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Modeling long-term impacts of alternative subsurface drainage systems and quantifying impacts of cover crops

Kristina Jo Craft
Iowa State University

Modeling long-term impacts of alternative subsurface drainage systems and quantifying impacts of cover crops

by

Kristina Jo Craft

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Michael Castellano
Robert Malone

The student author and the program of study committee are solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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ABSTRACT

The upper Midwest region has been dramatically altered since it was first settled in the 1800's. What was once dominated by perennial vegetation and wetland is now dominated by annual grain cropping systems, many artificially drained. These changes have made the landscape susceptible to nutrient loss that contributes to water quality degradation, including hypoxia in the Northern Gulf of Mexico. Nutrient reduction strategies, such as alternative drainage systems and a Cereal rye (*Secale cereal L.*) cover crop, have been cited for their success in reducing nutrient losses from row-crop agricultural systems.

The first study within this thesis examines subsurface drainage systems with an agricultural simulation model, RZWQM. We tested RZWQM using nine years (2007-2015) of field data from Southeast Iowa for controlled drainage (CD), shallow drainage (SD), conventional drainage (DD) and undrained (ND) systems, and simulated the long-term (1971-2015) impacts. RZWQM accurately simulated N loss in subsurface drainage, showing that CD and SD substantially reduced N loss. Long-term, RZWQM predicted a 26% N-loss reduction in CD and 40% in SD. During the spring (April-June), CD was found to be less effective (11% reduction) than SD (35% reduction). Improvement of CD systems within the spring to reduce N loss across the upper Midwest landscape may be required.

The second study investigates how delaying Cereal rye termination before soybeans impacted moisture and temperature within the soil profile from 2015 to 2016. In the early termination treatment (EC), rye was killed two weeks before corn planting and in the late termination treatment (LC), rye was killed two weeks before

planting corn and 6-17 days before planting soybeans. Delaying termination prior to soybeans increased rye biomass accumulation, on average by 3.5 times. Despite rye water use, rye treatments stored the same or more moisture from 0-50 cm than NC from mid-April to mid-October, indicating a mulching effect by the residue. Cover crop treatments were cooler and wetter during corn planting, which may be detrimental to germination. Delaying rye termination prior to soybeans reduced moisture content in the early spring, however this was quickly replenished and promoted greater water content during soybean flowering and grain fill, which could positively impact yield in a dry year.

CHAPTER 1. GENERAL INTRODUCTION

Background

Row crop agricultural systems that dominate the upper Midwest United States are among the world's most productive cropping systems. Of the roughly 1 billion tons of maize (*Zea mays* L.) and 300 million tons of soybean (*Glycine max* L. Merr.) produced each year, 36% and 33%, respectively, come from the United States, and the majority of this production is within the central area of the Midwest Corn Belt, (Foreign Agricultural Service, 2016; Goolsby et al., 1999). Prior to European settlement and land development in the 1800's, the Midwest region was primarily a prairie wetland with approximately 85% of the land covered by perennial prairie species and the rest in wetlands and woodlands; the fertile soils found throughout the Midwest Corn Belt region today were generated by the cycling of prairie vegetation via growth and decay, creating rich topsoil that is high in organic matter, (Iowa Association of Naturalists, 2001). In Iowa and much of the Midwest, most of the traditional upland and wet prairie, savannas and woodlands have been lost and this land cover is now comprised of over 70% in row crops or forage production systems, (Burkart et al., 1994). Less than 10% of Iowa's native vegetation is estimated to still remain, (Farrar, 1981). Today, the dominant grain system in Iowa includes an annual rotation of maize and soybean, which accounted for over 9.4 million hectares in 2015, or nearly 65% of Iowa's land, (NASS USDA, 2015). These systems leave a a fallow period between harvest and spring planting, which coincides with the timing of most drainage in Iowa (nearly 70%), from April to June, (Helmers et al., 2005). With little to no water use by a growing crop during this period, excess water and soluble nutrients can be leached from the soil system. The installation of artificial surface and subsurface drainage has made settlement and agricultural production possible in much of Iowa by draining nearly 90% of Iowa's wetlands, which were once uninhabitable and prevented land cultivation for production purposes, (Burkart et al., 1994). As indicated by the greater than 20 million hectares that have been artificially drained for mostly row crops throughout the region since the late 1800's, these drainage systems have allowed for the high productivity throughout the Midwest, (Goolsby et al., 1999). This artificially enhanced drainage, however, allows nutrient-rich drainage water to short-circuit directly from tile drains to surface water bodies or ditches, negatively impacting downstream water quality.

These agricultural production systems became even more vulnerable to losing soluble nutrients with the application of the Haber-Bosch process to artificially fix nitrogen from the atmosphere, which began in the early 1900's and have caused a de-coupling of the carbon and nitrogen cycles, (Keeney and Hatfield, 2008; Tonitto et al., 2006). Maize typically requires an application of inorganic nitrogen inputs of around 168 kg-N ha^{-1}, (Helmers and Castellano, 2015). Often less than 50% of applied nitrogen fertilizer is actually taken up by the crop, with the rest stored in the soil profile or lost from the system via erosion, volatilization or leaching, (Goolsby et al., 1999). Nitrogen mineralization, or the conversion of insoluble organic nitrogen into soluble inorganic nitrogen by soil bacteria, also occurs during the fallow period within the annual grain system, when soils become warm and wet in the spring. Nitrogen mineralization is within the range of 1-4% of the soil organic matter pool annually, or on the order of 112-448 kg-N ha^{-1} yr^{-1}, (Helmers and Castellano, 2015). In some years, this annual release of inorganic nitrogen can be the largest inorganic nitrogen input to the soil system as well as the greatest source of both nitrogen uptake by crops and nitrogen lost in leachate, (Helmers and Castellano, 2015). Though this process of nitrogen mineralization is naturally occurring, the historical perennial systems typically provided a crop demand for water and soluble nutrients during the spring, unlike the fallow period of the annual grain cropping systems.

The greater watershed for the Midwest region is the Mississippi/Atchafalaya River Basin (MARB) collects drainage and runoff from approximately 41% of the conterminous United States and carries it in the Mississippi River to its ultimate destination of the Gulf of Mexico, (Goolsby et al., 1999). The nutrients it carries are deposited in the gulf and contribute to the Northern Gulf of Mexico Hypoxic Zone, (Goolsby et al., 1999). Hypoxia is a phenomena which occurs in a body of water when concentrations of dissolved oxygen are too low to support aquatic life and is caused by an excess of nutrients such as nitrogen (N) and phosphorus (P) and mainly nitrate-N in saltwater systems, (EPA, 2016). Countless research has shown a direct association of nitrogen and phosphorus yield deposited into fresh or saline water bodies and the yield of algal biomass, as well as toxic cyanobacterial blooms in some freshwater lakes, (EPA, 2013; Michalak et al., 2013; Smith, 2003). Row crop agriculture dominates much of the landscape in the sub-drainage basins of the Ohio River Basin and Upper Mississippi River Basin, which together account for a major contribution of the nutrient loading from the upper MARB, (Goolsby et al., 1997). Throughout the central area of the MARB basin, including Iowa, Illinois and Indiana, row crops are grown on more than 50% of the land, (Goolsby et al., 1999).

In order to address the water quality issues related to the export of nutrients from the MARB, the Mississippi River/Gulf of Mexico Hypoxia Task Force was established to call upon the 12 contributing states to create action plans for limiting their contribution of nitrogen and phosphorus to ultimately reduce the size of the hypoxic zone, (Mississippi River Gulf of Mexico Watershed Nutrient Task Force, 2008). The 2008 Gulf Hypoxia Action Plan set a goal of reducing the five-year running average areal magnitude to less than 5,000 square kilometers using practical and voluntary measures, while the 2013 reassessment cited a five-year average of just under 15,000 square kilometers, (Mississippi River Gulf of Mexico Watershed Nutrient Task Force, 2013). The 12 contributing states created strategies for nutrient reduction, which led to the completion of the State of Iowa's plan in May of 2013, the Iowa Nutrient Reduction Strategy, (Mississippi River Gulf of Mexico Watershed Nutrient Task Force, 2013). To complete this strategy, the Iowa Department of Agriculture and Land Stewardship (IDALS), Iowa Department of Natural Resources (DNR) and the College of Agriculture and Life Sciences (CALS) within the state of Iowa's land-grant university, Iowa State University, partnered to conduct the science assessment for point source and nonpoint source pollution (NSP) of N and P, (Strategy, 2013). This strategy created an inventory of current knowledge as well as coordinated scientific research related to pollution mitigation practices. The Iowa Nutrient Reduction Strategy called for a 45%

reduction in total nitrogen (TN) and total phosphorus (TP). Of this 45% reduction in TN, it was estimated that 41% will have to come from nonpoint agricultural sources, (Iowa Department of Agriculture and Land Stweardship, 2015). The Iowa Nonpoint Source Nutrient Reduction Science Assessment recognizes specific practices and technologies that have the greatest potential to minimize nitrate-N loss from agricultural systems. Practices are categorized as either in-field N management, land use practice or edge-of-field practice, (Thompson et al., 2016). As a nitrogen management practice, a winter cover crop is used to minimize or eliminate the fallow period and add a water and nutrient demand by growing a crop between harvest and planting of maize and soybean. As an edge-of-field practice, alternative subsurface drainage systems, such as shallow drainage or controlled drainage, are used to reduce the volume of drainage and it's carried nutrients from the field. Based on the nonpoint source science assessment, on average in Iowa, the use of a winter cover crop, such as cereal rye (*Secale cereal L.*), has been cited to reduce nitrogen loss by 31% and the alternative drainage systems of controlled and shallow drainage are cited to reduce nitrogen loss by 33% and 32%, respectively, (Thompson et al., 2016).

The specific objectives of this thesis work include:

1. Examine the long-term impacts of subsurface drainage engineering on water and nitrogen balances in Southeast Iowa
2. Consider how a winter rye cover crop impacts the water and temperature dynamics of the soil environment

Thesis Organization

Chapter 2 investigates how well an agricultural simulation model, the Root Zone Water Quality Model, release version 2, (RZWQM2), performs when calibrated for a conventional artificial subsurface drainage system and tested for two alternative drainage systems as well as a naturally poorly drained system without enhanced artificial drainage. The nine-year field dataset used for calibration and testing of the model were collected from 2007 to 2015 from a research field in southeast Iowa. The long-term impacts of the artificial drainage systems and the undrained system are also examined. Chapter 2 also includes a brief review of the literature on agricultural drainage and nutrient reduction strategies of controlled and shallow drainage. Chapter 3 utilizes two years of field research conducted in central Iowa to quantify how the presence of a winter cover crop impacts the soil water and temperature dynamics. This research also observes how cover crop management decisions, including termination date, impact these same soil dynamics. A brief review of the literature on nutrient reduction and soil water and temperature dynamics with a winter cover crop is also included in Chapter 3. Chapter 4 gives an overall summary of the findings from the agricultural simulation modeling research for subsurface drainage impacts as well as the soil conditions research with field data. Recommendations for future research are made in Chapter 4, based off the current limitations found within agricultural modeling and field-application of agricultural best management practices for nutrient reduction.

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CHAPTER 2. SIMULATING EFFECTS OF SUBSURFACE DRAINAGE SYSTEMS ON WATER AND NITROGEN FOOTPRINTS WITH RZWQM2

A paper modified for submission to *Transactions of the ASABE*

Kristina Craft[1], Matthew Helmers, Rob Malone, Carl Pederson, Linda Schott

2.1 Abstract

Field research and simulation modeling studies have shown the potential to reduce nitrogen (N) leaving tile drained fields by allowing drainage only when necessary and minimizing the depth to which the soil profile is drained, with drainage water management (DWM) practices of controlled drainage (CD) and shallow drainage (SD). Developing DWM systems in the Midwest to reduce N transport to the Northern Gulf of Mexico Hypoxic Zone requires understanding the long-term performance of these systems. Few studies have evaluated long-term impacts of DWM, and the simulation of CD with the Root Zone Water Quality Model (RZWQM) is limited, while SD has not been examined. We tested RZWQM using nine years (2007-2015) of field data from Southeast Iowa for CD, SD, conventional drainage (DD) and undrained (ND) systems, and simulated the long-term (1971-2015) impacts. RZWQM accurately simulated N loss in subsurface drainage and the simulations agreed with field data that CD and SD substantially reduced N loss to drainage. As indicated in the field data, the SD nitrogen concentration was predicted to be greater than DD and CD, likely due to a reduced time of travel to

[1] Primary researcher and author

shallower drains. Corn and soybean production was well simulated, including corn yield loss due to a shallower water table in CD, SD and ND. Soybean yield loss due to this excess moisture stress, however, was not well simulated. Over the long-term, 45 year, dataset, CD reduced annual tile drainage by 18% compared to DD, while SD reduced drainage by 48%; associated N lost via tile drainage was reduced in CD by 26% and in SD by 40%. The annual percent reduction in NO_3-N lost via tile drainage ranged from 28% in the driest years to 22% in the wettest years for CD and from 56% in the five driest years to 35% in the five wettest years for SD. The simulated FWANC (mg L^{-1}) was the highest in the SD system at 11.8, followed by 10.2 in the DD system and 9.2 in the CD system. FWANC ranged from averages of 26.4, 14.6 and 12.1 for SD, DD and CD, respectively, in the five driest years, to 8.9, 7.8 and 7.5 for SD, DD and CD, respectively, in the five wettest years. On average, corn yield was reduced by 1.5% in CD, 1.2% in SD and 2.2% in ND. Considering spring N-loading for the purpose of addressing hypoxia in the Gulf of Mexico, CD was found to be less effective than SD and in many years CD exported more N in the spring than DD. Spring N-loading, April through June, was indicated by the EPA Science Advisory Board to have the greatest impact on hypoxia in the Northern Gulf of Mexico. Therefore, improvement of CD systems within the months of April-June to reduce N loss via drainage across the upper Midwest landscape may be required. Limited research in the upper Midwest has addressed spring N-loading under controlled drainage systems (CD). This research will help model developers, model users, and agricultural scientists more clearly understand N transport under different systems, including CD, SD, and ND, which will aid in developing the design and management of drainage systems to reduce N transport from tile-drained agriculture to surface waters.

