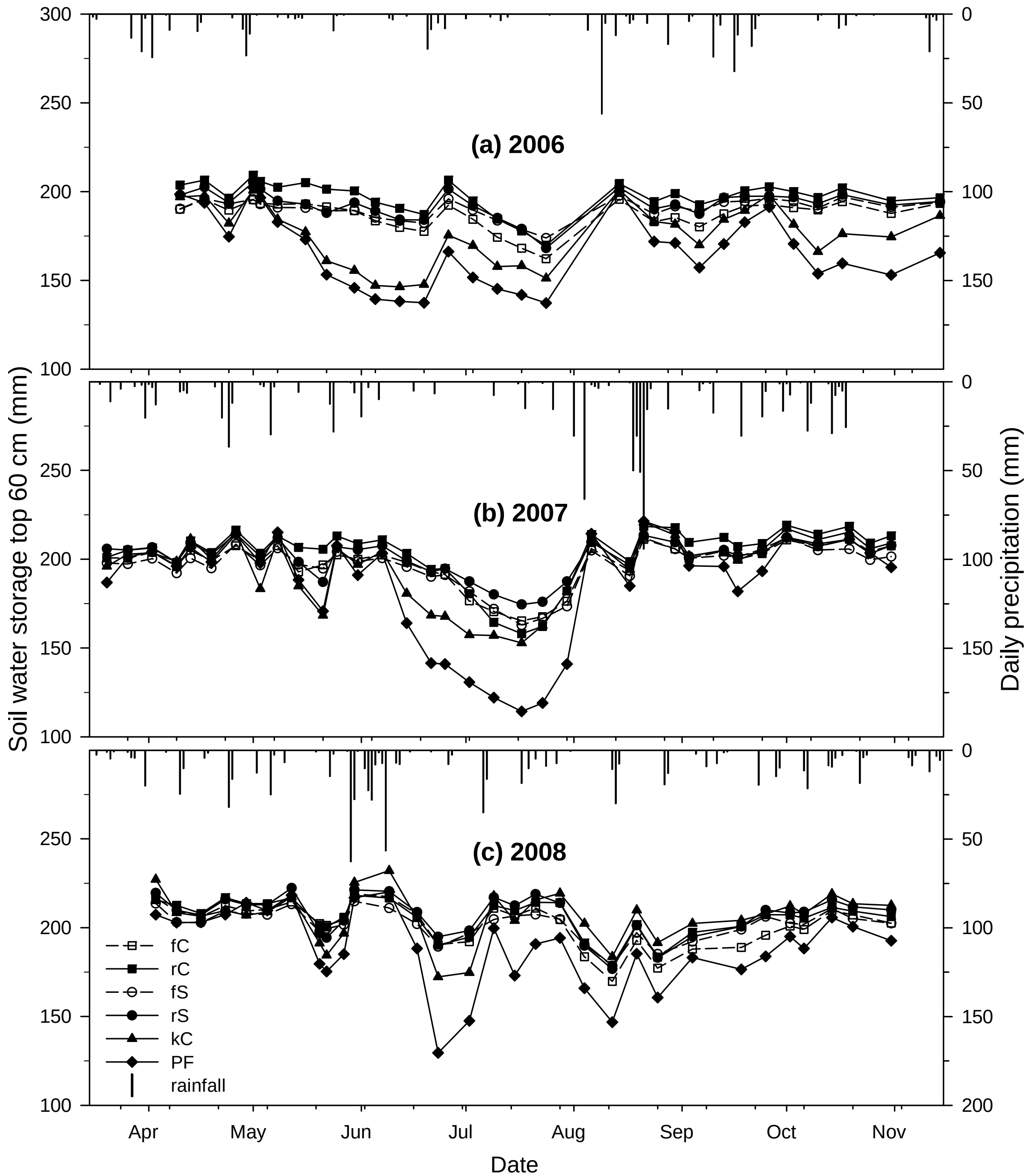

Figure 4.5. Soil water storage (SWS) in 0-60 cm soil profile for various land cover treatments in (a) 2006, (b) 2007, and (c) 2008.

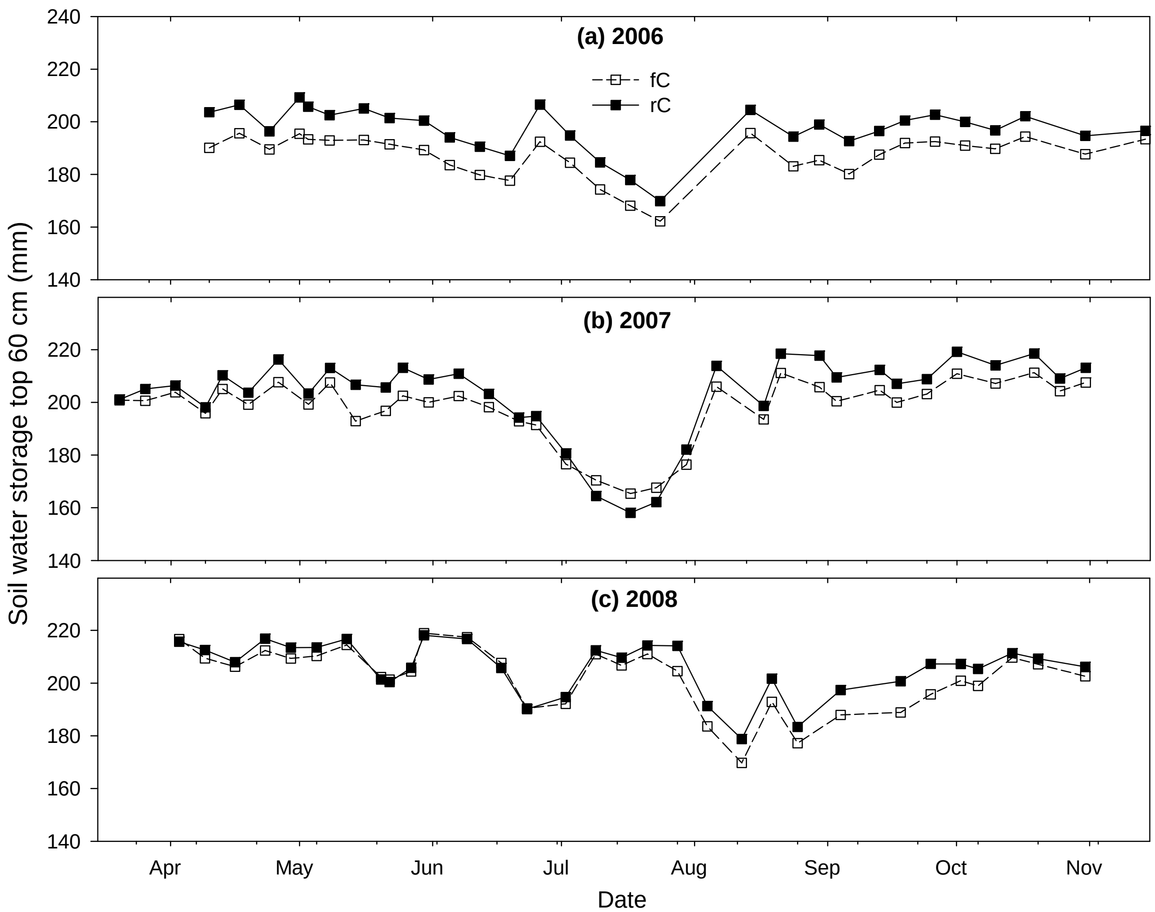

Figure 4.6. Comparison of SWS in fC versus rC in (a) 2006, (b) 2007, and (c) 2008.

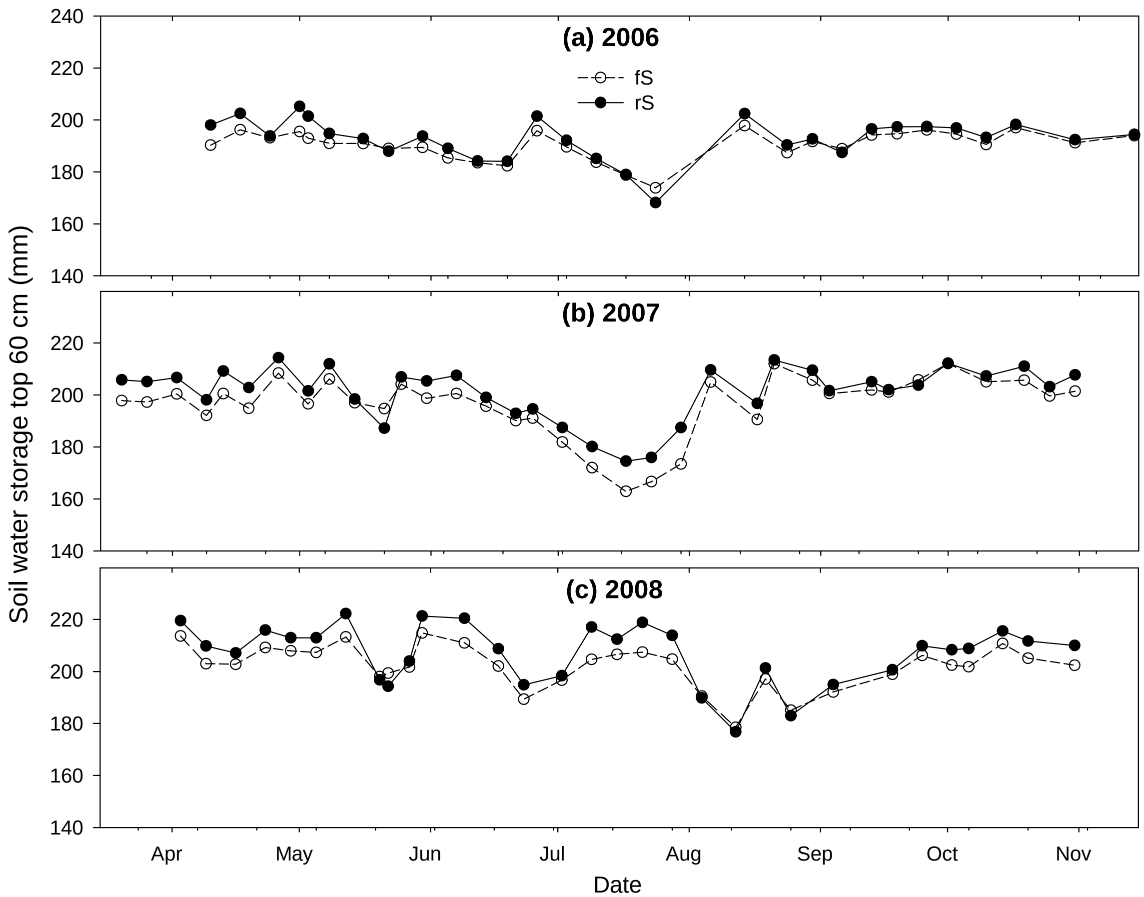

Figure 4.7. Comparison of SWS in fS versus rS in the three years from (a) 2006, (b) 2007, and (c) 2008.

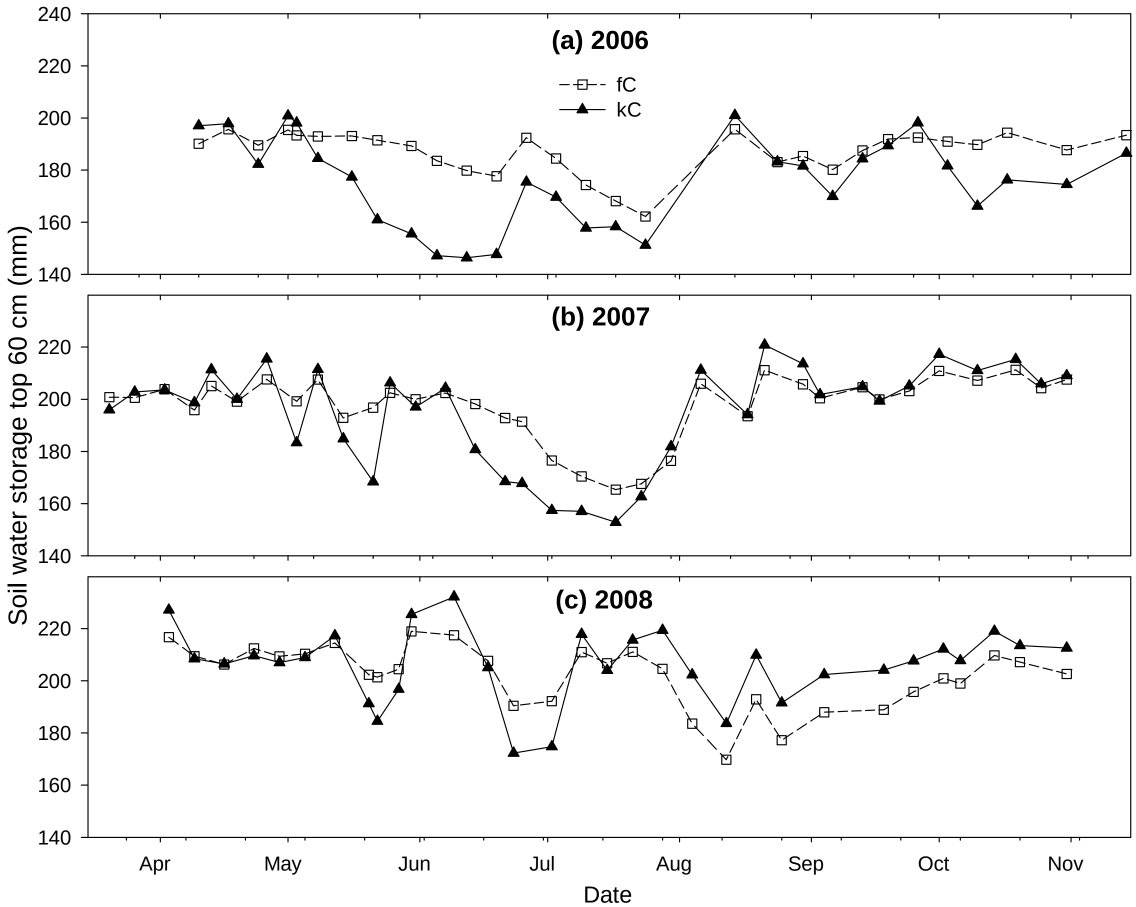

Figure 4.8. Comparison of SWS in fC versus kC in (a) 2006, (b) 2007, and (c) 2008.