2.2 Introduction

Subsurface drainage systems are frequent throughout the Midwestern United States Corn Belt region and have converted naturally poorly drained soils into highly productive cropping systems that are among the most productive in the world. Of the roughly 1 billion tons of maize (*Zea mays* L.) and 300 million tons of soybean (*Glycine max* L. Merr.) produced each year, globally, 36% and 33%, respectively, come from the United States, and the majority of this production is within the central area of the Midwest Corn Belt, (Foreign Agricultural Service, 2016; Goolsby et al., 1999). Estimates indicate that a quarter of all cropland in the United States and Canada required enhancing the soil's poor natural drainage with an artificial drainage system in order to produce crops, (Skaggs et al., 1994). Within the state of Iowa's 14.6 million ha total land area, it is estimated that 5.21 million ha, or about 35%, are drained via artificial subsurface drainage systems, (USDA NASS, 2012). During wet growing seasons, subsurface drainage removes excess soil moisture from the field to prevent excess water stress on growing crops, as their roots and soil biota require air within the soil profile. Soils that are poorly drained can experience a yield benefit with the installation of artificial tile drainage due to the increased rate of excess water removal from the field and in wet springs can allow producers to enter fields sooner, (Skaggs and Schilfgaarde, 1999).

A negative side effect of these artificial drainage systems throughout the Midwest, however, is that NO_3-N rich drainage water is fast-tracked from fields to nearby surface water bodies. Nitrate is mobile within a soil system because it is highly water soluble and therefore can travel with tile drainage, (Evans et al., 1995). Infiltrating water that is intercepted by tile drains is carried to a waterway or channel where it is able to directly enter into a surface water body, rather than diffusely traveling to a surface or subsurface water system, (Gilliam et al., 1979). Between 1870-1920 and 1945-1960, there was widespread installation of agricultural drainage systems in the central area of the MARB, summing to a total of over 20 million hectares of tile drained land, (Zucker and Brown, 1998). When these drainage systems were installed into poorly drained soils in this region, the water table was locally lowered in fields as the NO_3-N rich drainage water was sent to ditches and streams. The conversion of land from naturally drained or mostly surface drained to an enhanced subsurface drainage system, however, will generally decrease the rate of surface runoff and therefore decrease the loss of sediment and sediment-laden nutrients including particulate phosphorus and organic-N, (Evans et al., 1995; Skaggs and Schilfgaarde, 1999). Decreased surface runoff and peak outflow rates with enhanced subsurface drainage systems have been found in multiple research studies, (Skaggs et al., 1980). With a deeper water table, subsurface drainage systems enhance soil profile aeration which creates more available pore space for infiltrating rainfall, (Goolsby et al., 1999; Skaggs et al., 1994). The primary pathway for drainage water to leave an agricultural field, either surface or subsurface, can control the constituents lost from the field; generally, intense surface drainage promotes the loss of sediment-laden constituents while intense subsurface drainage supports the loss of mobile constituents including NO_3-N and some salts, (Skaggs et al., 1994). In multiple research studies, the increased loss of NO_3-N with enhanced subsurface drainage has mainly been attributed to increased nitrification, decreased denitrification with a deeper water table, and due to the introduction of a direct outlet for subsurface NO_3-N to directly exit, (Skaggs et al., 1994).

Conventionally, drainage design methodologies give recommendations of tile spacing and depth based on the soil type within a field in order to prevent prolonged saturation in the upper soil profile. Two alternative subsurface drainage systems, controlled drainage and shallow drainage, as outlined in the Iowa Nutrient Reduction Strategy, are engineered to control the timing and reduce the volume of drainage leaving agricultural fields. This reduction in drainage is primarily achieved by decreasing the depth of the outlet from the drainage system, which minimizes the local fall in water table within the field being drained, (Skaggs et al., 2012). There are three cited processes responsible for nutrient reduction with these alternative drainage systems: 1) an increased anaerobic zone of the soil profile which enhances denitrification, 2) reduced volume of drainage water leaving the field via drains and 3) reduced depth of soil profile that drainage water infiltrates through which potentially reduces exposure to soil NO_3-N, (Dinnes et al., 2002). A controlled drainage system utilizes an outlet control structure, installed at the exit of the tile system, which allows the manager to change the depth of the outlet. Within the control structure, removable boards act as a dam, holding back drainage water when it is not necessary for production purposes, (Dinnes et al., 2002). As summarized by Skaggs et al. (2012), the central goal of controlled drainage is to reduce the drainage intensity during times of the year when it isn't needed for crop production, such as the winter months, as well as to conserve water in the fields during the summer months. In shallow drainage systems, the tile lines are installed closer to the ground surface to keep the water table higher in the soil profile. By positioning the tile lines closer to the ground surface, less of the soil profile will then be accessible for water table interception by the tiles, thus permitting a smaller volume of water to be drained and the rest to be kept in the soil profile or seeped deeper into the profile, (Gilliam et al., 1979).

Both alternative drainage systems can be considered a type of drainage water management. They both provide a producer the ability to manage the water table in their fields compared to a conventional drainage system that is solely designed to achieve a desirable rate of excess water removal. The controlled drainage outlet structure allows for active management of the water table throughout the year. A shallow drainage system allows for passive management of the water table based on the installation of the system. Adoption of a controlled outlet or shallow drainage system would be a management decision that could minimize NO_3-N loss from a tile-drained field and is therefore a nutrient reduction strategy. A trade off of maintaining a higher water table with these alternative drainage systems is a potential yield loss with excess water stress more likely on a growing crop.

The Iowa Nutrient Reduction Strategy science assessment summarized multiple field studies and states that controlled and shallow drainage have shown to reduce nitrate load by 33% and 32%, respectively, (Thompson et al., 2016). Controlled drainage has been heavily studied since the 1970s and 1980s, initiating mostly within the Eastern United States, where it was found to reduce annual NO_3-N losses by 40-50%, (Gilliam et al., 1979). Multiple other studies from the Eastern US have demonstrated the effectiveness of controlled drainage systems in reducing NO_3-N loss, (Doty and Parsons, 1979; Evans et al., 1995; Skaggs et al., 1980). It has also been found that the annual reduction in subsurface drainage will greatly depend on weather and precipitation and that control may be greatest in drier years and least in the wettest years, (Evans et al., 1995).

Maintaining a higher water table greatly effects nitrogen transformation processes occurring within the soil profile, such as denitrification, mineralization and immobilization, as well as the hydrology of a soil system. Past research has hypothesized that controlling drainage system outflow to maintain a higher water table within a drained field increases the deep seepage of water through saturated and reduced subsurface zones, where it is susceptible to undergo denitrification processes, (Gilliam et al., 1979; Skaggs et al., 1994). Due to this increased denitrification, it has been found in some select studies, such as by (Evans et al., 1995), that the concentration of NO_3-N in controlled drainage outflow is less than that of an uncontrolled outflow. Most research, however, has only documented a reduction in NO_3-N concentration in the reduced zone of the soil profile, with little to no effect in NO_3-N concentration in the drainage system outflow, (Skaggs et al., 1994). The mass of NO_3-N reduced from controlled drainage experiments, compared to conventional systems, has been mainly attributed to a reduction in drainage volume rather than to a reduction in NO_3-N concentration, (Evans et al., 1995; Skaggs et al., 2012). Subsurface seepage losses have been found to be substantial in fields with a high water table and since they pass through the reduced zone with little to no NO_3-N, the mass of NO_3-N export via seepage has been found to be minimal, (Gilliam et al., 1979). Additionally, maintaining a higher water table aerates less of the soil profile which may reduce nitrogen mineralization as microbial decomposition of organic matter requires oxygen.

The need to advance water quality research related to subsurface drainage systems has been emphasized in the field of agricultural water resources for many years. In a research review conducted in the early 1990's by Skaggs et al. (1994), the physics and chemistry controlling hydrology and nutrient loss from agricultural subsurface systems were described to be "complex" and said to "vary with conditions prior to drainage improvements and other factors: land use, management practices, soils, site conditions, and climate." Additionally, Skaggs et al. (1994) pointed out the need for quality datasets accompanied by agricultural simulation modeling to better understand the complex interactions dictating nutrient loss from drained agricultural systems. Current field research of drainage related nutrient reduction strategies is presently limited to a narrow range of time periods, weather conditions, soil types, and locations throughout the Midwest. Agricultural simulation modeling tools, such as The Root Zone Water Quality Model, (RZWQM), will be essential to advance research and scientific understanding of the effects of drainage systems over a broader range of conditions. As described by L.R. Ahuja (2000), simulation models, such as RZWQM, synthesize current knowledge by interpreting and extending on physical, chemical, and biological processes and extrapolating management impacts to additional locations or climates. RZWQM is capable of simulating interactions between agricultural management and hydrology, nutrient and biology within the soil root zone. RZWQM has been found to be successful in simulating crop rotation and yield, daily and annual drainage volume, as well as nitrogen dynamics such as NO_3-N loss in artificial subsurface drain flow, as documented by Ma et al. (2007b) and Qi et al, (2011). With RZWQM, Fang et al. (2012) successfully simulated the effect of a controlled drainage system on monthly tile drainage, N loss, and FWANC, compared to a conventional or unmanaged system and found that the percent N loss from controlled drainage was higher with increased annual rainfall. Early drainage simulation model studies examining the effects of water table management strategies on water quality found field-documented effects of NO_3-N loss reduction and increased denitrification, (Skaggs and Gilliam, 1981; Wright et al., 1992). Simulation studies for both controlled and shallow drainage have been successful in correctly predicting the reduction in drainage and greater excess water stress that can generate yield loss in some soils and climates, (Luo et al., 2010; Singh et al., 2006).

Additionally, properly parameterized simulation models can be applied with long-term weather datasets to provide information over a wide range of weather conditions. Recent simulation modeling research has demonstrated the use of long-term datasets to provide additional information from short-term, field-calibrated subsurface drainage datasets, (Ma et al., 2007c; Randall and Iragavarapu, 1995). With information on the long-term impacts, it is then possible to make observations of the sustainability of subsurface drainage systems. As water quality issues continue to persist in the state of Iowa and globally, it will be vitally important for researchers to extend on the knowledge gained within field studies with simulation modeling. Long-term evaluations of DWM systems are lacking in related research. Additionally, RZWQM simulations of controlled drainage systems are limited to a few studies and none currently exist for shallow drainage systems. There were three specific objectives of this study: 1) calibrate RZWQM for a naturally poorly drained soil in Southeast Iowa with a conventional drainage system, 2) test the parameterized model for DWM systems of shallow and controlled drainage and system without artificial drainage, and 3) apply the calibrated model to a 45-year historical data set to examine the long-term impacts of drainage systems in Southeast Iowa.

2.3 Materials and Methods

2.3.1 Overview of RZWQM

RZWQM release version 2 (RZWQM2) (version 3.29) was developed as a field-scale, one-dimensional agricultural simulation model by the United States Department of Agriculture, Agricultural Research Service (USDA-ARS). RZWQM2 is capable of simulating biological, chemical, and physical processes within the soil-root-zone. RZWQM2 has been well tested for its ability to simulate various agricultural management scenarios as well as the transport and transformation of water, nutrients, and pesticides, (Ma et al., 2006b; Ma et al., 2005b; Ma et al., 2007b; Malone et al., 2007). RZWQM2 operates at a daily time step level, first calculating the effects of management processes followed by a daily estimate of potential evapotranspiration (PET), sub-hourly time loop calculations of the energy and water balance modules, snowpack dynamics, and transport of solutes and chemicals, and lastly, daily calculations are made for pesticide processes, nutrient (carbon and nitrogen) processes, soil chemical processes, and plant growth processes, (L. Ma, 2011). The crop simulation model Decision Support System for Agrotechnology Transfer (DSSAT version 4.0) was nested into the RZWQM2 interface, which includes multiple parameterized crop models, including CERES-maize (Ma et al., 2006a) and CROPGRO-soybean (Ma et al., 2005a). Daily PET is estimated with a modified Shuttleworth-Wallace equation that extends off of the Penman-Monteith concept, as described by Farahani and DeCoursey (2000). The soil water balance is modeled using the Green-Ampt equation for infiltration into the soil profile, with the Richards' equation for redistribution within the profile, and the steady-state Hooghoudt equation for tile drainage, (L. R. Ahuja, 2000). Macropores can be simulated to hydraulically connect large soil pores to tile drains and have been used to successfully simulate concentrations of chemicals in drain flow, such as pesticide transport, additionally, an express fraction can be used to describe the percentage of pores that are directly connected to the tile drains, (Fox et al., 2004). Rainfall excess of soil infiltration rate is routed next to macropore flow, where the maximum flow rate is modeled by Poiseuille's law and the lateral seepage from macropores by the lateral Green-Ampt equation, (Ahuja et al., 1993). The soil nutrient module, Organic Matter/Nitrogen Cycling Model (OMNI)

(Shaffer et al., 2000), cycles carbon (C) and nitrogen (N) throughout three microbial pools, two surface residue pools, and three soil humus pools. Nutrient cycling is controlled by C:N ratios and rate coefficients. The microbial populations simulated in OMNI include aerobic heterotrophs which are soil decomposers, anaerobic heterotrophs, which are denitrifying facultative bacteria, and autotrophs, which perform nitrification, (L.R. Ahuja, 2000). The primary processes involved with C and N cycling simulated within OMNI are sensitive to environmental conditions and include death and growth of microbial populations, nitrification of ammonium (NH_4) to nitrate (NO_3), denitrification to produce nitrogen (N_2) or nitrous oxide (N_2O) gases, mineralization-immobilization of organic material, and production or consumption of methane (CH_4) or carbon dioxide (CO_2) gases, (Kumar et al., 1998).

2.3.2 Site description and management

The experimental field site is located on the Iowa State University Southeast Research and Demonstration Farm (SERF) near Crawfordsville, Iowa. Field slope is less than 1% and soil types at this site include Taintor (silty clay loam, fine smectitic, mesic Vertic Argiaquolls) and Kalona (silty clay loam, fine, smectitic, mesic Vertic Endoaquolls), both poorly drained soil types. The subsurface drainage system was installed in 2006 and has been monitored for crop growth, and nitrogen and water dynamics from 2007 to 2015. The cropping system includes an annual rotation of corn (*Zea mays* L.) and soybean (*Glycine max* L. Merr.), and a split-plot design warrants each plot to be cropped half in corn and half in soybeans within every year. A 17 ha field site consists of eight experimental plots, each 1.2 to 2.4 ha in size, which include two replications of three drainage treatments and one naturally drained, or undrained, treatment (ND). The two cropping rotations within each plot constitutes a total of 16 subplots. Drainage flow and nutrient analysis is collected on a plot basis rather than subplot, meaning drainage analysis includes half corn ground and half soybean ground each year. The three drainage treatments include conventional drainage (DD) with 1.2 m drain depth and 18 m spacing, shallow drainage (SD) with 0.76 m depth and 12.2 m spacing, and controlled drainage (CD) with 1.2 m depth and 18 m spacing with a controlled outlet structure (Figure 2.1). All subsurface drainage systems were designed with an outlet tile main size to set a maximum daily drainage coefficient of 1.9 cm day^{-1}. For the CD system, control boards, or gates, within the control outlet structure are opened about two weeks before planting in the early spring, typically mid-April, to allow for any winter or early-spring drainage water to be drained from the field and allow for field entry, when applicable. The boards are then replaced to set the outlet height at 0.76 meters deep after planting, typically in early June. If there is water being held back by the control outlet gates in the fall, the boards are removed again to permit field entry for harvest and replaced after fall tillage is carried out, commonly in early November. For SD plots, the tile lines are installed closer to the ground surface, or not as deep as, the conventional drainage tiles and 6 m closer together to accommodate a similar drainage intensity within all plots and drainage treatments in the study. All drainage systems include a parallel tile drainage layout with curtain tiles installed between plots to eliminate influence and cross-contamination of neighboring drainage treatments. Each spring, 150 kg-N ha^{-1} is injected as anhydrous ammonia to the corn half of each plot. Field cultivation is carried out every spring to both corn and soybean ground and corn residue is chisel plowed each fall.

2.3.3 Data collection

2.3.3.1 Weather data

To run simulations in RZWQM2, the minimum required climate data include minimum and maximum air temperature, wind run, shortwave solar radiation, relative humidity, and rainfall hydrographs, (Ahuja et al., 2000). Historical weather data for SERF was collected from three different climate data networks, based on the best available data over time. The meteorology dataset utilized data from the Legacy network of Iowa State University (ISU) Ag Climate automated weather station and the ISU Soil Moisture Network automated station, both located on site, as well as the National Weather Service (NWS) Cooperative Observer Program (COOP), located approximately 18 km away in Washington, Iowa. The ISU Ag Climate station was installed on site in 1988 and replaced with the new ISU Soil Moisture Network station in December of 2013. Rainfall for the breakpoint, or hydrograph, data was acquired from manual readings taken on site for 2007 to 2013 and from the ISU Soil Moisture Network automated tipping bucket rain gauge for 2014 and 2015. Quality hourly rainfall data was only available for 2014 and 2015, therefore the breakpoint curves for 2007 to 2013 were created using typical rainfall intensities and durations commonly observed in the region. Quality control of weather data is essential in agricultural simulation modeling, as Malone et al. (2011) showed that a data bias of 10% in humidity, solar radiation, and rainfall can account for 40% error in simulated tile drainage and NO_3-N loss in Iowa cropping system simulations. Only weather data that had been quality controlled by data specialists was utilized and these data were checked against multiple nearby sources, when available. As solar radiation is used for PET calculations, which is a large factor in the water and energy balances, the dataset was only considered acceptable once annual averages were within a regionally acceptable range and below a theoretical maximum for the region, (Malone et al., 2011).

2.3.3.2 Soil data

Soil texture and chemical analysis was completed in 2011, 2013 and 2015 by collecting push probe samples from each plot and measuring the fraction of particle sizes. Measured values were averaged across all plots in order to create a representative set of soil properties for the field site; this was done for simplicity within the calibration and simulation process, however this is acceptable due to the limited variation in soil properties between the eight plots. Hydraulic properties of bulk density and soil water content at 33, 10 and 1500-kPa matric potentials were measured by collecting undisturbed soil cores in 2011, 2013, and 2015. Sample collection and calculations processes for bulk density and soil water retention properties are described in Schott et al. (2016). Some soil hydraulic properties that were not measured in the field were estimated from the USDA ARS, ROSETTA Model (version 1.0) Pedotransfer function (PTF). These modeled parameters include saturated hydraulic conductivity, K_s, and residual and saturated water contents, θ_r and θ_s. The estimates for K_s were applied cautiously because much faster infiltration rates have been observed at this particular site. Soil properties were only measured in the field to a depth of 60 cm for bulk density and soil texture properties and 20 cm for soil water retention properties. For horizons below these depths, values were either repeated or estimated by adjusting from default values for a silty clay loam soil within the literature review of soil properties completed by (Rawls et al., 1982). These measured and estimated soil properties are provided in Table 2.1.

2.3.3.3 Hydrology data

Drainage from the interior tiles of each plot were continuously monitored for flow rate during the drainage season. Most years, drainage monitoring began near or after spring thaw, in March or early April, and usually continued through December. Each of the six monitored tile lines drained a single plot with half of the plot cropped to corn and half to soybeans each year. Grab samples were taken weekly, when available, for nutrient analysis, as fully described in Helmers et al. (2012). Interpolated NO_3-N concentration and representative tile drainage volume are multiplied to calculate NO_3-N load from each plot. A flow weighted annual NO_3-N concentration (FWANC) was used to quantify the annual NO_3-N loss from each plot which is normalized to the annual drainage volume.

Also described by Helmers et al. (2012), the depth to the water table was continuously monitored in observation wells installed directly in the center of the plots, midway between an interior set of tile lines. For use with RZWQM2, this water table data was averaged to daily depth from ground surface. Average daily soil water storage was derived from continuously measured soil volumetric water content data within each plot. Measurement equipment for continuous monitoring of volumetric water content was installed in 2011 and is fully described in work by Schott et al. (2016). Full methodologies for monitoring drainage flow rate, drainage nutrient analysis, and depth to water table have been previously outlined by Helmers et al. (2012) and the procedure for volumetric soil water content measurement was outlined by Schott et al. (2016).

2.3.3.4 Agronomic data

Grain yield was recorded each year of the nine year field study with a combine yield monitor. The yield measurement was limited to the center rows to minimize effects from neighboring plots; these methods for agronomic data collection at SERF are outlined by Helmers et al. (2012). From 2011 to 2015, corn and soybean biomass was collected prior to harvest to obtain measurements of total aboveground biomass production and nitrogen contents, (Schott et al., 2016). Nitrogen content was measured for crop grain, which was conducted by The Iowa State University Soil and Plant Analysis Laboratory (Ames, Iowa).

2.3.4 Model initialization

RZWQM2 was initialized with a 26-year dataset of historical weather data (1981-2006). During initialization, the cropping and tillage system in place during the study period was executed to set up the microbial and residue pools and to establish the hydraulic and nutrient cycles within the soil profile. The slow and fast crop residue pools were initialized by the historic management, which established an initial estimate of the surface residue pools. Measured soil carbon content was allocated between the fast, medium and slow organic matter pools by 5, 35 and 60%, respectively, based off similar methods described by Kumar et al. (1999) and

Hanson et al. (1999). Percent SOM was measured at depth increments of 0-10, 10-20, 20-40, and 40-60 cm in 2011, 2013, and 2015 at the field site. Due to little variation between years, an average SOM value by depth increment was used. A carbon-to-nitrogen (C:N) ratio of 60 and a conversion factor for soil organic matter (SOM) to soil organic carbon (SOC) of 0.58 was used based off of typical estimates for corn-soybean system residue, (Christianson et al., 2012). Default C:N ratios were used for microbial and humus pools.

Based on similar modeling methods demonstrated by Landa et al. (1999) and Hanson et al. (1999), within the simulation control function of RZWQM2, multiple iterations of the 26 years of typical management and climate data were run continuously until the soil humus and biota pools reached a steady state and the sum of the humus carbon pools were close to measured values, or around 2-3%, which can be found in Table 2.1. Minor iterative adjustments to microbial death rates, humus decay rates, and organic matter inter-pool transfer coefficients were required until the slow humus pool size was stable and the microbial and organic matter pool sizes reached equilibrium, (Hanson et al., 1999; Kumar et al., 1999). These rate coefficients were also used to simulate an acceptable rate of annual soil N-mineralization for the general region, which was presumed to be within the range of 112 to 504 kg-N ha^{-1}, (Helmers and Castellano, 2015). Zhiming Qi (2011) simulated an average annual N-mineralization rate of 140 kg-N ha^{-1} for an artificially drained corn-soybean system with silty clay loam and clay loam soils in North-Central Iowa. Ma et al. (2007c) simulated an annual average of 109 kg-N ha^{-1} with a 26-year range between 67 to 223 kg-N ha^{-1} for a similar system in

Northeast Iowa. The inter-pool transfer coefficients were slightly adjusted based off those calibrated by Ma et al. (2007a) and Thorp et al. (2007), including adjusting the slow residue to intermediate SOM to 0.2, the fast residue to fast SOM to 0.5, the fast SOM to intermediate SOM to 0.5, and the intermediate SOM to slow SOM to 0.7. The adjustment to the intermediate SOM to slow SOM transfer coefficient aided in simulating N-mineralization rates, (Hanson et al., 1998).

The denitrification rate coefficient was adjusted to $1.8x10^{-13}$ to fit to acceptable annual denitrification rates. Thorp et al. (2007) modeled an annual denitrification rate of 6.8 ± 5.2 kg-N ha^{-1} for a tile-drained corn-soybean system simulated with RZWQM and other modeled estimates for the Midwest have been found to be between 6-30 kg-N ha^{-1}, (Christianson et al., 2012). The background chemistry of rainwater was set using National Atmospheric Deposition Program estimates, with pH of 5.1, 0.5 mg-N L^{-1} for NH_4 and 1.3 mg-N L^{-1} for NO_3-N, (National Atmospheric Deposition Program, 2015). Initial chemical status of the soil profile was set with three-year averages of measured pH and CEC values which were obtained from chemical analysis performed by The Iowa State University Soil and Plant Analysis Laboratory (Ames, Iowa) in 2011, 2013, and 2015. Initial moisture conditions were entered based off of field capacity and saturated water contents to initialize a water table within the soil profile.

2.3.5 Model calibration and evaluation

Manual parameterization was iteratively carried out, similar to methods described by Ma et al. (2003), until a successful fit was achieved between RZWQM2 simulations and observed data for the DD system from 2007 to 2015.

Two replicate scenarios were executed to model the split-plot cropping system, with each replication having one of two cropping rotations: corn-following-soybeans and soybeans-following-corn. Numerical results from the two scenarios were averaged for hydrology information to compare simulation results with field collected data, as each field plot consisted of an equal area planted in corn and soybeans within each year. Simulated crop production estimates for both corn and soybean were calibrated within each year using both simulation scenarios. Utilized field collected data included crop production, nutrient and hydrology measurements. Crop production measurements included corn and soybean yield, biomass production, harvest index and grain nitrogen uptake. Nutrient measurements involved nitrate-nitrogen (NO_3-N) load and FWANC as well as fall soil nitrate. Lastly, hydrology measurements included tile drainage volume at the annual, monthly and daily levels, soil water content to a depth of 60 cm, and depth to water table. The quality of simulation was determined by evaluating discrepancies between simulated and measured, or observed, data and were based on quantitative and qualitative measures of goodness-of-fit, similar to methods described in (Bakhsh et al., 2001). Crop production simulations were considered satisfactory when percent error (PE%) was within ±15%, based off methods described by L.R. Ahuja (2000) and the relative root mean square error (n-RMSE%) was <30%, as per Liu et al. (2011) methods. Hydrology and NO_3-N load simulations were considered satisfactory when the Nash-Sutcliffe efficiency (NSE) was >0.50, percent bias (PBIAS%) was within ±25%, and the root mean square error normalized to the standard deviation of the observed dataset (RSR) was <=0.70, (Moriasi et al., 2007). A coefficient of determination, R^2, was used to quantify the proportion of variance in measured data explained by the model, which was deemed acceptable when >0.50, (Moriasi et al., 2007). Qualitative goodness-of-fit tests included review of graphical representations of model simulation differences from observed measurements. Observed and simulated measures, within a single drainage treatment, were plotted together on either daily or monthly timescales to visualize how well the model is predicting the observed trends over time.