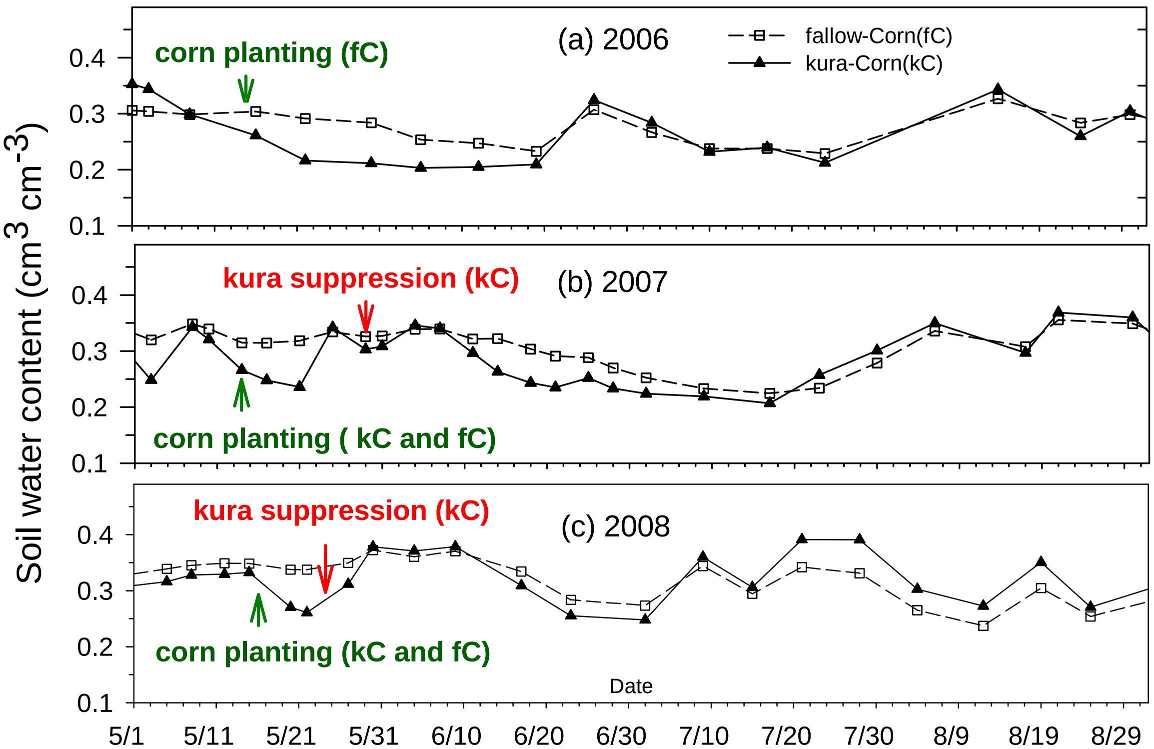

Figure 4.9. Soil water content at 5-15 cm of kC and fC treatments in (a) 2006, (b) 2007, and (c) 2008.

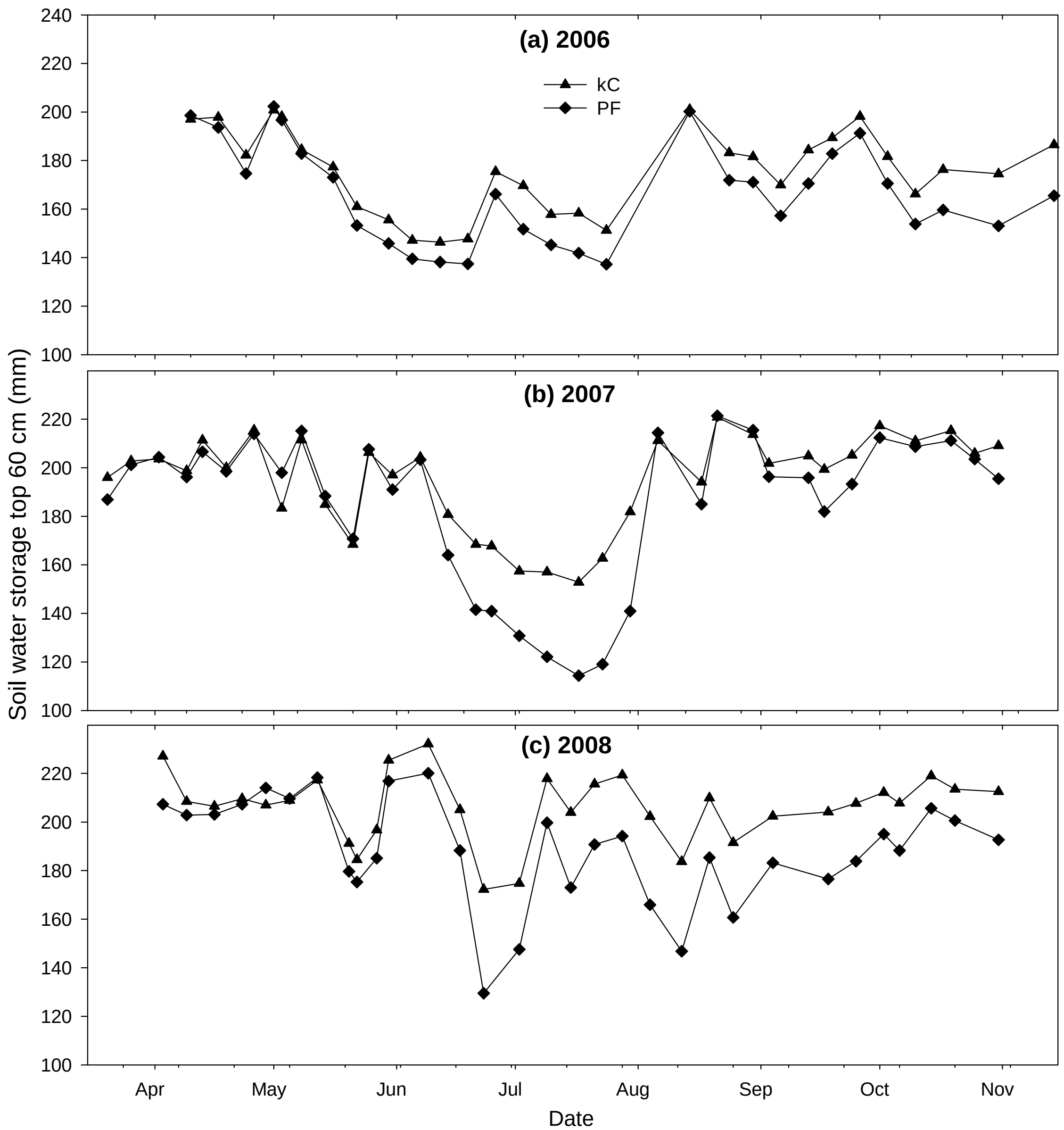

Figure 4.10. Comparison of SWS in kC versus PF in (a) 2006, (b) 2007, and (c) 2008.

CHAPTER 5. SIMULATING LONG-TERM IMPACTS OF A WINTER COVER CROP WITH CORN-SOYBEAN ROTATION ON HYDROLOGIC CYCLING AND NITROGEN DYNAMICS USING THE RZWQM-DSSAT MODEL

A paper to be submitted to the Transactions of the ASABE

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5.1 Abstract

Planting winter cover crop into the conventional corn-soybean rotation is a promising approach for reducing subsurface drainage and nitrate-nitrogen losses in the Midwest of the United States. However, the long-term impact of this alternation needs investigation. The objective of this study was to evaluate the performance of RZWQM-DSSAT model against field measured data and to use this model as a tool to study the long-term impacts of a cover cropping system with corn-soybean rotation on hydrologic and nitrogen balance. In this study, hydrology, nitrogen, and crop growth for a corn-soybean rotation with winter rye cover crop cropping system were simulated using RZWQM-DSSAT (version 1.72.2008) and the results were tested against four years of field data collected near Gilmore City, Iowa. The model adequately simulated the subsurface drainage, soil water storage (0-60cm), NO_3-N loss, and crop growth of rye, corn, and soybean. Nash-Sutcliffe model efficiency (EF) for annual, monthly, and daily drainage prediction was 0.95, 0.82, and 0.44, respectively. Weekly soil water storage, main crop yield, above ground dry biomass, and leaf area index (LAI) were generally simulated in a reasonable manner with EF of 0.34, 0.96, 0.87, and 0.89, respectively. Annual and monthly simulated NO_3-N losses were within percentage difference (%D) of 4% from the observed averages, with EF equal to 0.92 and 0.55, respectively. Simulation of average total nitrogen uptake by rye and main crops was within 13.6% and

3.2% difference from field measured data. The tested RZWQM-DSSAT model was used with a 49-year weather and management data set to study long-term impacts of a cover cropping system on hydrologic cycling and nitrogen dynamics. Simulation results showed that adding rye as a winter cover crop reduced annual subsurface drainage and NO_3-N loss by 20% (4.0 cm) and 19% (8.5 kg N ha^{-1}), respectively, and increased annual ET by 7% (4.0 cm). The reductions mainly occurred during the spring months. Results suggest that introducing winter rye cover crop to conventional corn-soybean rotation is a promising approach to improve the water quality from Iowa's subsurface drained agricultural systems.

5.2 Introduction

Agricultural nutrient loading to the Mississippi River is suspected to be a main contributor to the hypoxia zone in the Gulf of Mexico (Rabalais et al., 2001). Iowa has been listed as one of the four highest annual total N yield regions. Annual average total N yields during 1980-1996 were 2750, 2290, 2020, 3090 and 1850 kg N km^{-2} yr^{-1} in the Cedar, Iowa, Skunk, Raccoon, and Des Moines Rivers in the state of Iowa, respectively (Goolsby et al., 2001). Approximately 24.5% of agricultural land is artificially drained in Iowa (Baker et al., 2004) and the subsurface drainage is the main source of nitrate leaching which is closely related to subsurface drainage volume (Baker et al, 1975; Cambardella et al., 1999). Hatfield et al. (1998) documented that nitrate loading had the same pattern as subsurface drainage discharge in the Walnut Creek watershed in central Iowa. Strong linear relationships between nitrate leaching and drainage flow volume have also documented in Iowa's tile drained crop fields (Bakhsh et al., 2002; Kanwar et al., 2005).

The time period from April through June, when the row crops have not been plant or still in the early stages, was found to be the main subsurface drainage period. A fifteen-year study indicated that nearly 70% of the annual drainage occurred within these 3 months in north-central Iowa (Helmers et al., 2005). Growing winter cover crop is one of the strategies to reduce nitrate leaching in tile-drained Midwestern soils (Dinnes et al., 2002). Strock et al. (2004) found that using rye as a winter cover crop in Minnesota reduced subsurface drainage volume by 11% and mass of nitrate loss by 13%. Kassavalou and Walters (1999) reported that winter rye cover crop reduced residual soil nitrate by 18% and 33% in Nebraska. Nitrogen (N) uptake by winter rye was reported to be 42-48 kg N ha^{-1} in Nebraska, 21-74 kg N ha^{-1} in Minnesota, 9-34 kg N ha^{-1} in Wisconsin, and 35-52 kg N ha^{-1} in Illinois (Kessavalou and Walters, 1999; Ruffo et al., 2004; Andraski, 2005; DeBruin, 2005). In Iowa, confined lysimeter studies suggested that winter rye cover crop significantly reduced subsurface drainage volume and nitrate loss (Logsdon et al., 2002; Parkin et al., 2006; Qi and Helmers, 2009). In field studies, Kaspar et al. (2007) reported that rye cover did not reduce the cumulative annual drainage but significantly decreased the flow weighted NO_3-N concentration by 59% and NO_3-N load by 61%, whereas Qi et al. (2008) documented that NO_3-N concentrations in soil water of rye prior to soybean was significantly reduced but annual drainage volume and nitrate load was not significantly reduced by rye. Overall, the inconsistency of drainage and nitrate loss reductions by winter rye as a cover crop may be at least partially attributed to the variability of field and weather patterns.