Previously parameterized crop models for maize (IB1 068 Dekalb 521) and soybean (990002 M Group 2) were utilized and some minor parameter adjustments were required. Both corn and soybean yield were calibrated for each year from 2007 to 2015 for the DD system. Crop model parameter adjustments were carried out following methods described by Ma et al. (2006) and Thorp et al. (2007). Parameters were initialized with values used for simulations in North-Central Iowa by Zhiming Qi (2011), and adjusted to match observed annual grain yield (2007-2015) as well as aboveground biomass and harvest index (2011-2015). In order to simulate nine years of corn yield measurements for SERF, it was required to simulate two maize hybrids with minor differences in maturity length, as the relative hybrid maturity ratings of corn hybrids planted at SERF ranged from 106 to 113. The parameters that required minor adjustment for corn included the thermal time from seedling emergence to the end of the juvenile phase (P1), thermal time from silking to physiological maturity (P5), maximum possible number of kernels per plant (G2), kernel filling rate during the linear grain filling stage under optimum conditions (G3), and the phylochron interval between successive leaf tip appearances (PHINT). The only parameter that was adjusted for the soybean model including the maximum leaf photosynthesis rate (LFMAX), which was calibrated to 0.725 to fit soybean yield and harvest index. The simulation parameters of the two maize models and the soybean model are provided in Table 2.2. The soil root growth factor (SRGF) was adjusted for the maize and soybean models to fit nitrogen concentration in grain to a reasonable level and to measured values for 2011-2015 for corn and 2012-2015 for soybean. For depths of 5, 15, 30, 40, 60, 90 and 120 cm, the SRFG was set to 1, 1, 0.32, 0.2, 0.12, 0.12 and 0.0 for soybeans and 1, 1, 0.8, 0.4, 0.27, 0.1 and 0.06 for corn, by making minor adjustments from settings in past corn and soybean system modeling work by Zhiming Qi (2011), Malone et al. (2010) and Ma et al. (2006a). These SRGF parameter settings simulated rooting depths of around 90 cm for soybeans and 115 cm for corn, on average.

Soil hydraulic information was parameterized for annual, monthly and daily tile drainage, and daily depth to water table and soil water content. Table 2.1 provides the measured and calibrated soil hydraulic properties by soil layer used to parameterize the soil profile for SERF. To simulate a water table within the soil profile, a constant flux boundary condition was chosen for the redistribution model. An impermeable layer was set at the bottom of the soil profile by a K_{sat} value of 0.01 cm hr^{-1}, similar to methods described in Ma et al. (2007a) and a water table leakage rate of 1e-6 cm hr^{-1} was used. Similar to work by Singh et al. (1996), the impermeable layer and was defined at 2.6 m below the ground surface based on field observations and USDA Web Soil Survey (2013) estimates of the depth to restrictive layer. The lateral hydraulic conductivity (LK_{sat}), drainable porosity (θ_s – $\theta_{1/3}$), and lateral hydraulic gradient (LHG) have been found to be highly sensitive parameters for simulation of tile flow in RZWQM, (Ma et al., 2007a; Singh and Kanwar, 1995), which was also observed for calibration of SERF. Additionally, LK_{sat} has been found to be most important for simulating tile flow and NO_3-N loss at the soil layer containing the tile drain, followed by the layer directly above, (Ma et al., 2007a). For this reason, it was necessary to calibrate LK_{sat} values for simulation of tile drainage in layers six and seven, as the conventional tile depth is within layer seven. Within layer seven, LK_{sat} was calibrated to match a peak daily drainage rates of 1.9 cm day^{-1}, which was the design drainage intensity for SERF. Setting LK_{sat} for layers four and five was done similarly to aid in simulation of drainage for the alternative drainage systems during the testing period.

The lateral hydraulic gradient (LHG) was parameterized to a value of 1.2e-5 $\theta h\ \theta L^{-1}$ to fit annual observed drainage volumes for the conventional system. To facilitate soil water flow to the tile drains and maintain a lateral loss pathway, LK_{sat} was set to twice the value of K_{sat} within each layer. Maintaining high LK_{sat} values throughout the soil profile was done to promote tile drainage as well as additional lateral losses in the system other than subsurface drainage, as we hypothesized subsurface lateral loss to be the next largest subsurface loss pathway after tile drainage. It becomes evident that there are additional subsurface losses other than tile drainage at SERF when observing the depth to water table over time in the undrained plots: the water table in the undrained plots will recede fairly quickly after it has been recharged from a high rainfall event. It is not obvious whether this water loss pathway is fully in the lateral direction or if some travels below the system to a groundwater storage location, but the lateral loss (LAT) estimate calculated in RZWQM2 accounts for all subsurface pathways. Based off methods described by Bakhsh et al. (2004), the drainable porosity of the upper 5 cm profile was calibrated limit evaporation off of the soil surface. Additionally, setting a sufficient drainable porosity allowed for minimizing runoff by increasing infiltration rate into the soil profile. To correctly simulate evapotranspiration (ET), albedo coefficients were adjusted based on simulations by Zhiming Qi (2011) and Thorp et al. (2007) to fit ET within acceptable ranges for the region, including the albedo of dry soil, wet soil, the mature crop, and fresh residue, which were set to 0.2, 0.1, 0.25, and 0.8, respectively.

2.3.6 Model testing

The parameter set that performed satisfactorily for the calibration of a conventional drainage system was tested for a shallow, controlled, and an undrained system to assess the ability of RZWQM2 for simulating alternative drainage water management systems and a naturally poorly drained system. Testing these systems aided in determining the level of confidence that could accompany long-term simulations of these systems for similar soil types and climate regions. To simulate SD, the depth was decreased from 120 cm to 76 cm and the tile spacing was also decreased from 18 m to 12.2 m to maintain the same drainage intensity, as was done in the field experiment. For the CD simulation, the timing and depth of outlet structure management from 2007 to 2015 was used, which can be seen in Table 2.3. Generally, the boards in the control structure were removed to set an outlet depth of 120 cm in the early spring before planting, and replaced shortly after planting in the later spring to set an outlet depth of 76 cm. In 2007 to 2010, there was also management carried out in the fall to raise the outlet to a depth of 30 cm, however there was rarely enough rainfall during the fall and winter to be held back with the outlet structure during this time, therefore fall management was not continued for 2011 to 2015. To simulate ND for this location, it was necessary to simulate a very widely spaced drainage system with a small drain radius to maintain the subsurface lateral loss pathway with no artificial tile drainage simulation. Goodness-of-fit parameters used in calibration were also used to test the model simulation of alternative drainage systems and the undrained system.

2.3.7 Model application

After testing the calibrated parameter set for drainage water management and undrained systems, the model was then applied with a long-term weather dataset to observe the impacts on hydrology and nitrogen dynamics of the naturally poorly drained and three artificial subsurface drainage systems. To carry out long-term simulations, 45 years of historical climate and management data, from 1971 to 2015, were used after the model had been initialized for organic matter and microbial pools, as discussed in the model initialization and calibration section of the methods. Additionally, 11 years of weather and management data were added from 1960 to 1970 to initialize the processes within RZWQM prior to the long-term summary period. To simulate long-term effects of CD, the average dates of control outlet structure management were taken from the nine-year study at SERF; this included opening the control boards to a depth of 120 cm on April 15 and replacing the boards to a depth of 76 cm on June 14.

With this analysis, we wanted to observe the impacts of artificial drainage systems compared to a poorly drained system without artificial drainage. Additionally, we wanted to observe the impacts of a conventional drainage system compared to those of the alternative systems, or the drainage system nutrient reduction strategies. It was also an important goal to observe the differences between CD and SD, as a drainage system with a control structure requires additional management but allows for active manipulation of the water table within a field to allow for field entry or to prevent crop root excess moisture stress.

2.4 Results and Discussion

2.4.1 Model calibration and evaluation

2.4.1.1 Crop growth and yield

Corn and soybean production was well simulated for the nine-year dataset. The calibrated model crop growth and yield simulations for the conventional drainage system are provided in Table 2.4. Corn grain yield was satisfactorily simulated for DD with a PE% of -3.3% and n-RMSE of 12.9%, which are within the error limits of 15% and 30%, respectively (Table 2.5). All of the nine years of corn yield are within 20% PE%, and seven of the nine years are within 16% PE%. Manual calibration of maize model parameters posed somewhat of a challenge, likely due to variability within some of the calibration corn yield measurements; the average standard deviation of the observed nine-year dataset of dry matter corn grain is around 800 kg ha^{-1} yr^{-1} and ranges from 500 to 1150 kg ha^{-1} yr^{-1}. Corn yield was well simulated for the CD, SD and ND systems (Table 2.5).

Corn grain yield simulations correctly predicted a yield loss in each of these systems compared to the conventional system, as was experienced in the field study. It was hypothesized by Schott et al. (2016) and Helmers et al. (2012) that the reduction in grain yield was due to higher water tables in CD, SD and ND that reached within the potential root zone of the crops, thus generating slight excess water stress on the growing crops. The measured corn yield impacts from CD, SD and ND over the nine-year study were 5%, 4% and 8% yield loss, respectively, while the related RZWQM2-predicted impacts were 3% for all three systems. The average yield reduction in CD and ND over the nine years were statistically significant, (Schott et al., 2016). In the wettest year of the study, 2009, the measured yield loss for CD, SD and ND was 12%, 6% and 20%. During 2009 the yield loss in CD and ND were statistically significant, (Helmers et al., 2012). The simulated yield loss in 2009 was agreeable at 17%, 13% and 21% for CD, SD and ND, respectively. The PE% of the nine-year average corn simulations were -2.0, -1.8 and 3.0% for CD, SD and ND, respectively. These simulations of water excess yield reductions are reasonable compared to the field study as well as with other simulation work, such as Singh et al. (2007) and Luo et al. (2009) with DRAINMOD, where it was also found that excess water stress hindered corn yield in a CD system with higher water tables.

Soybean yield was also well simulated for DD with a PE% of -0.5% and n-RMSE of 14.1%. During soybean yield calibration, it was noted that unlike the

DSSAT-maize model, the DSSAT-soybean model does not simulate excess water stress, or water logging, likely causing some of the model over-prediction in yield in high precipitation years, such as 2010 when wetness stunted soybean yield, (Malone et al., 2010). Soybean yield reductions in the three alternative systems were measured over the nine-year field study, on average at 2, 3 and 12% for CD, SD and ND, respectively, however the only significant yield reductions occurred with the ND system nine-year average yield as well as in the years 2009, 2010 and 2014, (Helmers et al., 2012; Schott et al., 2016). RZWQM2 was unable to simulate the observed soybean yield loss from excess water stress experienced within the CD, SD and ND systems. Though deficit water stress seems to have been well developed with the CROPGO-soybean model, (Nielsen et al., 2002), little research has been done regarding this model in high soil water conditions. The PE% of the average nine-year soybean simulations were 1.3, 2.1 and 12.5% for CD, SD and ND, respectively.

In the calibration dataset, measured corn harvest index (HI) values were on average 0.49 for 2012 to 2015 while simulated values were 0.50 for those years and 0.50 for the 9-year average. Corn total aboveground biomass (AGB) simulations for 2012 to 2015 were also well simulated for DD with a PE% of -6.3% and n-RMSE of 19.6%. Soybean ABG was well simulated in calibration with a PE% of -0.8% and n-RMSE of 18.6%, however the observed dataset only included three years from 2013 to 2015. Aboveground biomass production and harvest index were also well simulated for both corn and soybeans for the three tested systems, similar to calibration performance.

Corn grain nitrogen uptake was over-estimated, making the percent nitrogen of the corn grain in the calibration dataset over estimated at 1.35% on average for 2012 to 2015, while the measured nitrogen content was only 1.15%, on average. Regional variation of corn nitrogen content, however, has been cited to be within the range of 1.2% to 1.6% N, (Christianson et al., 2012). The PE% for soybean grain total nitrogen for calibration was 4.7% and the n-RMSE was 13.8%, also indicating that the nitrogen content of the soybean grain was well simulated at 6.1%, while measured nitrogen content was 5.9% and regional estimates cite this value to be within 6-6.5% N, (Christianson et al., 2012). Within the testing datasets, nitrogen uptake in the grain was well simulated for soybeans, though generally over-predicted throughout the nine years, however this was not as well simulated for corn grain; calculated PE% and n-RMSE% were 11% and 24% for the CD system and 12% and 19% for the SD system, indicating a satisfactory simulation yet a slight over-prediction in nitrogen uptake in corn grain. Predictions of corn grain nitrogen in the ND system was not satisfactory at 25% and 28% for PE% and n-RMSE%, respectively, further indicating over-prediction error in nitrogen uptake by corn grain. Similar issues with RZWQM2 over-prediction of corn grain nitrogen uptake have been found in multiple simulations studies, as is well described in work by Thorp et al. (2007). Overall, these simulations of crop production and nitrogen uptake demonstrate adequate calibration and testing, which can be seen from the goodness-of-fit statistics provided in Table 2.5.

1.4.1.2 Hydrology

The average annual components of the nine-year hydrologic balance are provided in Table 2.6 for calibration with DD and testing with CD, SD and ND. In Table 2.6, the percent of precipitation is given for each water balance component to indicate its relative magnitude as an input/output pathway to and from the system. Additionally, the average annual simulated change in soil profile water storage is provided as “Delta S” which equals precipitation minus lateral seepage, runoff, ET and tile drainage (TD).

The single water input to the system, precipitation, was on average 105 cm for the nine-year study. The years of 2007 to 2010 as well as 2015 experienced average to above-average rainfall, while 2011 to 2014 experienced average to below-average rainfall. On average, over the nine-year study, 65% of annual rainfall occurred in March through August, with 28% in March through May and 36% in June through August. The seasonal distribution of rainfall for the site is shown in Figure 2.2.

The greatest loss from the system is ET, which includes evaporation from plant, soil, and residue surfaces plus transpiration by the growing crop. The annual nine-year average ET was simulated as 51 cm $yr^{-}1$, which is close to measured estimates by Bakhsh et al. (2004) from a tile-drained corn-soybean system in central Iowa, which included a range of 33.4 to 49.3 cm yr^{-1}. Simulated ET was also near model estimates simulated by Thorp et al. (2007) at an average ET of 46.8 cm yr-1. A modeled water-balance method was used by Sanford and Selnick (2013) to estimate ET across the conterminous United States and estimates ET in the range of 51-70 cm yr^{-1}, or 60-69% of annual rainfall, for the area of Southeast Iowa. Estimates for the nine years accounted for 48% of the water inputs, on average.