Agricultural systems models are promising tools for evaluating the effects of emerging agricultural practices on the local hydrologic cycle and water environment. In Iowa, Kanwar (1981) developed a computer model to simulate water and nitrate movement in a subsurface drainage system and predicted average annual tile flow and nitrogen loss were very close to the 7-year observed data set (Kanwar et al., 1983). DRAINMOD (Skaggs, 1978) was calibrated and validated to simulate long-term effect of drainage design and management on hydrologic components (Singh et al., 2006; Singh et al., 2007) and to predict the future subsurface drainage pattern under projected weather conditions due to climate change (Singh et al., 2009). Modified SWAT (Du et al. 2005) adequately simulated the effects of different management practices and cropping systems on water balance and water quality in Iowa's agricultural watersheds (Gassman et al., 2006; Saleh et al., 2007; Schilling et al., 2008). Bakhsh and Kanwar (2001) simulated the effects of tillage on nitrate loss in Iowa using the GLEAMS model (Knisel, 1993). Other models, such as APSIM, DCNC, and CERES have been utilized to evaluate agricultural management and fertilization rate on Iowa's subsurface drainage water quality and crop production with reasonable well performance (Garrsion et al., 1999; Paz et al., 1999; Li et al., 2006; Malone, et al. 2007).

The Root Zone Water Quality Model (RZWQM, Ahuja et al., 2000) describes the physical, biological, and chemical processes in the agricultural crop root zone and from this simulates plant growth, water movement, and fate of nutrient and pesticides. RZWQM has been widely used to simulate the response of subsurface drainage and water quality, as well as crop production, to the change in agricultural management, fertilization rate, tillage, and cropping systems. RZWQM was evaluated by field measured data from MESA sites across the Midwestern United States (Hanson et al., 1999; Jaynes and Miller, 1999; Wu et al., 1999; Ghidey et al., 1999) and the strength of its hydrologic and nutrient cycling algorithms under various climatic conditions was recognized by model users. RZWQM has been proven to be reliable for simulating soil water content, residual soil nitrate, and crop production with irrigated wheat-corn double cropping system in China (Wang and Huang, 2008; Yu et al., 2006) and in the Mediterranean region (Cameira et al, 2007; Cameira et al., 2005).

In Iowa, RZWQM has been intensively tested and used as a tool to evaluate the effect of potential agricultural management on water balance and drainage water quality. Singh (1994) modified the soil water movement component and added a drainage component to RZWQM, which increased its reliability in predicting soil water dynamics and facilitated nitrate leaching simulation. Using the modified and calibrated model, Azevedo (1997) simulated water quality and crop yield under different N application strategies and rates in Iowa for 14 years (1978-1992). Kumar et al. (1998) found that RZWQM was capable of simulating subsurface drainage flow and nitrate concentration with different manure application rates under the weather and soil conditions of Iowa. RZWQM was demonstrated to be sufficient in simulating corn and soybean yield and nitrate loss as affected by variable nitrogen application rates at two drainage sites in Iowa (Bakhsh et al., 2001; Bakhsh et al., 2004). Recently, sensitivity of RZWQM was analyzed using observed data in Iowa and the results suggested that drainage and NO_3-N loss was sensitive to lateral saturated hydraulic conductivity (Ma et al., 2007). The RZWQM has also been used to simulate the long-term effect of crop rotation, tillage, controlled drainage, and N application rate on crop production, water balance, and nitrate loss in northeast Iowa (Malone et al., 2007a; Ma et al., 2007).

CERES and CROPGRO models were recently coupled with RZWQM (Ma et al., 2005; 2006), generating RZWQM-DSSAT model. Saseendran et al. (2007) reported that this hybrid model showed no advantages over the previous generic crop growth module within RZWQM at the Nashua site in Iowa, but could be potentially improved by obtaining site-specific weather data and reducing the uncertainty of input parameters. Based on more detailed site specific data and parameters from previous RZWQM modeling studies conducted in Iowa, Thorp et al. (2007) found that RZWQM-DSSAT performed reasonably in simulating corn yield and nitrogen dynamics for a crop production field near Story City, IA. The calibrated hybrid model was subsequently adopted by Li et al. (2008) and successfully used to simulate nitrate leaching under winter rye cover crop at a site in Boone County, IA. Since there is no rye option in CERES model, CERES-wheat was used by Li et al. (2008) because of the similarity in growth of wheat and rye. In addition, a previous study indicated that winter rye cover crop production was well described by the CERES-wheat model in southeast Ontario, Canada (Wagner-Riddle et al., 1997). However, there has been no study investigating the long-term effects of adding winter rye cover crop to the corn-soybean rotation on hydrologic and nitrogen cycling. With the increased concern related to water quality in Iowa, there is a need to investigate the long-term effectiveness of introducing winter rye cover crop on subsurface drainage and nitrate loss reduction. The objectives of this research were to: 1) parameterize and evaluate the performance of RZWQM-DSSAT using subsurface drainage, soil water content, and crop growth data; and 2) predict the long-term subsurface drainage and NO_3-N loss for a corn-soybean rotation with and without a winter rye cover crop.

5.3 Material and Methods

5.3.1 Model overview

RZWQM-DSSAT (version 1.72.2008) is an one-dimensional agricultural system model consisting of hydrology, nutrition and pesticide transport and transformation, plant growth, and management practice components (Ahuja et al., 2000). The infiltration at the event of rainfall, irrigation, or snow melting is computed by a modified Green-Ampt approach and the water redistribution in the soil profile, considering surface evaporation and plant uptake as sinks, is simulated by the Richards equation. Water stored in the soil profile, if in excess of the field capacity, is drained to build up a water table above the impermeable layer and the subsequent tile drainage flux is calculated using the steady state Hooghoudt equation. For the upper boundary, soil evaporation and plant transpiration are estimated by the double layer model of Shuttleworth and Wallance (1985), which is an extension of the Penman-Monteith concept. The deep seepage and lateral flow are quantified by the user defined parameters of constant bottom layer water flux rate and the hydraulic gradient, respectively.

The nutrient chemistry processes model incorporated in RZWQM-DSSAT is OMNI (Ahuja, et al., 2000), a state-of-the-art model for carbon and nitrogen cycling in soils. It integrates the crop residue and soil humus pools in existing models such as CENTURY (Parton et al., 1983) and NTRM (Shaffer and Larson, 1987) and also includes new features such as chemical rate process, soil microbial growth, and environmental interaction. Nutrient and organic matter cycling are determined by soil water, temperature, microbial population, and user defined rate coefficients. The microbial population growth is described by the organic carbon and nitrogen decay. Chemical equilibrium approach is used to calculate the ion changes in the soil solution. The model also includes pesticide transport and degradation, agricultural management practices, soil heat transport, soil freezing and snowpack, and overland flow and sediment routing.

The coupled DSSAT family of crop growth models enhanced the capability of RZWQM-DSSAT in describing crop establishment and water and nutrient uptake.

Parameters of crop cultivars that have been commonly planted in the United States are tested and well documented for the model users. Output of DSSAT crop models, such as growth stage, silking/anthesis day and maturity day, facilitates the calibration of crop parameters. The crop root water uptake can be conveniently adjusted by model users by changing the soil root growth factor for each calculated soil layer. Water and nutrient stress is included in the RZWQM-DSSAT model to estimate response of crop growth to environmental conditions.

5.3.2 Site description and management

The field study was conducted at the Agricultural Drainage Water Quality - Research and Demonstration Site (ADWQ-RDS, former Agricultural Drainage Well Site) near Gilmore City in Pocahontas County, north central Iowa. This site, which was established in 1989, has 76 individually drained plots with the same layout. The size of each plot was 38 m in length and 15.2 m in width. Predominant soils are Nicollet (fine-loamy, mixed, superactive, mesic Aquic Hapludoll), Webster (fine-loamy, mixed, superactive,calcareous, mesic Typic Endoaquolls), Canisteo (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls), and Okoboji (Fine, smectitic, mesic Cumulic Vertic Endoaquolls). As part of this study, the Plot No. 7-1 was used because it is located in a relatively higher area and is separated from upper land by an open ditch. Soil in this plot was mapped as Canisteo according to soil survey (USDA, 1985). Plots were established after the installation of corrugated plastic drain tiles through the center and both boundaries parallel to the long dimension (7.6 m spacing) at a depth of 1.06 m. The two border drains, which were installed to help prevent lateral, subsurface drainage flow from adjacent plots, have an outlet to the surface at a remote location. Only the center drainage line is monitored for drainage volume and pollutant concentrations. Drainage water from the center line is collected in an aluminum culvert with automatic pumping, volume monitoring and water sampling systems. The subsurface drainage volume of each plot has been continuously monitored since 1990. Detailed design of this drainage site has been described in greater detail by Helmers et al. (2005), Singh et al. (2006), and Lawlor et al. (2008).

The experimental phase that included winter cover crop as a treatment was initiated in October 2004 by the first planting of rye under a winter cover crop for a commonly adopted corn-soybean rotation cropping system in Iowa. Agronomic field activities were completed in a timely manner prior to and during the crop season beginning in October 2004 with plot tillage and seeding (Table 5.1). Prior to rye planting, corn residue was chopped, disked twice and smoothed with a field cultivator, and soybean residue was disked once and field cultivated. 'Rhymin' rye (Secale cereale) was drill seeded at a rate of 100 kg ha^{-1} (3638000 seeds ha^{-1}) in 19 cm rows with a skip row every 76 cm for subsequent corn or soybean planting in the spring. Glyphosate resistant corn (Zea maize) and soybean (Glycine max) were used and planting dates were dictated by field conditions. Seeding rates were 77,000 seed ha^{-1} for corn (DAKLB 50-45) and 439,750 seed ha^{-1} for soybean (Pioneer 92M40-Group 2 middle season). Rye was planted in every October and the growth of rye was terminated by glyphosate at a rate of 239 mL ha^{-1} in the following April or May. Corn was planted in odd years and soybean in even years to the Plot No. 7-1. Commercial-grade 28% aqueous ammonia-nitrogen (N) was applied at 140 kg N ha^{-1} to the corn in spring closely following corn emergence. N fertilizer was applied mid-row to corn, with a conventional knife applicator. Recommended N application rates for the study area are 112 to 168 kg N ha^{-1} (Blackmer et al., 1997). For weed control, glyphosate was subsequently applied two more times during the growing season, dictated by weed pressure. The experiment is still ongoing and this study presents data obtained until December 2008.

5.3.3 Data collection

5.3.3.1 Weather data

An automatic meteorological weather station at the site recorded rainfall, air temperature, soil temperature at 4-inch depth, solar radiation, relative humidity and wind speed at a 5-minute interval. Rainfall was also recorded by an additional tipping-bucket rain gauge (Campbell Scientific, Inc., Logan, Utah) installed near the center of the site area. To ensure the rainfall data collection when the those two electronic rain gauges were interrupted by thunder storms, two cylinder rain gauges were mounted at the north and south edges of the site and was checked on a weekly basis. Daily rainfall was obtained from the average of automatic meteorological weather station record and the tipping-bucket rain gauge record. Missing daily rainfall data was obtained from a National Climate Data Center (NCDC) at Humboldt (Station No. 070), IA, 15 km to the east of the site. Humboldt daily rainfall data was carefully compared with the weekly onsite cylinder rain gauge records. Daily snowfall data was not measured at the site but was available at the NCDC weather station in Humboldt. Snowfall depth was converted into water depth by dividing the snowfall depth by of 10 (Luo et al., 2000). Chemical background of precipitation was set 0.6 ppm for NH_4-N, 0.6 ppm for NO_3-N, and 6.2 for pH value according to field measurement in Iowa (Tabatabai and Laflen, 1976). Daily maximum and minimum temperature were picked from the 5-minute interval temperature record. Daily solar radiation, relative humidity, and wind speed, which are necessary to drive RZWQM, were summed or averaged over the 5-minute interval data. Weather information for 2004 through 2008 were prepared via the way described above, whereas the long-term weather data from 1960 through 2003 were from another Iowa weather station in the Walnut Creek watershed in central Iowa (Malone, personal communication) because weather observations at the study site were not long enough.

5.3.3.2 Soil hydraulic properties

Site specific soil hydraulic properties, including bulk density, particle distribution, saturated hydraulic conductivity, and soil water characteristic curve, were determined from undisturbed soil cores. To obtain soil bulk density, undisturbed soil cores were extracted by a truck mounted Giddings Probe (#25-SCS Model HDGSRPS, Giddings Machine Company Inc, CO) at the northeast center of the plot. Another set of undisturbed soil cores was sampled at the southwest center to determine soil water characteristic curves. The draining part of the soil water characteristic curves was measured using tempe cells with porcelain plates as documented by Powers et al. (1999) under pressures of 1, 4, 10, 20, 40, and 80 kPa. The wetting part of the soil water characteristic curves was obtained following the procedure described by Lu et al. (2008) using a WP4 Dewpoint Potentiometer (Decagon Devices, Inc.). Bubbling pressure (P_b) and pore size distribution (λ) were fit using the Brooks and Corey (1964) equation over the pressure range of 0 to -1500 kPa. Residual water content was estimated by extrapolating each of the soil water characteristic curves to a point at which the gradient ($d\theta / dh$) approached zero (van Genuchten, 1980). Soil moisture at matrix potentials of 10, 33, and 1500 kPa was either interpolated or extrapolated from the soil water characteristic curves. Saturated hydraulic conductivity was measured using the falling head method (Klute and Dirksen, 1986) with 3 runs for each soil core. Soil chemistry properties including cation exchange capacity and pH value were analyzed by Ward Laboratory (Kearney, NE).

5.3.3.3 Drainage volume and NO_3-N loss

A flow meter was used to measure the subsurface drainage flow volume and the meter reading was manually recorded on a weekly or biweekly basis. Starting in April 2006, the flow meter was switched to a magnetic one which was connected to an electronic data logger, facilitating the measurement of drainage flow volume in increments of 14 L (0.5 cubic foot) which represented a drainage flow depth of 0.005 cm. A fraction of the drainage flow was directed to a 20 L carboy through a plated orifice nozzle. Subsamples of the drainage water were collected after approximately every 1.3 cm of drainage flow, and thereafter were stored in a cooler at 4 ºC until analyzed. NO_3-N concentration was analyzed in the Wetland Research Laboratory, Iowa State University through the second-derivative spectroscopy technique (Crumpton et al., 1992). Drainage water pumping and water sampling system is well documented in Lawlor et al. (2008). NO_3-N concentration was multiplied by the representative drainage volume to calculate NO_3-N loss.

5.3.3.4 Soil moisture

A PR2 Profile probe and a Theta probe (Delta-T Services, UK) were used to measure the soil permittivity starting in fall 2005. Soil permittivity was measured at two locations, centered in the southwest and northeast area of the plot. At each of the measurement locations, a fiberglass access tube was installed in fall 2005 to facilitate soil permittivity measurement in the soil profile (0-100 cm) at different layers by the PR2 probe. The permittivity of the top soil (0-5 cm) was measured five times around each access tube with the Theta probe to provide adequate replication. Measurement was not conducted in the winter because the soil was frozen and the probes are not capable of monitoring soil permittivity in frozen soils. The PR2 probe was calibrated by in-situ soil sampling in two consecutive years (Qi and Helmers, 2008). Permittivity measured by PR2 probe was converted to volumetric water content by the calibrated equations. The permittivity output of the Theta probe was converted into volumetric water content by the calibrated equation from Kaleita et al. (2005) that used field data collected in Des Moines Lobe soils. The observed volumetric water content data were multiplied by the representative depth intervals to compute the soil water storage (SWS) for each depth and summed up to obtain SWS information. Because the soil water content at 100 cm would be largely influenced by the high water table, SWS was calculated in the soil layers from 0 through 60 cm below the ground surface.

5.3.3.5 Biomass and LAI

Above ground biomass of rye and main crops were sampled in 2006, 2007, and 2008. Rye shoots were sampled weekly from early spring until chemically desiccated by glyphosate. From July, corn and soybean biomass were sampled once every three weeks until early October. Rye, corn and soybean were sampled along a 30-cm long section at four randomly selected locations in the plot. Samples were dried at 60 ºC for a week at the Agricultural Engineering Farm of Iowa State University. Total nitrogen (TN) content was analyzed for all sets of rye samples, and two sets of corn and soybean samples. TN analysis of the crop tissue was conducted in the Soil Plant Analysis Laboratory at Iowa State University by the combustion method. In 2006 and 2007, leaf area index of crop growing in Plot No. 7-1 was measured by a AccuPAR/LAI ceptometer (Decagon Devices, Inc.).

5.3.4 Model Initialization

Soil hydraulic properties for Plot No. 7-1 are included in Table 5.2. Soil depth above impermeable layer was selected to be 390 cm according to a similar modeling study by Singh et al. (2006) for this site. Lateral hydraulic conductivity (LKsat) was initially approximated as 1.4 times saturated hydraulic conductivity (Ksat) according to Singh et al. (2006) but subsequently adjusted to 2*Ksat to match the peak of daily drain flow. Soil properties from 0-120 cm depth were measured using soil cores while hydraulic properties of soil below 120 cm were not measured and as such were assumed to be the same as the 90-120 cm layer. To maintain a water table in the soil profile, Ksat of the bottom soil layer was assumed to be 0.01 cm h^{-1}. Soil dry heat capacity for the soil layers from 0-60 cm depth were estimated by the sum of the heat capacity of sand, silt, clay, and organic matter content for the soil in each depth (Jury and Horton, 2004). The calculated dry heat capacities averaged 1.31 MJ m^{-3} $°C^{-1}$ for 0-60 cm soils and 1.35 MJ m^{-3} $°C^{-1}$ for 60-389 cm soils.

Other input information, including soil and crop residue albedo, initial residue pools and microbial biomass, and crop growth parameters of rye were obtained from studies conducted in Iowa (Bakhsh et al., 2001; Ma et al., 2007; Thorp et al., 2007; Li et al., 2008; Thorp et al., 2009). Plant parameters for maize (IB 1068 DEKALB 521) and soybean (990002 M Group 2) were essentially default values with minor calibration as described below. For the model calibration and evaluation, the agronomic management practices from October 2004 through 2008 were conducted using the actual practices for this plot. For the

5.3.5 Model calibration

For the soil hydraulic properties, only the lateral hydraulic gradient, which controls the water loss by lateral flow, was calibrated indirectly using the observed subsurface drainage flow volume in 2004, the year prior to the initiation of rye planting. In 2004, the plot was planted with half corn and half soybean during the summer growing season and rye cover crop in the fall. The RZWQM model was executed with varied lateral hydraulic gradient for corn-rye and soybean-rye, respectively, and the simulated drainage averaged over corn-rye and soybean-rye were compared with observed drainage in 2004. For the DSSAT crop growth parameters, LFMAX for soybean, PHINT for maize, and soil root growth factors (SRGF) for soybean, maize, and rye were calibrated using the observed crop growth and soil moisture data. In this study, the main goal was to evaluate the hydrologic cycling and N dynamics, so the crop growth component of the model was calibrated using data obtained in all the 4 years of study from 2005 through 2008 (soil moisture was not monitored in 2005).

5.3.5 Model evaluation

Four-year field measured data from 2005 through 2008, including drainage flow, soil water storage, nitrate leaching, were compared with the simulated output. To get a stable humus and soil microbial biomass, as required for running RZWQM-DSSAT, weather data and conventional agronomic management in the years of 1960 through 2004 were loaded into the model and run as a pretreatment for the plot. In summary, input parameters were from site specific measured soil information, literature values for nutrient and soil microbial biomass, mainly default crop growth factors, and several calibrated parameters as described above.

In this study, the following four statistical factors were used to evaluate the performance of parameterized RZWQM-DSSAT in modeling water balance, nitrogen dynamics, and crop growth in the subsurface drained Iowa field.

Percentage difference: $\%D = \frac{P_i - O_i}{O_i} \times 100\%$

Nash-Sutcliffe model efficiency: $EF = \frac{\sum (O_i - \overline{O})^2 - \sum (P_i - O_i)^2}{\sum (O_i - \overline{O})^2}$

Coefficient of determination: $r^2 = \frac{\left[\sum (O_i - \overline{O})(P_i - \overline{P})\right]^2}{\sum (O_i - \overline{O})^2 \sum (P_i - \overline{P})^2}$

Index of agreement: $IoA = 1 - \frac{\sum_{i=1}^{N} (P_i - O_i)^2}{\sum_{i=1}^{N} \left(|O_i - \overline{O}| + |P_i - \overline{O}| \right)^2}$

where O_i and P_i are the observed and predicted output, and $\overline{O}$ and $\overline{P}$ are the mean of observed and predicted value. N is the number of data pairs. A model shows an excellent performance when the %D approaches 0 and EF, r^2, and IoA are close to 1. According to Moriasi et al. (2007), model performance was considered to be ‘satisfactory’ when EF and %D (same as PBIAS in Moriasi et al. (2007)) were >0.5 and within ±25%, respectively; model simulation can be judged as ‘good’ when EF >0.65 and %D within ±15%, and ‘very good’ when EF>0.75 and %D within ±10%. In this study, for the other two factors which Moriasi et al. (2007) did not provide criteria, model performance was considered to be ‘satisfactory’ when r^2 and IoA were greater 0.65, ‘good’ when r^2 and IoA were greater than 0.80, and ‘very good’ when greater than 0.9. Since data presented in Moriasi et al. (2007) were on annual and monthly basis, the simulation for daily flow and daily NO_3-N loss was considered to be acceptable when EF was greater than 0.4.

5.3.6 Model application

The evaluated RZWQM-DSSAT model was used to simulate the long-term effects of growing winter rye as a cover crop on hydrologic cycling and nitrogen dynamics for a corn-soybean rotation cropping system in Iowa. The weather and agronomic management information from 1960 to 2008 was input into the model. The first 9 years (1960-1968) was considered to be initialization period for RZWQM-DSSAT with corn-soybean rotation cropping system while in the later 40 years from 1969 to 2008 the hydrologic cycling and N dynamics was simulated by the model with two cropping scenarios: corn-soybean rotation with or without winter rye cover crop. Corn was grown in odd years and soybean in even years. Corn and soybean were planted alternatively on May 12 and May 20, respectively, and were harvested on Oct 5. Aqueous ammonia-nitrogen (N) was injected at a rate of 140 kg N ha^{-1} to corn at planting. The field was tandem disked and field cultivated in every October between corn or soybean harvest and rye planting. For the scenario with rye cover crop, rye was planted on Oct 12 in every year and rye growth was terminated on April 30 if prior to corn and May 18 if prior to soybean. The other scenario without rye was considered to be a baseline scenario, and was run in the model by removing the rye while holding all other management unchanged. Model output of annual hydrologic and nitrogen components in the 40 years from 1969 through 2008 were compared between the two scenarios to evaluate the effects of the winter rye cover crop.

5.4 Results and Discussion

5.4.1 Model calibration

5.4.1.1 Lateral hydraulic gradient

The calibrated value for lateral hydraulic gradient was 5×10^{-7} cm cm^{-1} in this study. The comparison of simulated and observed cumulative subsurface drainage for the calibration year of 2004 was shown in Figure 5.1. The statistical factors of %D, EF, r^2, and IoA were 3%, 0.88, 0.82, and 0.95 when comparing the observed manual reading of the flow volume with corresponding simulated values in 2004. The calibrated value for lateral hydraulic gradient was ten times smaller than the value obtained by Thorp et al. (2009). The ADWQ-RDS site is more intensively drained than the site in Story City (Thorp et al., 2007) so the water loss by lateral flow should be lower than that in Story City site. In RZWQM, the lateral flow was computed by the production of LKsat, distance from water table to the bottom of soil profile, and hydraulic gradient (Ma et al., 2007). At the ADWQ-RDS site, the high water table from the impermeable layer and high hydraulic conductivity, along with the low lateral water loss, led to a low calibrated lateral hydraulic gradient than the value in Thorp et al. (2009).

5.4.1.2 Crop growth parameters

For the calibration of crop growth component, the LFMAX was adjusted to 0.95 for soybean to improve the prediction of the soybean production. For corn, phylochron interval between successive leaf tip appearances (PHINT) was adjusted to obtain full maturity within 130 days because the corn planted in this field was supposed to mature around 101 days. The PHINT value was modified within the range between 60 (Thorp et al., 2007) and 38.9 (Ma et al., 2006) and a value of 45 was selected to get a maturity date in late-September. Kernel number (G2) and grain fill (G3) parameters were adjusted to 750 and 6.75, respectively, to reduce the error between measured and simulated yield, biomass, and leaf area index. In the previous version of RZWQM-DSSAT, soil root growth factors (SRGF) were not allowed to vary independently among crops in a rotation (Thorp et al., 2007). The updated version of the model improved this component and SRGF was adjusted for individual crops to fit the crop growth and the moisture and measurements. In the soil depths of 5, 15, 30, 40, 60, and 90 cm, the SRGF were 1, 1, 0.3, 0.05, 0.05, and 0.01 for corn, 1, 1, 0.3, 0.1, 0.1, and 0.1 for soybean, and 1, 1, 0.7, 0.54, 0.4, and 0.1 for wheat, respectively.

The simulated main crop yield of corn and soybean responded to the observed yield reasonably well (Table 5.3). Leaf area index (LAI) was only measured in 2006 and 2007 due to the limitation of time and labor. Corn and rye were not sampled for biomass measurement in 2005. When averaged over the four years, the simulated grain yield of the main crops was within 4.9% error of difference when compared to the measured value. Other statistical factors for the main crop grain yield were 0.96, 0.99, and 0.97 for EF, IoA and r^2, respectively. Water stress in 2007 led to corn yield reduction which was also reasonably captured by the RZWQM-DSSAT hybrid model.

In general, simulated total above ground dry biomass and leaf area index (LAI) were in good agreement with the observed data. The maximum above ground biomass and LAI of the main crops were well predicted by the model with percentage error of -7% and 1%, respectively. Figure 5.2 illustrates the simulated and observed total above ground biomss for winter rye cover crop and main crops. In the four study years from 2006 through 2008, the overall %D, EF, IoA, and r^2 were 2%, 0.87, 0.96, and 0.88, respectively when comparing the simulated total above ground biomass with the site sampled biomass. The RZWQM-DSSAT mimicked the corn above ground biomass accumulation every well with EF, IoA, and r^2 all equal to 1.0, respectively. This may be attributed to the robust build-in cultivar option of DKALB series. When simulating the soybean biomass accumulation in 2006 and 2008, the model reached to values of 0.56, 0.85, and 0.62 for statistical factors of EF, IoA, and r^2. The soybean biomass in the early stage was overestimated while was underestimated at maturity. For winter rye cover crop, the simulated above ground biomass across the three study years was acceptable relative to observed values with statistical values of 0.43, 0.84, and 0.74 for EF, IoA, and r^2, respectively. However, the simulated maximum above ground biomass and LAI were 25% and 18% higher than the observed values on average (Table 5.3). The subdued response of the model to the rye cover crop growth may have been due to the abnormal temperature pattern in 2007. In early April, 2007 when the rye was about 5 cm high, abnormally cold weather occurred and a part of the rye shoots was killed. However, the model did not respond to the biomass loss under this unexpected cold weather during the rye growing season.