Annual drainage was slightly under-predicted for calibration data by 35 cm over the nine years, as seen in Figure 2.3, for a simulated total of 248 cm, which accounted for 26% of precipitation, on average, and ranged from 9-35% of annual precipitation. The calibration with DD annual drainage dataset was well simulated post-manual-calibration, however only eight years of tile drainage measurements were used due to issues with simulations in the year 2014. Data from 2014 was not used because the measured drainage was higher than expected because of low annual precipitation and had the highest ratio of annual precipitation to occur within a single month. Similar weather patterns, i.e. low annual precipitation with a high ratio within a single month, occurred in 2011 and 2013 as well as less severe over-predictions in drainage by RZWQM2. The ratio of precipitation that becomes drainage for each year is presented in Figure 2.4. For 2014, the percentage of precipitation that becomes subsurface tile drainage was measured as 45%, which is the highest of all the nine years, followed by 42% in 2013 and 38% in 2011. Kladivko et al. (2001) found a range of 0 to 40% of annual rainfall across multiple studies in humid regions of North America, indicating a potential that the 2014 drainage data may be overestimated. Hatfield et al. (1998), however, showed an average of 45% precipitation became drainage with watershed-scale measurements. The simulated percentage for 2014, 2013, and 2011, respectively, was 18%, 33%, and 32%, pointing out simulation error in 2014 drainage. The driest of the nine ears are between 2011 and 2014 with 86, 86 and 90 cm of rainfall in 2011, 2013 and 2014, respectively, yet these are not the lowest measured drainage years. The greatest ratios of annual drainage in a single month occurred within the years of 2011, 2013 and 2014, which included 24%, 29% and 29%, respectively. Also included is 2010 with 26% of rainfall in June. For all years other than 2011, 2013 and 2014 of the nine-year dataset, percent of precipitation becoming simulated drainage are within 4% of the observed percentage.

With the exclusion of 2014, the annual goodness-of-fit statistics are satisfactory for the calibration dataset at 3.3% for PBIAS%, 0.93 for NSE, 0.27 for RSR and 0.88 for R^2. Including all nine years, the monthly and daily measurements of DD drainage compared well to simulated values; PBIAS%, NSE, RSR and R^2 are equal to 16.5%, 0.78, 0.53 and 0.74, respectively for monthly drainage and 14.0%, 0.69, 0.55 and 0.70 for daily drainage. Goodness-of-fit statistics for annual and monthly tile drainage and NO_3-N loss for DD are provided along with the tested drainage systems, CD and SD, in Table 2.8.

For mass balance purposes, all nine years were used to compare all four simulated systems. Cumulative tile drainage was over-predicted over the nine years in simulations by about 40 cm for CD and 7 cm for SD. For CD, average annual tile drainage volume was simulated at 20 cm yr^{-1}, which is 4 cm yr^{-1} higher than the observed average annual drainage of 16 cm yr^{-1} and most of the error comes from 2015. For SD, average annual tile drainage volume was simulated and observed at 15 cm yr^{-1}. The impacts of the DWM systems of CD and SD on annual and monthly tile drainage were fairly well simulated throughout the nine years.

Figure 2.5 presents the monthly observed and simulated tile drainage for each drainage system as well as monthly precipitation. For annual drainage volume of the two alternative drainage systems, the simulated percent reduction, compared to DD, was under-predicted for both CD and SD due to over-prediction in CD and SD drainage and under-prediction in DD drainage volume. For the nine years, the CD system average annual drainage reduction was simulated to be 26%, which is lower than the observed reduction of 47%. That of the SD system was simulated at 46%, or slightly lower than the observed reduction of 50%. The simulated annual percent reduction in tile drainage, compared to DD, was higher in the below average and average rainfall years of 2011 to 2014, at 30% for CD and 50% for SD, and lower in the above average rainfall years, at 23% for CD and 44% for SD. These simulations were similar to findings in the measured dataset, (Schott et al., 2016).

In addition to drainage volume, this data set also allows for model assessment of simulation of depth to water table and 60 cm soil water storage. Using daily average measurements of the depth to water table from April through October for 2008 to 2015, calibration fit is satisfactory with a PBIAS% of -2.2%, NSE of 0.82 and RSR of 0.43. Depth to water table for calibration is presented in Figure 2.6. Note that data for some years within dry periods of the year, usually after July in 2011 through 2014, were not available due to the observation well drying out and no data could be collected by the pressure transducers.

Daily depth to water table was also well simulated for CD and SD (Table 2.9), however was not well simulated for the ND system. For CD and SD, the

RZWQM error is generally due to simulations of depth to water table being slightly too shallow in the spring and too deep in the summer. This may be directly related to the over-estimation bias in tile drainage for CD and SD, as most drainage occurs in the spring. The simulations for ND water table had much more variability in daily estimates than what was found in the measured data, causing high simulation error. In general, spring ND water table is fairly well simulated, however summer drawdown is over-estimated by the model.

Estimates of 60 cm soil water storage from field collected volumetric water content at 10, 20, 40 and 60 cm compared fairly well with simulated soil water storage, though simulations are often over-predicting soil water storage (Figure 2.7). For the five years of calibration data, fit-statistics of PBIAS% and R^2 are satisfactory at -9.77% and 0.52, however, NSE and RSR statistics are unsatisfactory at 0.26, 0.86. Though the fit-statistics of NSE and RSR are close, but not quite satisfactory, these RZWQM2 simulations of soil water storage are similar to simulations presented with work by Zhiming Qi (2011) and Ma et al. (2003).

Soil water storage was decently simulated for CD, SD and ND as well, with R^2 values of 0.53, 0.75 and 0.53, and with PBIAS% values of -12.6%, -18.8% and -14.4% (Figure 2.8). Daily fluctuations seem to track fairly well between observed and simulations soil water storage estimates, similar to that of the calibration dataset. Goodness-of-fit statistics for both the daily depth to water table (WT) and daily average soil water storage (SWS) in a 60 cm profile are provided in Table 2.9.

The subsurface lateral loss pathway was essential for simulating the water balance, as little surface runoff occurs at this site due to minimal slope, which left a generally large portion of the simulated nine-year calibration water balance, 21% of precipitation, or 201 cm, that was lost in a subsurface pathway other than via tile drainage. For CD, 25% of precipitation was lost laterally, similar to 29% lost for SD and 33% for ND. Compared to the DD system, both alternative drainage systems increased the proportion lost via the subsurface lateral pathway. The simulated percentages lost laterally in DD, CD and SD were similar to or greater than their simulated percentages lost via tile drainage. Over the nine years, simulations of DD lost 26% of precipitation via tile drainage, while that of CD and SD was less at 20% and 15%, respectively. Similar results were found in a RZWQM-simulation of control drainage in Central Iowa where the reduction in tile drainage in a controlled drainage system was accounted for in lateral seepage losses, (Ma et al., 2007b).

Simulated surface runoff in calibration was nominal, only accounting for 4% of precipitation, or 37 cm over nine years, which was expected in the well-drained plots at SERF with minimal ground slope. Due to the higher water table simulated with the CD, SD and ND systems, the model simulated increased runoff compared to the little runoff simulated with conventional drainage. To generate this runoff, RZWQM is simulating an excess of rainfall rate over a lesser soil profile infiltration rate, which is exacerbated by the wetter soil profile simulated with a higher water table, (Ahuja et al., 2000).

1.4.1.3 Nitrogen dynamics

The simulated nitrogen balances for the nine-year datasets of the conventional drainage system along with the three tested systems are provided in Table 2.7. The greatest input to the system includes N added with fertilizer and soybean fixation, summarized together each year by averaging the fertilizer added to the corn with the fixation by the soybeans. The only other input to the system includes the N deposited from the atmosphere with precipitation. Outputs from the system include N lost with lateral flow and deep seepage, N in runoff, denitrification, export of N via grain harvest and N lost via tile drainage. Grain N-export was used to give a broad view of the N-balance on a whole system level.

Simulation of annual NO_3-N loss was similar to that of annual tile drainage, as the goodness-of-fit statistics for calibration were satisfactory without the year 2014 included and poorer with 2014 included (Table 2.8). Again, for mass balance purposes, all nine years were used to compare all four simulated systems. The simulated average annual N-loss was 25 kg-N ha^{-1}, which was under-predicted compared to the measured value of 32 kg-N ha^{-1}. Annual NO_3-N load for CD and SD were well simulated. An average annual load of 17 kg-N ha^{-1} was simulated for CD, which compared well to a measured value of 16 kg-N ha^{-1}. For SD, average annual load was simulated as 18 kg-N ha^{-1}, similar to the average field measurement of 17 kg-N ha^{-1}. The simulated percent reduction for NO_3-N load compared to DD was again under-predicted for both CD and SD, similar to drainage volume. The CD system average annual reduction was simulated to be

31%, which is lower than the observed reduction of 48%. That of the SD system was simulated at 28%, lower than the observed reduction of 44%.

The annual nitrate loss normalized to the annual drainage, or FWANC mg-N L^{-1}, was fairly well simulated, as the simulated nine-year average FWANC of 10.4 mg-N L^{-1} is close to the observed value of 10.2 mg-N L^{-1}. It was noteworthy that RZWQM2 predicted high FWANC in dry years, shown in 2012, 2013 and 2014 and average or below average predictions for average or high rainfall years; this was also observed in the field data by Schott et al. (2016). The worst simulated FWANC occurred in 2013, when it was over-predicted by 6 mg-N L^{-1}. This may have been because the year prior, 2012, experienced rainfall 30 cm below average, causing buildup of residual soil NO_3-N in the system and a high simulated FWANC in 2013. Randall et al. (2003) demonstrated that soil NO_3-N can accumulate in the profile in a dry year from mineralization and fertilization and flushed out with subsequent rain, causing an unusually high FWANC the following year. It is unclear why measured FWANC wasn't higher in 2013 but it could be due to overestimation of tile drainage in 2013 as was previously discussed as a hypothesis for 2011, 2013 and 2014. In general, the FWANC was slightly over-predicted in above average rainfall years (2007, 2008, 2009, 2010, 2015) and under-predicted in below average rainfall years. For the calibration FWANC dataset, the goodness-of-fit statistics for are acceptable only for PBIAS%, calculated at 6.83%. Other research reports have shown difficulty in simulating the year to year variability in FWANC well, as this variability is relatively low, (Thorp et al., 2007).

The FWANC was also not well simulated for CD and SD based on fit statistics (Table 2.8). However, the eight-year average simulated FWANC for CD, 9.3 mg-N L^{-1}, is close to the observed average of 10.8 mg-N L^{-1} and the range in simulations, 6.3 to 12.6 mg-N L^{-1}, is similar to that of measurements, 6.3 to 13.6 mg-N L-1. For SD, the average FWANC over eight years was fairly well predicted at 12.7 mg-N L^{-1} compared to the observed average of 11.9 mg-N L^{-1}. Measured values of FWANC for SD ranged from 9.2 to 15.5 mg-N L^{-1}, while simulated values ranged from 6.8 to 20.2 mg-N L^{-1}. The simulation of SD seemed to accurately describe the higher FWANC that was observed in the field with the SD system. A higher FWANC in the SD system was hypothesized by Schott et al. (2016) to occur due to a shorter retention time in the saturated soil profile after a rainfall-infiltration event, thus limiting the vulnerability to denitrification in water infiltrating into a shallower tile drain. Drainage water short-circuiting to more shallow drains seems to be well simulated in the model, as the increased FWANC in SD system was simulated, potentially indicating that less time is allowed for nitrogen to be lost via other pathways and carried directly to the tile drains.

Soil NO_3-N measurements, measured in the fall of 2011, 2012, 2014 and 2015 were well simulated for the 0-90 cm layer (Table 2.10). The distribution within the upper 90 cm layer, however, was not well simulated, as the 0-30 cm estimate was under-predicted and 30-90 cm layer was over-predicted. In RZWQM2 simulations, residual NO_3-N in the upper soil profile can be a greatly affected by crop nitrogen uptake, generating under-prediction of NO_3-N with an over-prediction of crop nitrogen uptake, (Thorp et al., 2007). The goodness-of-fit statistics of n-

RMSE and PE% for fall NO_3-N in the calibration data were 31.8% and -21.0% for the 30 cm profile and were 15.2% and -2.0% for the 90 cm profile. In 2012, 30 cm soil NO_3-N was the most under-predicted, by around 8.3 kg-N ha^{-1}, likely because grain N uptake was highly over-predicted by 33.8 kg-N ha^{-1} in 2012. N-mineralization was simulated highest of the nine years in 2012 at 154 kg-N ha^{-1}, followed by 2013 at 128 kg-N ha^{-1}, likely because as a the two driest years, the soil profile was well-aerated due to a consistently deep water table. Though it could be expected to have higher residual soil nitrate due to a high N-mineralization rate, it seems that high corn nitrogen uptake offsets the addition of available nitrogen from mineralization, as the two years with the highest mineralization are also among the years with greatest nitrogen concentration in corn (1.6% in 2012, 1.4% in 2007 and 1.4% in 2013). As discussed by (Ma et al., 2007c), the error in 2012 fall soil NO_3-N may also be somewhat due to difficulty in simulation due to the drought conditions experienced within this year. Fall soil NO_3-N simulations were unsatisfactory in the upper 30 cm soil profile for CD, SD and ND: n-RMSE% and PE% are 48% and -28% for CD, are 76% and -14% for SD, and are 56% and -9% for ND, indicating great under-prediction in residual NO_3-N in each system. The 90 cm fall soil nitrate simulations were better predicted with n-RMSE% and PE% of 10% and -1% for CD, 35% and 1% for SD and 15% and 17% for ND.

2.4.3 Long-term simulations

Corn grain yield was reduced, on average over the 45 years, by 209 kg ha^{-1} (2.2%) in the undrained system, 146 kg ha^{-1} (1.5%) in the controlled drainage system and 116 kg ha^{-1} (1.2%) in the shallow drainage system, and was due again to the higher simulated water tables generating excess water stress on the corn root system (Table 10). The long-term corn yield loss is less than that of the nine-year simulations, likely because the nine-year dataset annual average precipitation is 105 cm, or higher than the 45-year dataset average of 90 cm, and six years of the nine-year dataset had above-average rainfall. Within the long-term dataset, the lowest annual rainfall occurred in 1988, with only 47 cm, and the highest annual rainfall was within the nine-year field study, 2009, with 137 cm of rain. Additionally, this long-term simulation of corn yield reduction is likely an underestimation for the simulated field, as yield loss was slightly under-predicted in the nine-year dataset simulations. It is possible that more work needs to be done in the development of excess moisture stress within the maize model.