RZWQM-DSSAT model captured leaf development of corn, soybean, and rye in a reasonably good manner. Comparison of simulated LAI against the AccuPAR/LAI measured values in 2006 and 2007 is shown in Figure 5.3. The statistics factors of EF, IoA, and r^2 were 0.89, 0.97, and 0.91, respectively. The predicted defoliation of soybean in 2006 was earlier than observed, which may lead to the underestimation of total above ground biomass at maturity. In 2007 when water stress occurred during the growing season, the observed corn LAI in 2007 was lower than the normal values (Hatfield et al., 2007), nevertheless, the model was able to respond to water stress and predicted LAI were in good agreement with observed values under water stress.

5.4.2 Model evaluation

5.4.2.1 Hydrology

The average annual precipitation in the four evaluation years (2005-2008) for hydrology components was 86.2 cm, close to the long-term annual precipitation of 82.1 cm in this area. The simulated annual subsurface drainage flow matched well with the observed drainage (Table 5.4). The observed average percentage difference (%D), Nash-Sutcliffe model efficiency (EF), coefficient of determination (r^2), and index of agreement (IoA) of the predicted annual subsurface drainage were 3%, 0.95, 0.95, and 0.99, respectively. Overall the results indicate that RZWQM-DSSAT performed 'very good' in predicting the annual subsurface drainage flow according to Moriasi et al. (2007). The simulated annual average actual ET of 50.0 cm was slightly higher than the 46.8 cm in Thorp et al. (2007), which could be explained by different weather patterns and the presence of the winter rye cover crop. For the corn or soybean growing season in May through September, the simulated ET in the four years varied from 37.2 to 43.1 cm, comparable to the observed ET values (33.4-49.3cm) in 1992 to 1994 in middle Iowa (Bakhsh et al., 2004). The model calculated soil evaporation and plant evaporation were 16.0 and 34.0 cm when averaged over the 4 years. Simulated lateral seepage water loss was 5.5 cm year^{-1}, with a very low variance among years. The small variance of lateral flow could be attributed to the similar pattern of the water table fluctuation.

Detailed information on drainage was examined to evaluate the model performance in predicting subsurface flow which is the main path of nitrogen loss from Iowa's crop field. Observed and simulated monthly drainage are depicted in Figure 5.4. Data was not shown in Figure 5.4 when both observed and simulated monthly drainage equaled zero. The r^2 and EF of the monthly drainage comparison between observed and predicted were 0.85 and 0.82, respectively, indicating the sufficiency of RZWQM-DSSAT in simulating the monthly subsurface drainage at this study site. The simulation of monthly drainage closely matched observed drainage especially in the wet years. In the two wet years of 2007 and 2008, the general statistical factors of monthly drainage comparison were 0.91 and 0.89 for r^2 and EF, respectively. In the drier years, discrepancies between observed and simulated monthly were larger than those in wetter years.

The observed and simulated daily subsurface drainage in 2007 and 2008 are illustrated in Figure 5.5. Early drainage prior to April 13 and March 31 in 2007 and 2008 were not recorded by the magnetic flow meter with data logger but by a normal flow meter which was read manually on a weekly basis. Daily drainage in 2006 is not shown in the figure because little drainage was observed after the installation of the magnetic flow meter on April 13, 2006. Modeled daily drainage by RZWQM-DSSAT fit well with the observed data. In 2007 and 2008, the average daily observed drainage during the period when it was monitored by the magnetic flow meter were 0.170 and 0.128 cm, respectively, and the average daily predicted drainage were 0.162 and 0.125 cm, respectively. The model simulated the daily drainage flow in these two years with a percentage difference of 5.0% and the EF, IoA and r^2 statistics were 0.44, 0.84, and 0.52, respectively. That the daily flow at the beginning of fall drainage in 2007 and 2008 was not captured by the model may have been attributed to overestimating the deep water loss or crop water use during the summer.

5.4.2.2 Soil water storage

Water stored in the soil profile was mainly determined by both crop water uptake and soil hydraulic properties. The modeled and measured soil water storage (SWS) in 0-60 cm layer soil for the three observation years are shown in Figure 5.6. The average SWS was slightly overestimated by 0.7%, and the IoA, EF, an r^2 were 0.84, 0.34, and 0.52, respectively. Error statistics above demonstrated a satisfactory agreement between the simulated and observed soil moisture data. The overestimation of SWS in the spring of 2006 could be due to the underestimation of rye biomass growth and water uptake in this period. Both the observed and simulated soil water content in different soil layers showed a decreased temporal variance over the monitoring season with increase in soil depth. For instance, in 2006, the soil water content varied from 0.20 to 0.34 cm^3 cm^{-3} for the 0-15 cm soil layer, while the ranges were 0.26-0.37 cm^3 cm^{-3} and 0.30-0.39 cm^3 cm^{-3} for the 15-30 cm layer and 30-60 cm layer, respectively. The agreement between predicted and observed soil water content generally reduced with depth in the soil profile. For example, statistical factor of IoA was 0.81, 0.75, and 0.55 for the 0-15, 15-30, and 30-60 cm soil layers, respectively.

5.4.2.3 Nitrogen balance

The simulated annual total nitrate-nitrogen loss through subsurface drainage was a close reproduction of the observed NO_3-N loading. Annual observed NO_3-N loss varied from 9.3 kg N ha^{-1} in 2005 to 49.1 kg N ha^{-1} in 2007. The simulated average annual NO_3-N loss was 28.4 kg N ha^{-1}, within 4% error when compared with the observed average of 27.2 kg N ha^{-1}, with other statistical factors of 0.92, 0.98, and 0.96 for EF, IoA, and r^2, respectively (Table 5.5). The predicted monthly NO_3-N loss followed the trend of observed monthly N loss, as shown in Figure 5.7. Predicted average monthly nitrate loss was within 7% of percentage difference from the observed NO_3-N loading, and other statistical factors demonstrated a satisfactory fit between the simulated and measured monthly NO_3-N loss through subsurface drainage, with EF, IoA, and r^2 of 0.55, 0.92, and 0.80, respectively. The accuracy of subsurface drainage flow volume prediction played an important role in the accuracy of monthly NO_3-N leaching simulation. For most cases, when the monthly drainage was over- or underestimated, the monthly NO_3-N loss was correspondingly over- or underestimated.

The observed annual flow weighted average nitrate-nitrogen concentration (FWANC) ranged from 11.5 mg N L^{-1} in 2007 to 12.9 mg N L^{-1} in 2005 (Table 5.5). The Average simulated annual FWANC of 11.9 mg N L^{-1} was within 3% error of the average observed annual FWANC of 12.3 mg N L^{-1} in the four study years. The simulated and observed monthly FWANC in the subsurface drainage are depicted in Figure 5.8. The simulated and observed mean monthly FWANC were 11.2 and 12.3 mg N L^{-1}, respectively, with a percentage difference of 11%. Other statistical factors, such as EF, showed low values when evaluating the FWANC prediction by RZWQM-DSSAT, which is also reported by Thorp et al. (2007) and Li et al. (2008). This may be due to the low variance of NO_3-N concentration in the subsurface drainage water in the simulation years rather than a lack of response of the model to N transformation and transport.

The simulated and observed total N mass in the above ground biomass of rye cover crop and main crops are also listed in Table 5.5. The total nitrogen uptake by corn and soybean was well simulated by RZWQM-DSSAT, and the simulation of N uptake by rye was also satisfactory when averaged over 3 years. Simulated N content in above ground rye shoot was 41.6 kg N ha^{-1} on average, within 13.6% error from the observed average N content of 36.6 kg N ha^{-1}. For the simulation of main crop N content in above ground biomass, the percentage difference reduced to 3.2%, with EF, IoA, and r^2 equal to 0.51, 0.81, and 0.54 respectively.

5.4.3 Long-term simulations

The RZWQM-DSSAT model evaluated at the study site near Gilmore City, IA was used with long-term weather and agronomic management input data from 1960 through 2008 to investigate the simulated impacts of winter rye cover crop on hydrologic cycling and nitrogen dynamics in Iowa. The simulation was composed of two scenarios by merely including and excluding winter rye as a cover crop for a conventional corn-soybean rotation, while all other managements such as tillage and fertilization remained the same in these two scenarios. Corn or soybean residue was assumed to be disked and field cultivated in the fall and aqueous ammonia was applied to corn phase at a rate of 140 kg N ha^{-1}. In reality, corn residue usually would be chisel plowed rather than disked in fall when no following cover crop would be planted. Yearly hydrologic, nitrogen, and crop growth outputs from 40 years from 1969 through 2008 were summarized and compared.

5.4.3.1 Hydrologic cycling impacts

The annual precipitation during the simulation period (1969-2008) varied from 50.3 cm in 2000 to 125.9 cm in 1993. The probabilities that annual precipitation exceeded 64.7, 82.5, and 94.3 cm were 75%, 50%, and 25%, respectively. The simulated drainage was 0 for some dry years and was the highest in 1993 with a value around 77.0 cm for both scenarios. For the scenario without rye, the occurrence probabilities were 25%, 50%, and 75% when drainage exceeded 32.0, 16.7, 8.6 cm, respectively. For the scenario with rye, the corresponding drainage exceeded 24.8, 12.2, and 1.8 cm at probabilities of 25%, 50%, and 75% occurrence probability, respectively. There was a 18% probability that the simulated annual drainage was 0 for scenario with rye. However, for scenario without rye, the probability when the annual drainage was 0 reduced to 10%.

The simulation results indicate that rye cover crops reduced annual subsurface drainage by 20% and increased evapotranspiration (ET) by 7% (Table 5.6). Simulated impact of rye cover crop on infiltration and seepage were very limited because there is no vegetative interception component in the model and the seepage was calculated as a constant flux. When ET was partitioned into soil evaporation and crop transpiration, rye cover crop reduced the annual soil evaporation by 22% and increased the annual transpirational water use by 28%. The impact of winter rye cover crop on drainage and ET was more evident in April through June suggesting rye is a highly effective approach in modifying agricultural hydrology in these three months. Although rye growth was terminated no later than late-May, it may have exerted impact on drainage in June through reducing soil moisture. Therefore, an investigation of the effect of rye in spring was extended to June. In April through June, the simulated drainage with rye cover was reduced by 25% when compared to the drainage without cover crop. The simulated ET in rye scenario was increased by 26% relative to the simulated ET in no-rye scenario. The growing days of rye were 31 (April 1 to 31) prior to corn and 49 (April 1 to May 18) prior to soybean in the simulation. For the 40-year simulation, rye had existed for 40 days on average for every year, and the increase of ET was 3.92 cm during these 40 days. Therefore the calculated increase of ET by rye was 0.98 mm day^{-1}, close to the increase of 0.90 mm day^{-1} which was reported in a non-weighing lysimeter study conducted in Iowa (Qi and Helmers, 2009). Moreover, the annual drainage reduction by rye of 4.01 cm year^{-1} in this long-term simulation study was close to the reduction of 3.7 cm year^{-1} (average annual drainage of 38.7 cm for bare vs. 42.4 cm for rye) from the non-weighing lysimeter measurements (Qi and Helmers, 2009).

Simulated drainage reduction by rye was observed in every year when simulated drainage occurred (Table 5.7). Annual drainage reduction varied from 0.1 cm to 11.9 cm during all years. From the 40-year simulation, four years in which the average annual precipitation was 59.3 cm showed no simulated drainage. Drainage was reduced by more than 20% in 19 years. Note that the highest percentage of drainage decrease (50~100%)

occurred merely in soybean years with relative low annual precipitation, and the lowest percentage of drainage reduction (0~5%) was found in corn years with relative high annual precipitation. In the twenty corn years and soybean years, the average annual precipitation was 103.0 cm and 99.4 cm, respectively. However, the drainage reduction in corn years (2.8 cm) was 60% less than the average reduction in soybean years (7.0 cm). This provides some indication that growing rye cover crop prior to soybean is more effective than prior to corn for reducing subsurface drainage. To examine the effect of rye on drainage, cumulative frequencies of the simulated drainage are plotted in Figure 5.9. From this, 50% of the time simulated drainage with rye cover was 12.75 cm, 26.4% lower than the drainage of 17.3 cm in the check.

5.4.3.2 Nitrogen and yield impacts

The simulated NO_3-N load to subsurface drainage was reduced by 8.5 kg N ha^{-1} when a winter rye cover crop was included in the simulation, which was a 19% reduction in NO_3-N loss when compared to the simulation without cover crop (Table 5.8). According to Li et al. (2008), simulated NO_3-N reduction by rye would be 17.2 kg N ha^{-1} at a fertilization rate of 140 kg N ha^{-1} which was applied in this study. In this simulation, the reduction of NO_3-N load by rye was lower than the reported value by Li et al. (2008), but was higher than the simulated NO_3-N reduction of 3.9 kg N ha^{-1} by RZWQM (Malone et al., 2007a) and 4.8 kg N ha^{-1} by APSIM model (Malone et al., 2007b) at a fertilization rate of 150 kg N ha^{-1}. The simulated reduction in this study was higher than the reduction of 5.8 kg N ha^{-1} by a long-term simulation conducted for southwestern Minnesota with similar sowing and desiccation dates (Feyereisen et al., 2006). The simulated total N uptake by rye was 54.4 kg N ha^{-1} for rye prior to corn and 64.4 kg N ha^{-1} for rye prior to soybean, with simulated total rye above ground biomass of 2.3 and 4.2 Mg ha^{-1}, respectively. In contrast to the consistent drainage reduction by rye, the impact of rye on NO_3-N loss in the simulation varied over years. Table 5.9 classifies the effect of rye on NO_3-N loss. Except for the 4 years with no drainage, simulation results showed NO_3-N loss was increased in 12 years from the rye plots, and reduced in 24 years. Nitrate-nitrogen loss is a more comprehensive process than subsurface drainage. The probability of increased NO_3-N loss in rye treatment could be explained by the increased mineralization due to the incorporation of rye residue with low C:N ratio (DuPont et al., 2009). Among the 12 years of increased NO_3-N loss, 10 years were in rye-corn phase; whereas in the 24 years of reduced NO_3-N leaching, 16 years were in rye-soybean phase.

The annual FWANC was slightly reduced by 3% in the scenario with rye over the 40-year simulation. FWANC reduction due extensively to rye growing was not directly evident in this simulation, however, it may have been offset by increased mineralization. Annual mineralization from soil organic matter in the rye treatment compared with the no-rye treatment was 236.4 versus 170.6 kg N ha^{-1}, respectively. Rye residue added 17.2 kg ha^{-1} N to the agricultural system from root and 53.3 kg N ha^{-1} from the shoot based on the simulation values. The FWANC in April through June also showed a relative low reduction by the treatment of winter rye cover crop.

The long-term simulation showed a slight yield disadvantage in corn and soybean yield in treatment with rye cover (Table 5.8). The simulated grain yield with and without rye was 7.5 versus 7.8 Mg ha^{-1} for corn and 2.9 versus 3.1 Mg ha^{-1} for soybean, respectively. The RZWQM-DSSAT does not include a component for light interception by cover crop residue, therefore, the main crop growth could only be affected by water and nitrogen deficit that may have been caused by rye cover crop. During the period of corn or soybean growth from June through September, average simulated monthly nitrogen stress in treatment with rye (0.975) was slightly lower than in scenario without rye (0.971, 1 represents no stress), indicating that the nitrogen supply was more sufficient in soils with rye treatment. However, the water stress in the treatment with rye (0.959) was higher than the no-rye treatment (0.966, 1 represents no stress). The simulated minor yield loss of corn and soybean could at least in part be attributed to the water deficit exerted by the preceding cover crop.

5.5 Summary and conclusions

RZWQM-DSSAT hybrid model adequately simulated the subsurface drainage, soil water storage, NO_3-N loss, and crop growth for a four year study in an Iowa corn-soybean rotation field with winter rye cover crop based on the four-year field data collected in Iowa. According to the suggested criteria in Moriasi et al. (2007), the model performed well in predicting annual drainage, annual NO_3-N loss, main crop yield, above ground biomass, and leaf area index for a cover cropping system with Nash-Sutcliffe model efficiency (EF) of 0.95, 0.92, 0.96, 0.87, and 0.89, respectively. Weekly soil water storage and monthly NO_3-N loss were simulated satisfactorily with EF values of 0.34 and 0.55, respectively. The model simulation for the daily drainage flow in the two years was acceptable with an EF value of 0.44. The simulation for rye biomass accumulation showed a lower accuracy compared to the main crops of maize and soybean. Flow-weighted annual NO_3-N concentration was predicted with a low EF value, but the percentage of differences (%D) were within 4% and 10% of the observed annual and monthly FWANC, respectively.

Based on the long-term simulation, growing winter rye cover crop in a conventional corn-soybean rotation would reduce the annual subsurface drainage and NO_3-N loss by 20%

(4.01 cm) and 19% (8.5 kg N ha^{-1}), respectively, and increase annual ET by 7% (4.00 cm). Although reduction of FWANC was not significant by the rye cover crop, which may be due to increased mineralization, reduction of drainage effluent volume facilitated the decrease of NO_3-N loading to surface water bodies. In this study, biomass accumulation of rye cover crop was overestimated in two years with abnormal cold weather. The simulated above ground biomass and leaf area index for rye were 25% and 18% higher than the observed values, respectively. Therefore, a further study to refine the rye growth simulation procedure using RZWQM-DSSAT under a wider range of weather conditions is suggested.

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Table 5.1. Agronomic management

Activity	2004¶	2005	2006	2007	2008
rye growth termination	--	30-Apr	16-May	30-Apr	26-May
corn/soybean planting*	--	10-May	10-May§	14-May	23-May
N fertilization	--	25-May	No	5-Jun	No
corn/soybean harvest	10-Oct	10-Oct	7-Oct	22-Oct	20-Oct
disk plow & field cultivating	12-Oct	10-Oct	10-Oct	24-Oct	20-Oct
rye planting	15-Oct	11-Oct	12-Oct	25-Oct	21-Oct

* corn was planted in odd years and soybean was planted in even years;
¶ field management date prior to rye planting in 2004 was not listed;
§ corn/soybean planting dates were adjusted later than rye growth termination in the modeling because RZWQM-DSSAT does not work when intercropping.

Table 5.2. Measured soil hydraulic properties.

Depth (cm)	BD g cm^{-3}	sand %	silt %	SOM %	Pb *cm*	λ	Ksat cmh^{-1}	LKsat cmh^{-1}	θr (cm^3 cm^{-3})	θs (cm^3 cm^{-3})	θ_{33} (cm^3 cm^{-3})	θ_{10} (cm^3 cm^{-3})	θ_{1500} (cm^3 cm^{-3})
0-10	1.37	0.32	0.36	4.3	-2.89	0.17	4.8	9.7	0.071	0.482	0.376	0.383	0.189
10-20	1.38	0.32	0.36	3.8	-3.89	0.12	3.3	6.6	0.072	0.476	0.376	0.384	0.230
20-30	1.39	0.33	0.53	3.3	-3.89	0.12	5.1	10.1	0.079	0.473	0.376	0.384	0.201
30-40	1.39	0.4	0.30	1.3	-4.67	0.11	4.1	8.2	0.072	0.474	0.399	0.384	0.212
40-60	1.39	0.46	0.30	1.3	-4.31	0.11	4.1	8.2	0.065	0.474	0.368	0.408	0.218
60-90	1.45	0.44	0.34	0.6	-4.99	0.14	2.6	5.3	0.034	0.450	0.368	0.380	0.204
90-120	1.46	0.44	0.34	0.5	-2.99	0.11	2.6	5.3	0.033	0.450	0.299	0.312	0.184
120-200	1.46	0.44	0.34	0.5	-2.99	0.11	2.6	5.3	0.033	0.450	0.299	0.310	0.168
200-300	1.50	0.44	0.34	0.5	-2.99	0.11	2.6	5.3	0.033	0.450	0.299	0.310	0.168
300-389	1.50	0.44	0.34	0.5	-2.99	0.11	0.01	5.3	0.033	0.450	0.299	0.310	0.168

BD=bulk density; SOM=soil organic matter; Pb=bubbling pressure; λ=pore size distribution; Ksat=saturated conductivity; LKsat=lateral saturated conductivity; θr=residual water content; θs=saturated water content; θ_{33}=soil water content at pressure of 33 kPa; θ_{10}=soil water content at pressure of 10 kPa; θ_{1500}=soil water content at pressure of 1500 kPa.

Table 5.3. Observed and simulated crop growth and grain yield.

Year	main crop grain yield Mg ha^{-1}		cover crop above ground biomass Mg ha^{-1}			main crop above ground biomass Mg ha^{-1}			cover crop leaf area index			main crop leaf area index		
	SIM	OBS	SIM	OBS	Date	SIM	OBS	Date	SIM	OBS	Date	SIM	OBS	Date
2005	10.0	10.2	--	--		--	--		--	--		--	--	
2006	3.4	3.4	2.7	3.6	5/17	5.7	7.7	9/26	0.73	0.80	5/17	3.8	4.23	8/14
2007	8.1	7.1	1.4	0.3	4/30	14.8	13.9	9/9	0.94	0.62	4/30	2.94	2.56	7/23
2008	3.6	3.4	2.0	1.0	5/20	6.3	7.2	10/4	--	--		--	--	
average	6.3	6.0	2.0	1.6		9.0	9.6		0.84	0.71		3.37	3.40	

SIM=simulated; OBS=observed; -- not sampled.

Table 5.4. Annual water balance for continuous 4 year simulations (all values in cm)

Year	P	RO	ET	SP	SD		ΔS
					SIM	OBS	
2005	84.6	2.1	55.5	5.0	12.3	7.2	9.8
2006	62.6	4.2	47.9	5.3	6.7	10.4	-1.4
2007	105.0	6.3	49.3	5.8	44.3	42.8	-0.8
2008	92.6	2.4	47.5	5.7	31.3	31.2	5.7
average	86.2	3.7	50.0	5.5	23.7	22.9	3.3

P=precipitation; RO=runoff; ET=evapotranspiration; SP=seepage; SD=subsurface drainage; SIM=simulated; OBS=observed; ΔS=P – RO – ET – SP – SD

Table 5.5. Measured and simulated nitrogen components in 2005 through 2008.

Year	Drainage NO_3 kg N ha^{-1}		FWANC mg N L^{-1}		cover crop above ground N kg N ha^{-1}			main crop above ground N kg N ha^{-1}		
	SIM	OBS	SIM	OBS	SIM	OBS	Date	SIM	OBS	Date
2005	11.7	9.3	9.5	12.9	--	--	--	--	--	--
2006	9.4	13.3	14.0	12.8	46.0	71.6	5/17	204	238	9/26
2007	57.4	49.1	13.0	11.5	36.8	12.9	4/30	141	132	8/17
2008	35.3	36.8	11.4	11.8	42.1	25.4	5/20	198	156	9/4
average	28.4	27.2	11.9	12.3	41.6	36.6		181	175	

FWANC=flow-weighted average nitrate concentration; SIM=simulated; OBS=observed; --not sampled.

Table 5.6. Hydrologic components simulated by RZWQM with and with rye cover crop in 40 years during 1969-2008.

Components	Annual				April-June			
	no-rye	rye	difference	percentage difference	no-rye	rye	difference	percentage difference
	-------------- cm --------------				-------------- cm --------------			
Infiltration	79.5	79.6	0.02	0%	31.0	31.0	0.02	0%
Evaporation	22.5	17.5	-5.04	-22%	11.4	8.2	-3.13	-28%
Transpiration	32.2	41.2	9.04	28%	3.9	11.0	7.05	179%
Evapotranspiration	54.7	58.7	4.00	7%	15.3	19.2	3.92	26%
Seepage	4.80	4.75	-0.05	-1%	1.21	1.18	-0.03	-2%
Drainage	20.4	16.4	-4.01	-20%	13.9	10.4	-3.43	-25%

Note: difference = rye – no-rye; percentage difference = difference / no-rye * 100%.

Table 5.7. Effect of winter rye cover crop on subsurface drainage over 40 years.

Effect	Percentage	Year#	Year*	Precipi-tation § (cm)	Drainage (cm)	
					no-rye	rye
No drainage	-	4	1980 1981 1985 1988	59.3	0	0
Reduced drainage	0~ 5%	6	2007 1983 1993 1973 1991 1977	111.5	42.8	42.3
	5~20%	11	1975 2008 1998 2003 1979 1996 1984 1999 1995 1997 1990	84.5	27.1	23.7
	20~50%	12	2004 1992 1969 1971 2005 1974 2001 1986 1987 2006 1978 1972	84.2	20.6	13.9
	50~100%	7	1976 1970 1994 2002 1982 1989 2000	69.3	7.2	1.4

* Year in this column was arranged by reduction percentage at an ascending order;
§ Average annual precipitation in 1969-2008 was 86.2 cm.

Table 5.8. RZWQM simulated nitrogen dynamics and main crop yield with and without rye cover crop growing prior to the main crops in 40 years during 1969-2008.