The 45-year average annual water balances for the four systems are presented in Table 2.12, the nitrogen balances are provided in Table 2.13. The simulated average annual percent reduction in tile drainage volume over the 45 years was found to be 18% for CD and 48% for SD (Table 2.12), while average annual percent reduction in NO_3-N loss in tile drainage was 26% for CD and 40% for SD (Table 2.13). These reductions are in good agreeance with other simulation studies, such as simulations of 20-30% reduction in annual drainage NO_3-N loss in CD and SD systems in south central Minnesota by Luo et al. (2009). These estimates are lower than the reductions found in the field studies, (Helmers et al., 2012; Schott et al., 2016). On average, the DD system lost 20 kg-N ha^{-1} annually via tile drainage in the 45-year simulation, which is less than the tile drainage N-loss in the DD system for the nine-year study, which was 25 kg-N ha^{-1} annually.

This also occurred in the CD and SD systems, with 15 kg-N ha^{-1} lost long-term and 17 kg-N ha^{-1} in the nine-year simulation for CD and 12 kg-N ha^{-1} long-term and 18 kg-N ha^{-1} in the nine-year simulation for SD.

The nitrogen balances for the long-term simulations showed an average annual loss in soil nitrogen storage (kg-N ha^{-1} yr^{-1}) of 13 for DD, 11 for SD and for CD and the ND. Over the 45-year dataset, these reductions totaled to 587, 492 and 415 kg-N ha^{-1} lost, respectively. These values are within the range of soil nitrogen storage changes across the Midwest region, published by (Thorp et al., 2008). Also published by (Thorp et al., 2008), the loss in soil nitrate storage was generally greater in a conventional drainage system than in a drainage water management system, as was also found in these long-term simulations. The differences in soil nitrogen storage between DD and the other three systems in these long-term simulations is mostly due to decreased N-mineralization of soil profile organic material as well as increased denitrification in the CD, SD and the ND systems.

The alternative drainage systems altered the hydrologic balance compared to DD mostly by decreasing tile drainage and increasing runoff and subsurface lateral seepage. The N balance was impacted mostly with a decrease in N lost via tile drainage and slight decrease in N lost via grain harvest in the alternative drainage systems. These systems created an increase in denitrification, from 14 kg-N ha^{-1} in DD to 19 kg-N ha^{-1} in CD and SD. Lateral subsurface losses were also increased from 18 kg-N ha^{-1} in DD to 20 kg-N ha^{-1} in CD and 23 kg-N ha^{-1} in SD. N lost via surface runoff was minimal, <1 kg-N ha^{-1}, in all three drainage systems.

In the ND system, the nitrogen inputs were lost via denitrification, lateral seepage and runoff. In the ND system, on average, 13% was lost via subsurface pathways, including tile drainage and lateral seepage, 1% via runoff and 12% via denitrification, compared to 17% subsurface, <1% runoff and 8% denitrification, on average across the three tile drainage systems. This indicates that the pathways of N-loss in the system without tile drainage have converted some of the subsurface losses to a surface loss and gaseous loss pathway. The subsurface seepage loss is still significant in the ND system, however. This diffuse subsurface seepage loss may be available for other loss pathways over time, such as denitrification or plant uptake, however, they may also be laterally seeped into a water way or to groundwater sources. Research is needed to collect more information on the potential destinations of subsurface losses in undrained systems that are naturally poorly drained yet utilize a subsurface lateral seepage pathway for a large portion of their water and nitrogen balances.

The average annual precipitation for the 45-year dataset is 90 cm, which distinguishes five years of the nine-year dataset as above-average rainfall years (2007, 2008, 2009, 2010 and 2015), three years as below average rainfall year (2011, 2012 and 2013) and one year as an average rainfall year (2014). The lowest annual rainfall occurred in 1988, with only 47 cm, and the highest annual rainfall was within the nine-year field study, 2009, with 137 cm of rain. Within the 45-year simulations, five of the wettest years, five of the driest years and five average rainfall years were summarized to give the range of impacts of the two alternative drainage systems and the undrained system over the long-term dataset. Within the five driest years of the 45-year dataset (precipitation ranged from 47 to 69 cm) it was found that shallow drainage often generated no drainage or very little compared to the conventional and controlled drainage systems; the precipitation during the driest years were allocated between AET and LAT, rather than to tile drainage. This resulted in an average of 77% reduction in tile drainage (cm) and 56% reduction in NO_3-N loss (kg-N ha^{-1}) in the SD system. In these years, the CD system reduced tile drainage by 20% and NO_3-N loss by 28%. The tile drainage volume that was reduced by the CD system was lost via the subsurface lateral seepage pathway. In the undrained system within the driest years, all precipitation was lost via ET and lateral seepage. No runoff was generated for any of the four simulated systems. During these dry years, evaporative and plant transpiration requirements extracted moisture from the soil profile, shown by an average change in soil water of -15 cm across all four treatments over the five years.

Within the five wettest years (precipitation ranged from 119 to 137 cm), shallow drainage reduced annual tile drainage and NO_3-N loss by 43% and 35% and controlled drainage reduced by 18% and 22%, respectively. Percent of precipitation to become tile drainage went up for DD, CD and SD systems in the driest years from 7%, 6% and 2%, respectively, to 36%, 29% and 21% in the wettest years. The related change in runoff went up from 0% for all systems to 3%, 9%, 9% and 21% in the wettest years for DD, CD, SD and ND, respectively. The percentage of rainfall to become lateral seepage was similar from dry years to wet years for DD and CD (21% and 24% in dry years to 23% and 26% in wet years, respectively) and was increased for SD and ND from 25% and 25% in dry years to

32% and 37% in wet years, respectively. Evaporation and transpiration accounted for 40%, 38%, 40% and 43%, respectively, for DD, CD, SD and ND within the wettest years. The average change in soil water storage over all four systems in the five wettest years was -2 cm, indicating a nearly negligible soil water balance compared to the loss in storage found in the driest years.

Within five average rainfall years (precipitation from 90 cm to 92 cm), percent reduction in tile drainage and NO_3-N loss for CD was found to be 20% and 23%, respectively and 55% and 48% and for the SD system. Tile drainage in DD, CD and SD accounted for 19%, 16% and 9% of precipitation, respectively. The average change in soil water storage for the five average rainfall years was found to be 3, 4, 4, and 5 cm for DD, CD, SD and ND systems. It was important to note that percent-reduction in annual drainage N-load was greatest in dry years and lowest in wet years, especially for the SD system. This same phenomenon was observed in Southern Minnesota on a similar silty clay loam soil, as Sands et al. (2008) found that a shallow drainage system reduced annual drainage volume from 16.4% to 30.4% over a five year study and that the years with the largest rainfall produced the least percent reduction in drainage volume.

The FWANC (mg L^{-1}) within average years varied little between the three drainage treatments: 12.6 mg L^{-1} for DD, 11.6 mg L^{-1} for CD and 13.3 mg L^{-1} for SD. For the wet years, the FWANC variation was still minor: 7.8 mg L^{-1} for DD, 7.5 mg L^{-1} for CD and 8.9 mg L^{-1} for SD. The dry years had much greater variation between drainage systems: 14.6 mg L^{-1} for DD, 12.1 mg L^{-1} for CD and 26.5 mg L^{-1} for SD. The CD system likely reduced FWANC because denitrification was increased by 5, 5.4 and 2.4 kg-N ha^{-1} in the average, wet and dry years, respectively, as well as N-mineralization was decreased by 5.6, 6.7 and 3.2 kg-N ha-1 in the average, wet and dry years. This increase in denitrification and decrease in N-mineralization was similar in the SD system. As was mentioned before, the high FWANC simulated for the SD system may be due to infiltrating water short-circuiting to the shallower tile drain.

An annual exceedance probability (AEP) curve for N-load was estimated from the 45-year simulations for DD, CD and SD. We also analyzed the spring exceedance probability (SEP) for N-load. Spring N-loading included the months of April, May and June, as this was indicated by the EPA Science Advisory Board to have the greatest impact on hypoxia in the Northern Gulf of Mexico, (Dale et al., 2007). The probability of exceedance curves for N-load are provided in Figure 2.9, including both the exceedance probabilities for annual N-load (Figure 2.9a) as well as spring N-load (Figure 2.9b). In the CD system at SERF, the control boards are typically managed to release the water held back in the tiles to a depth of 120 cm around April 15 and to close them back up to 76 cm below the ground surface around June 14. This means that the tile drainage N-load reduction potential of CD may be limited from mid-April to mid-June.

Annually, there was a 10% exceedance probability for DD, CD and SD for N-loads of 36.6, 27.6 and 23.9 kg-N ha^{-1}, respectively, a 50% probability of exceedance of 19.6, 14.5 and 11.8 kg-N ha^{-1} and a 90% probability of exceedance of 2.7, 1.4 and 0 kg-N ha^{-1}. For the spring months, there was a 10% exceedance probability for DD, CD and SD for N-loads of 29.4, 23.1 and 20.5 kg-N ha^{-1}, respectively, a 50% probability of exceedance of 14.8, 13.2 and 9.5 kg-N ha^{-1} and a 90% probability of exceedance of 0.2, 3.2 and 0 kg-N ha^{-1}. These AEP and SEP curves demonstrate the importance of spring drainage for the upper Midwest region, where typically around 70% of annual drainage and N-loading occurs in the months of April, May and June, (Helmers et al., 2005).

The major difference found between the AEP and SEP curves involves N-load from the CD system. The CD system generated higher N-loads than DD at the high-probability, low drainage and N-load, discharges within the spring. This may mean that with CD, drainage water is held back from the previous fall or winter and is released during the spring months, while the DD or SD system had allowed this discharge to leave prior to the spring. Similarly, Ale et al. (2010) found that April experienced an increase in drain flow in the controlled, or managed, system after the control outlet was opened on March 31. Additional research on this effect of spring N-load from a CD is lacking. From these SEP curves, there was a high likelihood within the 45-year simulations that spring N-load contributions from CD were the same as or exceeded DD at the low drainage and N-load range of the simulated spring N-loadings. On average, the CD system only reduced spring N-load by 11% and increased N-load in about half of the years, compared to DD. The SD system, however, was effective in reducing spring N-load, with an average reduction of 35%. Improvement of DWM systems to reduce drainage N-loading within these critical spring months across the upper Midwest landscape may be required.

2.5 Summary and Conclusions

This work adds unique contributions to the relevant literature, first, by demonstrating that RZWQM is capable of simulating a shallow drainage system. Additionally, we have made an attempt to quantify long-term impacts of DWM systems, which only a few studies have done. This work points out potential limitations with RZWQM2-DSSAT simulation of crop production loss under high moisture stress conditions, especially with the CROPGRO-soybean model. Modeling this excess moisture stress will be vital for simulation models in order to fully understand the impacts and potential drawbacks of future adoption of DWM practices.

Estimating year-to-year variability in reduction of N loss for DWM systems is essential for those interested in predicting performance of such systems into the future, potentially for policy or goal-setting purposes for N reduction strategies. Based on the long-term simulations, the possibility of meeting the Iowa Nutrient Reduction Strategy goal of a 41% reduction in annual TN loss using DWM in Southeast Iowa is promising and can make a great impact. Considering the long-term 26% N-load reduction with controlled drainage and 40% with shallow drainage, 5.1 and 7.9 kg-N ha^{-1} yr^{-1}, respectively, shallow drainage seems to be more consistent in reducing nitrogen lost via tile drainage, yet both systems have shown substantial reduction in annual N-loading.

As previously shown in a long-term simulation across the Midwest region, controlled drainage was most effective in southern areas of the Midwest, such as Missouri, Illinois, Indiana and Ohio (reduction of 35.8 to 46.3 kg-N ha^{-1} yr^{-1}), and least effective in the northern areas, such as Iowa, Minnesota and Wisconsin (reduction of 7.1 to 20.4 kg-N ha^{-1} yr^{-1}), (Thorp et al., 2008). This has been mostly attributed to differences in the timing of precipitation and drainage. In west-central Indiana, for example, DRAINMOD modeling work by Ale et al. (2010) showed that the majority (>80%) of N loss reduction with DWM occurred during the non-growing season (November through April), which is also typically when the majority of annual precipitation and drainage occurs, (Adeuya et al., 2012). In regions similar to Southeast Iowa, however, the timing of the majority of annual precipitation (50%) and drainage (70%) (April, May and June) generally coincides with the release of drainage water within the control structure to allow for spring field activities, (Helmers et al., 2005; Thorp et al., 2008). Additionally, within this work, controlled drainage was found to be ineffective in years with low N-load at reducing N loss during the spring period, which is the critical time period for reducing the impact on hypoxia in the Northern Gulf of Mexico. Currently, research that focuses on the spring N-loading of a controlled-outlet drainage system is limited and therefore should be addressed in future research.

Additionally, in Iowa and the northern area of the Midwest region, production losses from higher water tables as well as added management and cost should also be considered with DWM application. Additionally, controlled drainage is limited to fields with minimal land slope so that the water table can be evenly managed with a control outlet structure, which limits its applications to certain field locations. There is additional cost associated with both systems, including the minimal cost of the control structure as well as the cost of increased length of tile drains with shallow drainage, as the tiles are installed closer together to maintain drainage rates.

Agricultural simulation modeling will continue to be vitally important as scientists, engineers and producers strive to prioritize and improve agricultural nutrient reduction strategies throughout the Midwest. Additional simulation studies will be needed to compare across landscapes and climates and aid model developers in improving model processes to enhance our understanding of agricultural nutrient loss.