Components	Annual				April-June			
	no-rye	rye	difference	percentage difference	no-rye	rye	difference	percentage difference
	------------- kg N ha^{-1} -------------				------------- kg N ha^{-1} -------------			
N in dead roots	81.0	98.1	17.2	21%	0.0	19.9	19.9	--
N in incorporated residue	37.6	90.9	53.3	142%	2.8	17.5	14.7	524%
N fixation	88.0	76.9	-11.1	-13%	3.7	3.3	-0.4	-11%
Denitrification	4.1	9.1	5.0	122%	1.0	4.1	3.1	317%
Voltilization	0.010	0.009	-0.001	-11%	0.010	0.009	-0.001	-12%
Mineralization	170.6	236.4	65.8	39%	48.0	68.5	20.5	43%
NO_3-N in runoff	0.0	0.0	0.0	-5%	0.0	0.0	0.0	-14%
NO_3-N in deep seepage	8.3	8.7	0.4	5%	2.1	2.1	0.1	3%
NO_3-N in drainage	44.0	35.6	-8.5	-19%	28.2	20.3	-7.9	-28%
Crop N uptake	254.1	310.4	56.3	22%	51.8	99.0	47.2	91%
	-------------- mg N L^{-1} ------------				-------------- mg N L^{-1} ------------			
Annual FWANC	22.9	22.2	-0.7	-3%	21.5	21.2	-0.2	-1%
	-------------- kg ha^{-1} -------------							
Corn yield	7777	7463	-314	-4%				
Soybean yield	3059	2880	-179	-6%				

Note: difference = rye – no-rye; percentage difference = difference / no-rye * 100%.

Table 5.9. Effect of winter rye cover crop on nitrate loss over 40 years (1969-2008).

Effect	Percentage	Year#	Year	Precipi-tation (cm)	NO_3 loss (kg N ha^{-1})	
					no-rye	rye
No drainage no NO_3 loss	-	4	1980 1981 1985 1988	59.3	0	0
Increased NO_3 loss	20 ~ 33%	3	1979 2007 2008	98.1	44.7	57.3
	5~20%	4	1995 1973 1983 1997	93.3	40.7	46.7
	0%~5%	5	1977 1990 1991 1975 1993	102.4	89.6	92.0
Reduced NO_3 loss	0%~5%	NO				
	5%~20%	3	1992 1984 1987	86.4	60.4	55.3
	20%~50%	12	2001 1998 2003 1969 1971 1986 1999 1978 2004 1974 2005 1996	84.4	48.8	32.3
	50%~100%	9	2006 1972 1976 1994 1970 2002 1982 1989 2000	71.4	27.8	5.69

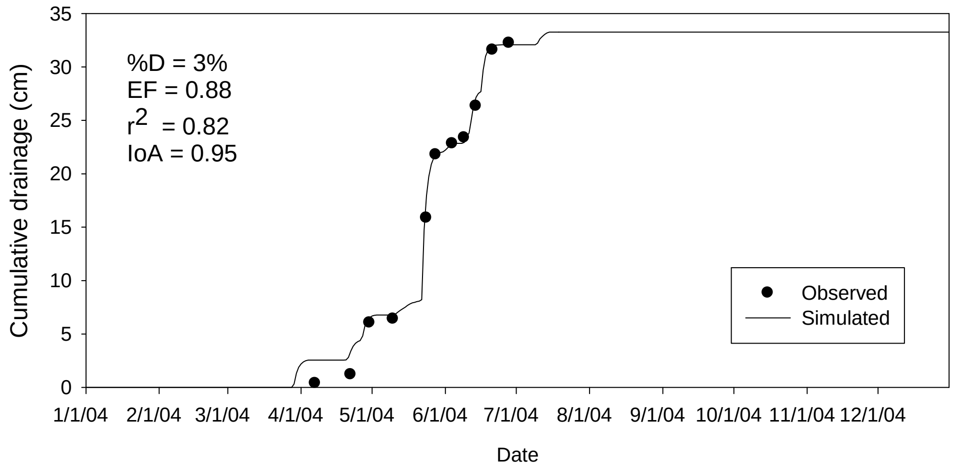

Figure 5.1. Simulated and observed cumulative drainage in 2004 for the lateral hydraulic gradient (LHG) calibration.

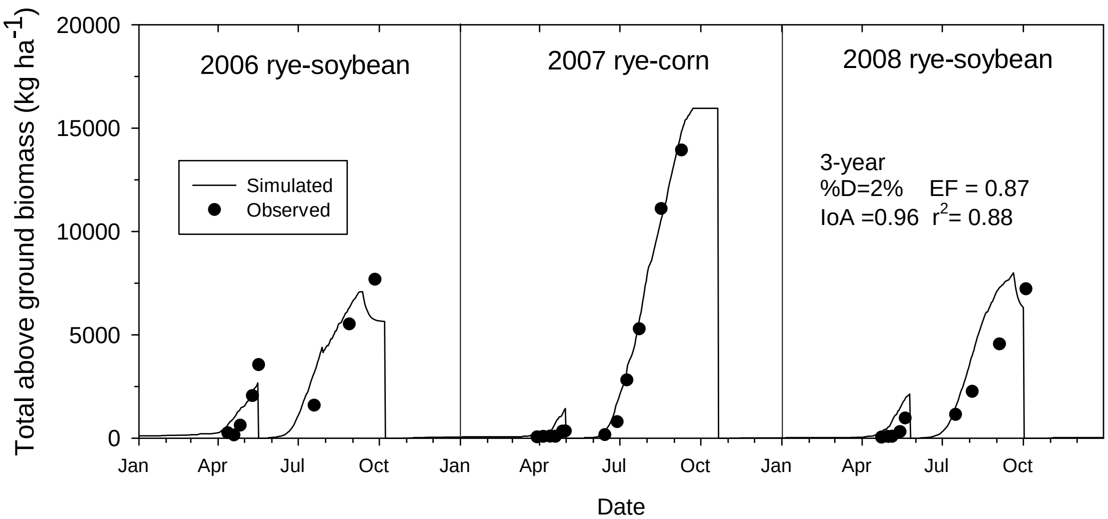

Figure 5.2. Simulated and observed total above ground biomass of rye and main crops in 2006, 2007, and 2008. Above ground biomass was not sampled in 2005.

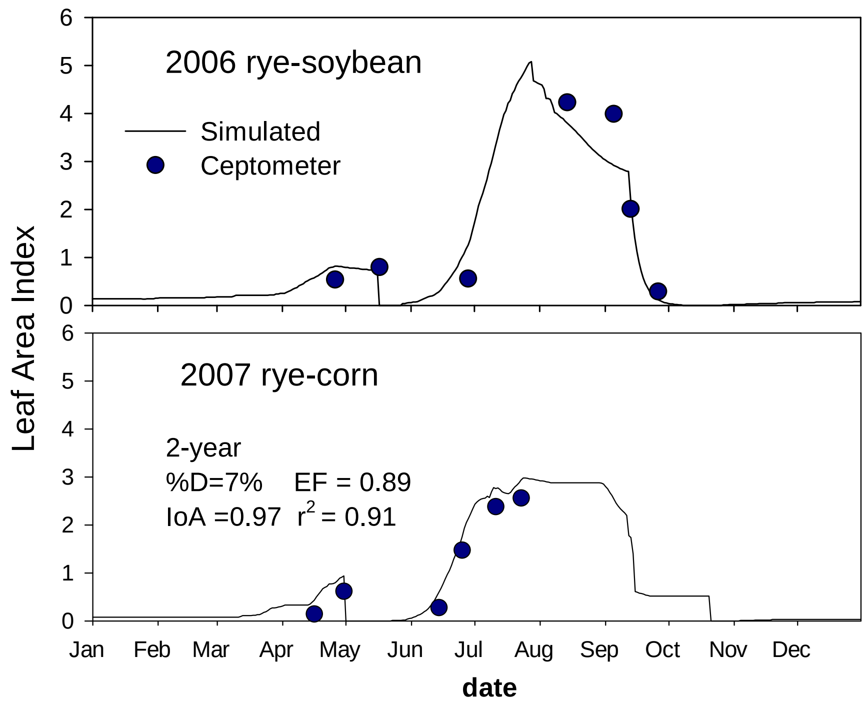

Figure 5.3. Simulated and measured LAI by AccuPAR/LAI ceptometer in 2006 and 2007. LAI was not measured in 2005 and 2008.

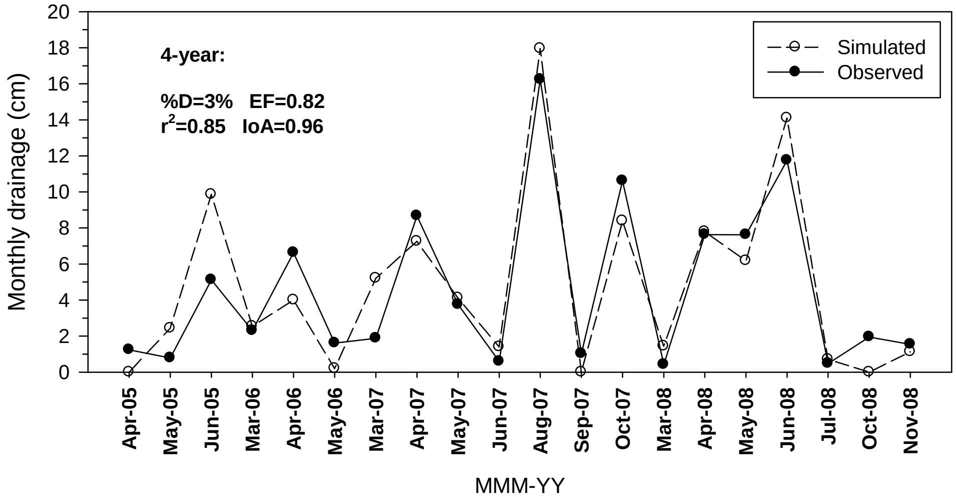

Figure 5.4. Simulated and observed monthly drainage flow volume in the four years from 2005 through 2008.

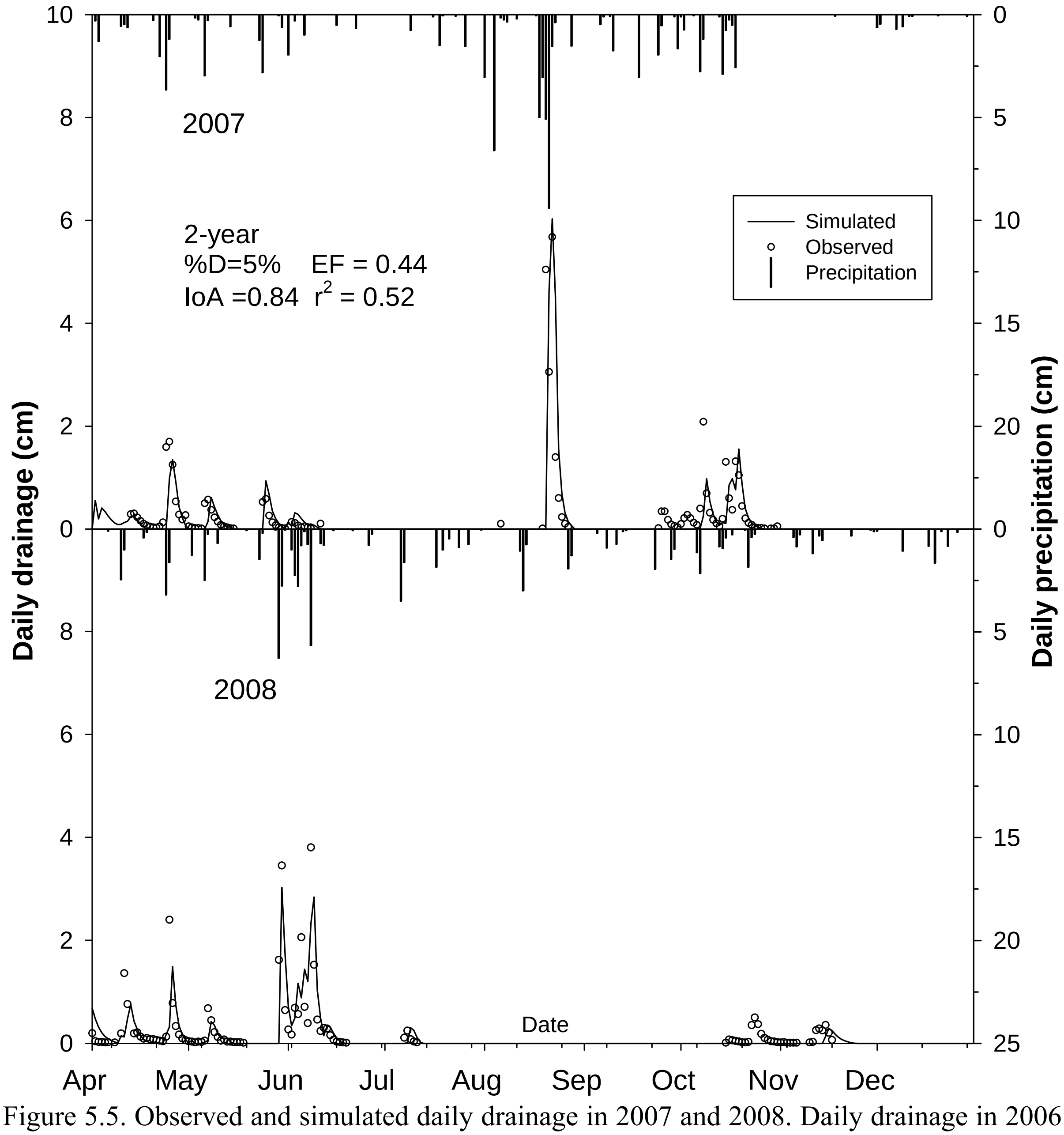

Figure 5.5. Observed and simulated daily drainage in 2007 and 2008. Daily drainage in 2006 was very little after April 12, 2006. Drainage flow in 2005 was not measured on a daily basis but on a weekly basis.

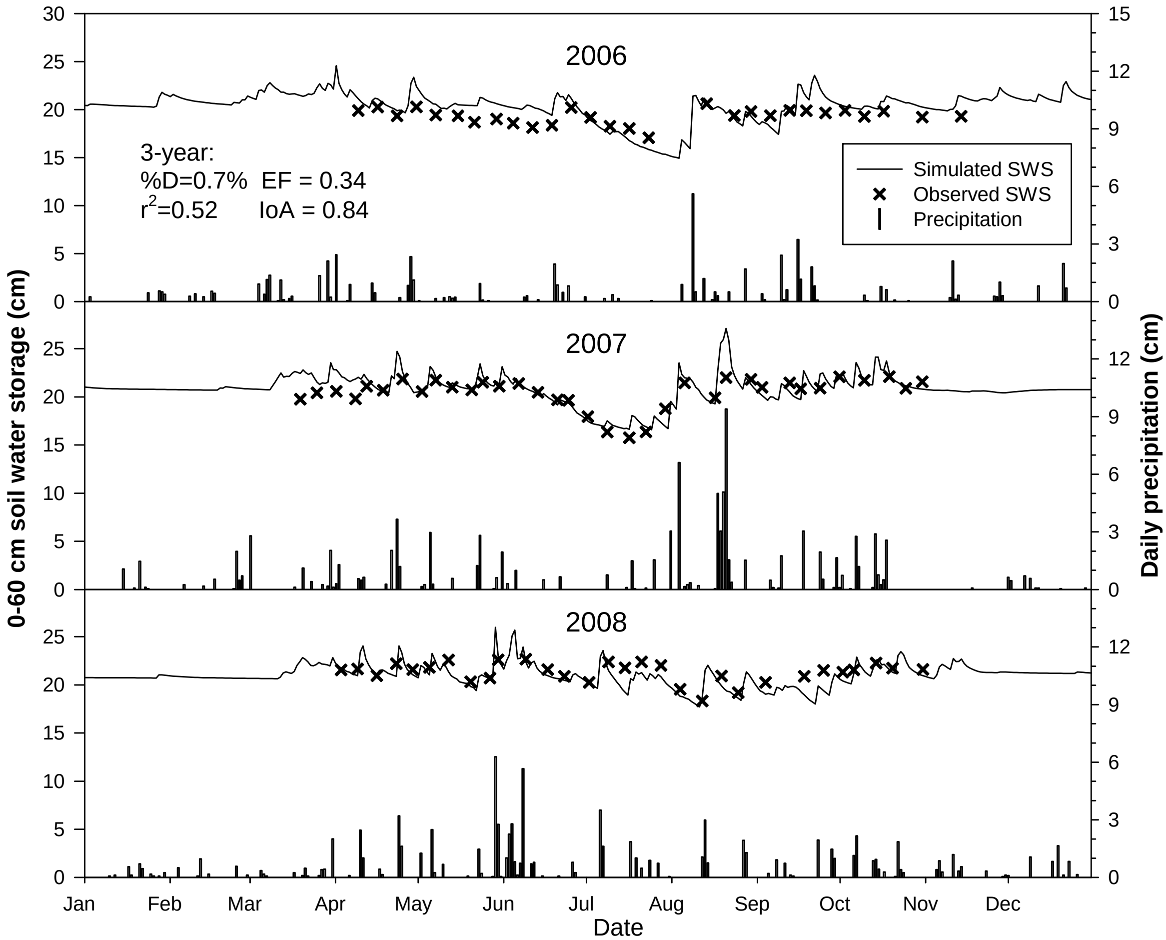

Figure 5.6. Simulated and observed soil water storage in 0-60 cm soil layers.

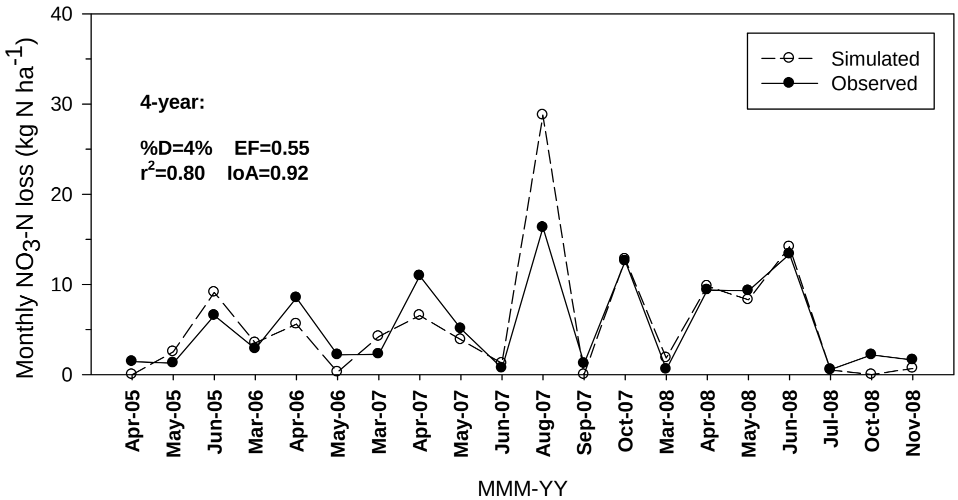

Figure 5.7. Simulated and observed monthly nitrate loss in the four years of observation from 2005 through 2008.

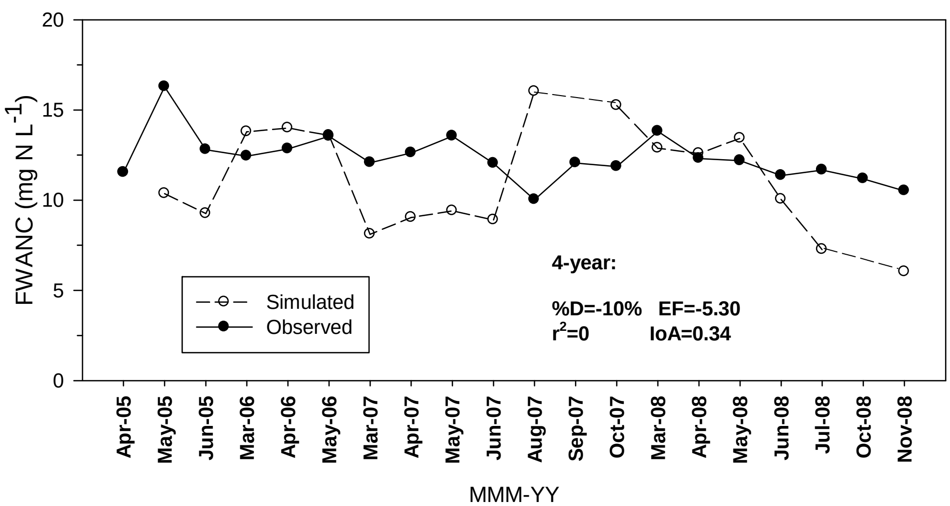

Figure 5.8. Simulated and observed flow weighted monthly nitrate concentration (FWMNC) in the four years of observation from 2005 through 2008. No simulated drainage in September, 2007 and October, 2008.

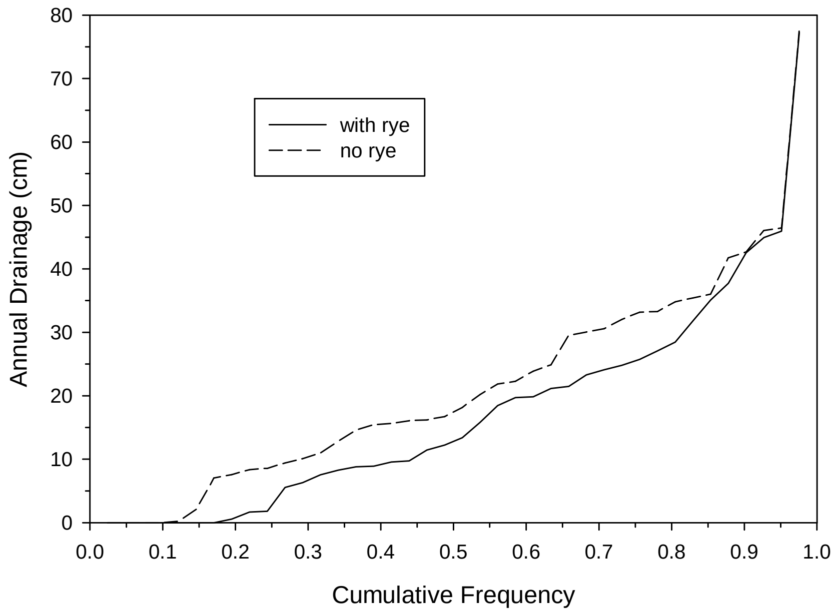

Figure 5.9. Cumulative frequencies of simulated annual drainage in a corn-soybean rotation with and without rye as a winter cover crop (1969-2008).

CHAPTER 6. GENERAL CONCLUSIONS

6.1. Conclusions

This dissertation reports the effects of various land covers on hydrologic cycling and nitrogen dynamics for the subsurface drained agriculture in Iowa through field investigation and modeling approaches. Land covers included in this study were conventional corn-soybean rotation, winter rye cover crop in corn-soybean rotation, kura clover as a living mulch for corn, and perennial forage. Field experiments consisted of two parts: one was conducted in plots including all the land covers near Gilmore City, Iowa from 2006 to 2008; the other was conducted in non-weighing lysimeters with two treatments of winter rye cover crop and bare soil during 2006-2008. The RZWQM-DSSAT was tested against the measured data from the field plot and the evaluated model was used to simulate the long-term impacts of winter rye cover crop on hydrologic cycling and nitrogen dynamics. Primary conclusions are reported in the following sections.

6.1.1 Subsurface drainage

In the field study at the plot-scale, impact on annual or spring subsurface drainage due to land cover treatments was not evident. However, in the non-weighing lysimeter study, the average drainage volume in the rye treatment was significantly lower than in the no-rye treatment. The observed drainage reduction by rye in the non-weighing lysimeters was 37 mm year^{-1}, which is close to the long-term simulated reduction of 40 mm year^{-1} by the RZWQM-DSSAT model. That the plot-scale study showed no difference in drainage between treatments with rye and without rye may be attributed to drainage variability. Of note is that rye growth in the lysimeters was extended to around June 2 for each year while it was terminated in late or middle May in the plot-scale study. Overall, rye has the potential to reduce drainage in the spring of the year.

6.1.2. Soil water dynamics

In contrast to subsurface drainage, soil water storage was significantly affected by land cover treatments in the field study. The field study in drainage plots indicates that the soil water storage in the perennial forage was significantly lower than any other treatments during the 3-year of study. In the plots with kura clover as a living mulch for corn, the soil water storage was significantly than lower than in the corn-soybean rotation with winter rye cove crop treatments which maintained the highest soil water storage. In addition, the rye-corn treatment showed significantly higher soil water storage than fallow-corn treatment, indicating a benefit for water conservation by rye.

6.1.3. Nitrate-nitrogen loading

Nitrate-nitrogen loss was significantly impacted by land cover treatments. When compared to conventional corn-soybean treatments, perennial forage significantly reduced NO_3-N concentration both in the drainage flow and soil water and NO_3-N loading through drainage; the kura clover as a living mulch for corn significantly reduced NO_3-N concentration and NO_3-N loss in the subsurface drainage, but the NO_3-N in the soil water was not significant different. Cover crop in corn-soybean rotation treatments significantly reduced monthly flow-weighted average NO_3-N concentration, but the reduction of NO_3-N loss was not significant when compared with the conventional corn-soybean rotation treatments. From the long-term simulation study, NO_3-N reduction by rye in corn-soybean rotation was 8.5 kg N ha^{-1} $year^{-1}$ higher than the value from this field study but within the range from literature.

Overall, Subsurface drainage water quality in terms of NO_3-N contamination can be effectively improved by converting conventional corn-soybean rotation into perennial forage, but at present there would be little economic value for the grasses. Additionally, the perennial cover may also alter the local hydrologic cycle. Planting corn in established kura clover living mulch also reduced the annual flow-weighted NO_3-N concentration in the subsurface drainage flow below the NO_3-N MCL for drinking water set by USEPA, but kura clover treatment significantly experienced corn yield loss in this study. Although not significantly impacting total NO_3-N loss in the plot scale study, rye as a winter cover crop significantly reduced the NO_3-N concentration in soil water within the soil profile, and rye showed a potential in reducing subsurface drainage in non-weighing lysimeter and modeling study. Therefore, rye cover crop has the potential to e an excellent cropping option under an integrated concern for the environment and economy.

6.2 Prospects for future research

The simulated above ground biomass and leaf area index for rye were overestimated by the RZWQM-DSSAT model in two years under cold weather. Therefore, a further study to refine the rye growth simulation procedure using this model under a wide range of weather conditions is suggested. Application of agricultural system models is a promising approach to evaluate the influence of kura clover living mulch and perennial forage on drainage and NO_3-N loss. Using non-weighing lysimeters to study the effect of kura clover as a living mulch for corn and perennial forage on subsurface drainage may help to complement the field study. Due to high field variability in subsurface drainage, it is a promising study in the future to investigate and eliminate the drainage variability by statistical models.

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