Tables

Table 2.1. Measured and estimated soil hydraulic properties.[a]

Depth	silt	clay	SOC	BD	Porosity	Pb	Ksat	LKsat	θR	θS	θ33	θ1500
cm	cm^3 cm^{-3}	cm^3 cm^{-3}	%	g cm^{-3}	cm3 cm^{-3}	cm	cm hr^{-1}	cm hr^{-1}	cm^3 cm^{-3}			
0-5	0.48	0.39	2.95	1.1	0.585	-1	5	10	0.025	0.573	0.253	0.153
5-20	0.49	0.38	2.81	1.348	0.491	-32	1.5	3	0.04	0.467	0.34	0.209
20-40	0.46	0.4	1.99	1.344	0.493	-32	0.5	1	0.04	0.463	0.331	0.198
40-60	0.47	0.39	0.93	1.383	0.478	-32	0.7	1.4	0.04	0.43	0.308	0.186
60-90	0.47	0.39	0.23	1.383	0.478	-32	2	4	0.04	0.43	0.308	0.186
90-100	0.47	0.39	0.23	1.383	0.478	-42	5	10	0.04	0.43	0.32	0.192
100-140	0.47	0.39	0.23	1.383	0.478	-42	2	4	0.04	0.43	0.32	0.192
140-180	0.47	0.39	0.12	1.45	0.453	-42	1.5	3	0.05	0.408	0.307	0.19
180-260	0.47	0.39	0.01	1.6	0.396	-42	0.01	2	0.07	0.357	0.276	0.182

[a]BD – bulk density, Pb – bubbling pressure, Ksat – saturated hydraulic conductivity, LKsat – lateral hydraulic conductivity, θR – residual water content, θS – saturated water content, θ33, θ15 –water content at 33 and 1500 kPa, SOC – soil organic carbon.

Table 2.2. Calibrated crop parameters for corn and soybean.

Crop	Coefficient	Description	Corn_1*	Corn_2*
Corn[a]	P1	Thermal time from seedling emergence to the end of the juvenile phase (°C above 8°C base temperature)	225	
	P2	Delay in development (days hr^{-1}) for each hour that day length is above 12.5 hours (0-1)	0.4	
	P5	Thermal time from silking to physiological maturity (°C days above 8°C base temperature)	750	795
	G2	Maximum possible number of kernels per plant	810	
	G3	Kernel filling rate during the linear grain filling stage and under optimum conditions (mg day^{-1})	7	8
	PHINT	Phylochron interval in thermal time (°C days) between successive leaf tip appearances	52	
Soybean[b]	LFMAX	Maximum leaf photosynthesis rate at 30 C, 350 vpm CO_2, and high light(mg CO_2 m^{-2} s^{-1})	0.725	

[a] Maize Cultivar IB1 068 Dekalb 521.
[b] Soybean Cultivar 990002 M Group 2.
*Corn_1 gives calibrated parameter set for the simulation of a shorter corn maturity group and Corn_2 for the simulation of a longer maturity group.

Table 2.3. Management dates used in from 2007 to 2015 simulation and long term simulation (1960-2006), including outlet control structure board removal and replacement for the controlled drainage system (CD).

Year	Corn Planting	Corn Harvest	Soybean Planting	Soybean Harvest	CD - Spring control Open(1.2m)	CD - Spring control Close (0.76m)	CD - Fall control Close (0.3 m)
2007	May. 05	Nov. 05	Jun. 02	Oct. 11	Apr. 30	Jun. 02	Jan. 07, 2008
2008	May. 09	Nov. 05	Jun. 06	Oct. 11	Apr. 14	Jun. 05	Nov. 19
2009	Apr. 17	Oct. 13	May. 31	Oct. 20	Apr. 15	May. 29	Nov. 05
2010	Apr. 15	Sep. 30	May. 28	Oct. 02	Apr. 15	Jun. 24	Oct. 18
2011	May. 03	Sep. 29	May. 11	Oct. 03	Apr. 25	Jun. 01	-
2012	Apr. 18	Sep. 24	May. 15	Oct. 24	Apr. 05	Jun. 14	-
2013	May. 17	Oct. 04	Jun. 12	Oct. 02	-	-	-
2014	May. 06	Nov. 07	May. 09	Oct. 10	-	-	-
2015	Apr. 30	Sep. 15	May. 02	Oct. 07	Mar. 31	May. 22	-
1960-2006	May. 01	Oct. 19	May. 20	Oct. 08	Apr. 15	Jun. 14	-

Table 2.4. Crop growth simulation results for calibration with conventional drainage (DD) for corn (C) and soybean (SB) with observed and simulated corn and soybean yield.[a]

	AGB		BGB		RD		HI		Corn Yield		Soybean Yield	
	C	SB	C	SB	C	SB	C	SB	OBS	SIM	OBS	SIM
2007	18057	6471	3357	976	119	91	0.44	0.50	9505	7997	3368	3212
2008	19677	6257	3186	909	114	91	0.56	0.48	9134	10972	2736	3035
2009	17333	7137	3587	1150	109	90	0.54	0.45	9045	9329	3928	3201
2010	15008	6454	2658	898	116	91	0.51	0.52	9066	7601	3081	3324
2011	18219	7490	2949	1044	120	91	0.47	0.50	8566	8509	3260	3718
2012	21191	7386	2451	1078	113	91	0.47	0.46	10567	9934	3446	3399
2013	20674	6272	3470	992	120	90	0.44	0.46	7731	9063	2150	2883
2014	19482	7266	3704	1179	109	90	0.55	0.42	11604	10673	3524	3068
2015	18371	7146	2238	960	114	91	0.56	0.46	12084	10333	3811	3313

[a] AGB = above-ground biomass, BGB = below-ground biomass, RD = rooting depth, OBS = observed, SIM = simulated.

Table 2.5. Goodness-of-fit statistics for crop growth for conventional drainage (DD), controlled drainage (CD), shallow drainage (SD) and undrained (ND) from 2007 to 2015 for corn (C) and soybean (SB).[a] [b]

		DD	CD	SD	ND
Corn Yield	PE%	-3%	-2%	-2%	3%
	n-RMSE%	13%	15%	13%	10%
Corn Grain-N	PE%	10%	11%	12%	25%
	n-RMSE%	19%	24%	19%	28%
Corn AGB	PE%	-6%	-7%	-6%	-2%
	n-RMSE%	20%	23%	20%	24%
Corn HI	PE%	4%	5%	4%	5%
	n-RMSE%	13%	12%	11%	18%
Soybean Yield	PE%	-1%	1%	2%	12%
	n-RMSE%	14%	13%	14%	16%
SB Grain-N	PE%	5%	6%	3%	5%
	n-RMSE%	14%	13%	10%	17%
SB AGB	PE%	-1%	-10%	-1%	1%
	n-RMSE%	19%	23%	15%	11%
SB HI	PE%	-2%	8%	-3%	8%
	n-RMSE%	15%	19%	13%	22%

[a] AGB = above-ground biomass, HI = harvest index.
[b] Corn AGB and HI measurements only available 2012-2015, soybean AGB and HI measurements only available from 2013-2015.

Table 2.6. Simulated average annual hydrologic components from 2007 to 2015 for conventional drainage (DD), controlled drainage (CD), shallow drainage (SD) and undrained (ND), along with observed tile drainage for comparison and the percent of precipitation for each component.

	DD		CD		SD		ND	
	cm	%	cm	%	cm	%	cm	%
Precipitation	105	-	105	-	105	-	105	-
Actual ET[a]	50	48%	48	46%	50	48%	53	51%
Runoff	4	4%	10	10%	9	9%	18	18%
Lateral seepage	22	21%	26	25%	30	29%	35	33%
Tile Drainage	28	26%	20	19%	15	15%	-	-
Tile Drainage_OBS[b]	*32*	*31%*	*16*	*15%*	*15*	*14%*	-	-
Delta S[c]	0.9	-	0.3	-	0.0	-	-1.1	-

[a] ET = evapotranspiration.
[b] Measured value for tile drainage.
[c] Average annual change in soil water profile storage.

Table 2.7. Simulated average annual nitrogen components from 2007 to 2015 for conventional drainage (DD), controlled drainage (CD), shallow drainage (SD) and undrained (ND), along with observed N-loss via tile drainage for comparison and the percent of inputs for each loss component.[a]

	DD		CD		SD		ND	
	kg-N ha^{-1}	%	kg-N ha^{-1}	%	kg-N ha^{-1}	%	kg-N ha^{-1}	%
Precipitation-N	16	-	16	-	16	-	16	-
Fertilizer + Fixation	196	-	196	-	196	-	196	-
Lateral Seepage-N	17	8%	20	9%	21	10%	26	12%
Runoff-N	1	0.4%	2	0.9%	2	0.8%	3	1.6%
Denitrification	14	7%	21	10%	19	9%	27	13%
Grain-N	157	74%	154	73%	155	73%	158	75%
Tile Drainage-N	25	12%	17	8%	18	8%	-	-
Tile Drainage-N_OBS[a]	*32*	*15%*	*16*	*7%*	*17*	*8%*	-	-
Delta S[b]	-3.3	-	-2.4	-	-1.9	-	-2.5	-
Net Min[c]	104.7	-	97.4	-	92.9	-	89.7	-

[a] Measured value for tile drainage N-loss.
[b] Average annual change in soil profile N.
[c] Average annual net N mineralization, equal to N-mineralization minus N-immobilization.

Table 2.8. Goodness-of-fit statistics for annual and monthly tile drainage (cm), nitrate loss (kg-N ha^{-1}) and FWANC (mg L^{-1}) for conventional drainage (DD), controlled drainage (CD) and shallow drainage (SD).[a]

		DD	CD	SD
TD - Annual	PBIAS	3.3%	-17.1%	3.8%
	NSE	0.93	0.62	0.61
	RSR	0.27	0.61	0.63
	R^2	0.88	0.68	0.57
TD - Monthly	PBIAS	16.5%	-19.1%	2.1%
	NSE	0.78	0.66	0.62
	RSR	0.53	0.58	0.61
	R^2	0.74	0.78	0.67
N Loss - Annual	PBIAS	9.4%	-5.9%	8.4%
	NSE	0.73	0.72	0.54
	RSR	0.52	0.53	0.68
	R^2	0.53	0.55	0.31
N Loss - Monthly	PBIAS	14.3%	-9.3%	-2.9%
	NSE	0.63	0.71	0.31
	RSR	0.68	0.54	0.83
	R^2	0.60	0.78	0.55
FWANC	PBIAS	6.8%	10.8%	-6.9%
	NSE	-0.46	-0.06	0.12
	RSR	1.21	1.03	0.94
	R^2	0.01	0.13	0.00

[a] Of the nine years of data from 2007 to 2015, the annual datasets for DD, CD and SD exclude the years 2014, 2015 and 2011, respectively, while monthly datasets include all nine years.

Table 2.9. Goodness-of-fit statistics for daily average depth to water table (WT) and daily average soil water storage (SWS) in 60 cm soil profile.[a]

		DD	CD	SD	ND
WT - Daily	PBIAS	-2.2%	2.1%	-9.0%	-34.2%
	NSE	0.82	0.80	0.72	0.27
	RSR	0.43	0.45	0.53	0.86
	R^2	0.39	0.56	0.57	0.47
SWS - Daily	PBIAS	-9.8%	-12.6%	-17.2%	-14.4%
	NSE	0.26	-0.64	-1.08	-0.03
	RSR	0.86	1.28	1.44	1.01
	R^2	0.52	0.53	0.69	0.53

[a] Depth to water table data includes 2008 to 2015 while soil water storage data includes 2011 to 2015.

Table 2.10. Goodness-of-fit statistics for fall soil nitrate within the 0-30 cm and 0-90 cm soil profile.

Depth		DD	SD	ND	CD
0-30 cm	PE%	-21%	-14%	-9%	-28%
	n-RMSE%	32%	76%	56%	48%
0-90 cm	PE%	-2%	1%	17%	-1%
	n-RMSE%	15%	35%	15%	10%

Table 2.11. Average annual crop production of 45 year simulations (1971-2015) for corn-soybean systems with conventional drainage (DD), controlled drainage (CD), shallow drainage (SD) and undrained (ND), along with the difference in CD, SD and ND compared to DD (given as kg ha^{-1} and as a percentage).[a]

			Difference			Difference			Difference	
	DD	CD	(kg ha^{-1})	(%)	SD	(kg ha^{-1})	(%)	ND	(kg ha^{-1})	(%)
Corn Grain Yield	9551	9405	-146	-1.5	9434	-116	-1.2	9341	-209	-2.2
Corn AGB	19352	18789	-563	-2.9	18936	-416	-2.1	18515	-837	-4.3
Corn BGB	3872	3955	82	2.1	3897	25	0.6	3842	-31	-0.8
Soybean Grain Yield	3495	3516	21	0.6	3494	-1	0.0	3487	-9	-0.2
Soybean AGB	7439	7458	19	0.3	7432	-7	-0.1	7411	-28	-0.4
Soybean BGB	1096	1090	-6	-0.6	1091	-5	-0.5	1080	-16	-1.5

[a] AGB = aboveground biomass production, BGB = belowground biomass production.

Table 2.12. Annual hydrologic components of 45 year simulations (1971-2015) for corn-soybean systems with conventional drainage (DD), controlled drainage (CD), shallow drainage (SD) and undrained (ND), along with the difference in CD, SD and ND compared to DD (given as cm and as a percentage).

	DD	CD	Difference		SD	Difference		ND	Difference	
	(cm)	(cm)	(cm)	%	(cm)	(cm)	%	(cm)	(cm)	%
Precipitation	90	90	-	-	90	-	-	90	-	-
Actual ET[a]	53	50	-3.1	-6	53	0.3	1	55	1.8	3
Actual Evaporation	*11*	*11*	*0.7*	*6*	*11*	*0.6*	*6*	*14*	*2.9*	*28*
Actual Transpiration	*42*	*39*	*-3.7*	*-9*	*42*	*-0.3*	*-1*	*41*	*-1.1*	*-3*
Potential ET[a]	119	111	-7.2	-6	119	0.9	1	122	3.1	3
Potential Evaporation	*36*	*36*	*0.0*	*0*	*37*	*1.0*	*3*	*39*	*3.2*	*9*
Potential Transpiration	*43*	*39*	*-3.8*	*-9*	*42*	*-0.4*	*-1*	*42*	*-1.2*	*-3*
Runoff	2	4	2.2	112	4	2.4	121	9	7.4	374
Lateral Seepage	20	23	3.2	16	26	6.1	31	29	9.0	45
Tile Drainage	19	16	-3.5	-18	10	-9.2	-48	0	-	-
Delta S[b]	-4	-2	1.1	-32	-3	0.4	-12	-3	0.7	-21

[a] ET = evapotranspiration.
[b] Average annual change in soil water profile storage.

Table 2.13. Annual nitrogen dynamics of 45 year simulations (1971-2015) for corn-soybean systems with conventional drainage (DD), controlled drainage (CD), shallow drainage (SD) and undrained (ND), along with the difference in CD, SD and ND compared to DD (given as kg-N ha-1 and as a percentage).

	DD	CD	Difference		SD	Difference		ND	Difference	
	kg-N ha^{-1} yr^{-1}	kg-N ha^{-1} yr^{-1}	kg-N ha^{-1} yr^{-1}	%	kg-N ha^{-1} yr^{-1}	kg-N ha^{-1} yr^{-1}	%	kg-N ha^{-1} yr^{-1}	kg-N ha^{-1} yr^{-1}	%
Precipitation-N	14	14	-	-	14	-	-	14	-	-
Fertilization	77	77	0.0	0	77	0.0	0	77	0.0	0
Fixation	120	123	-3.6	-3	122	-2.0	-2	122	-2.5	-2
Lateral Seepage-N	18	20	-1.8	-10	23	-4.8	-26	27	-8.7	-47
Runoff-N	0.3	0.7	-0.4	-119	0.8	-0.5	-138	1.8	-1.4	-427
Denitrification	14	19	-4.2	-29	19	-4.5	-31	25	-10.3	-71
Volatilization	0	0	0.0	-	0	0.0	-	0	0.0	-
Grain-N Export	171	169	1.5	1	169	2.0	1	168	2.4	1
Tile Drainage-N	20	15	5.1	26	12	7.9	40	-	-	-
Delta S[a]	-13	-9	-4.3	32	-11	-2.5	19	-9	-4.5	33
Net N-mineralization[b]	120	114	5.2	4	116	3.5	3	113	6.4	5
	(mg-N L^{-1})	(mg-N L^{-1})	(mg-N L^{-1})	%	(mg-N L^{-1})	(mg-N L^{-1})	%			
FWANC[c]	10.5	9.2	1	12	11.8	1	13			

[a] Average annual change in soil profile N.
[b] Average annual net N mineralization, equal to N-mineralization minus N-immobilization.
[c] Flow-weighted annual nitrogen concentration, calculated as annual N-load normalized to the annual drainage volume.

Figures

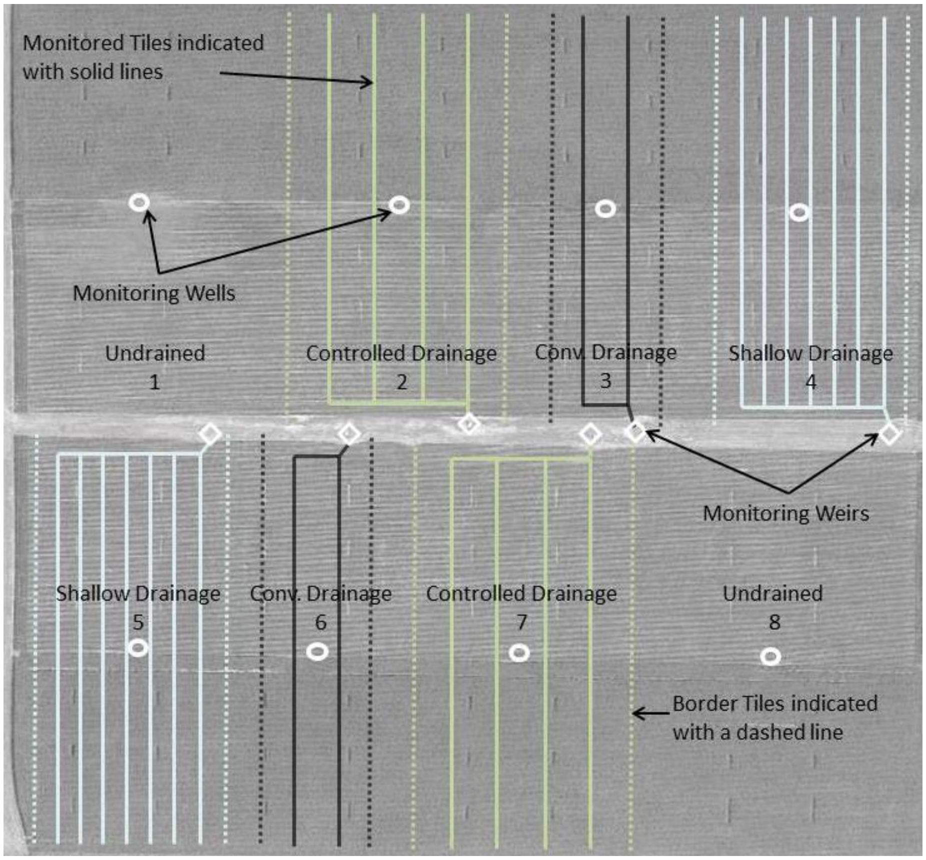

Figure 2.1. Aerial image and field map of SERF with two replications of each treatment, including conventional drainage (DD), controlled drainage (CD), shallow drainage (SD) and undrained (ND).

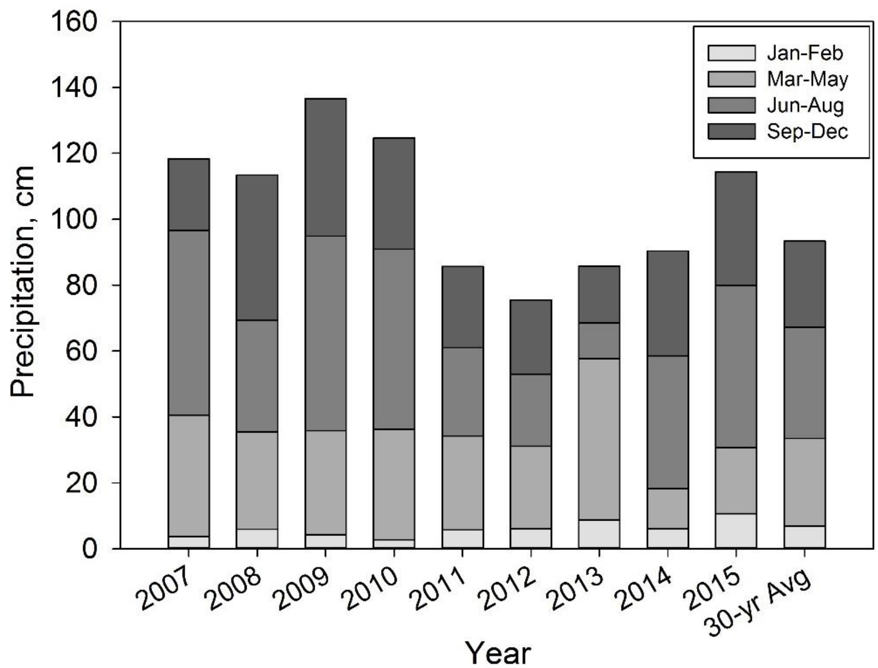

Figure 2.2. Seasonal distribution of rainfall for the nine-year study.

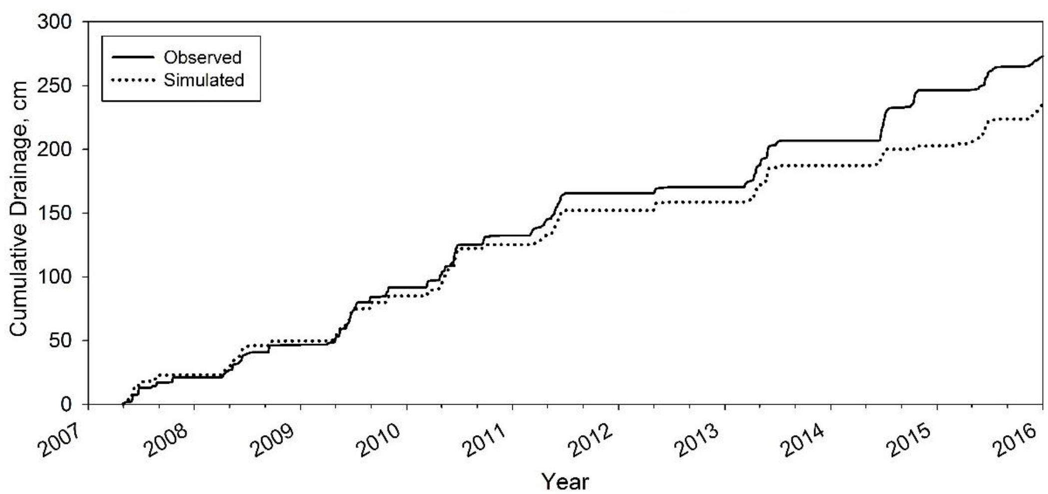

Figure 2.3. Nine-year cumulative drainage for DD system with observed shown with dotted line and simulated with solid line.

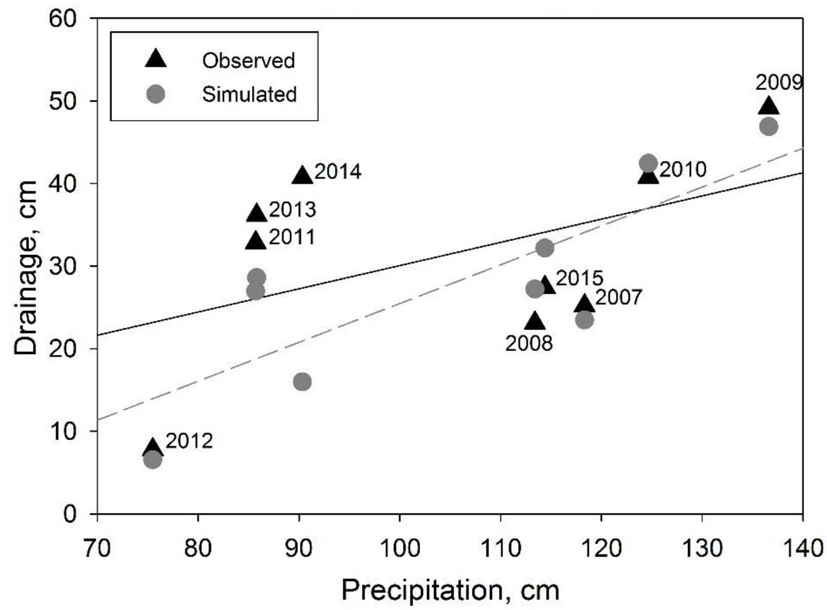

Figure 2.4. Ratio of drainage-to-precipitation for each year of the nine-year study.

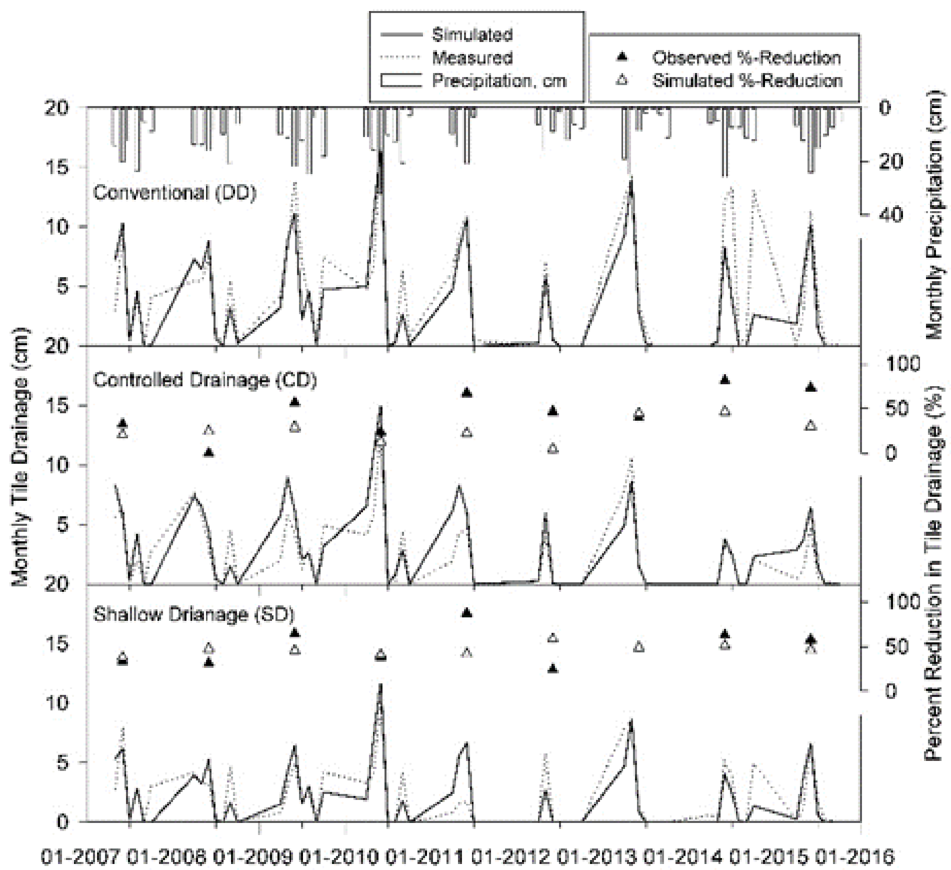

Figure 2.5. Monthly simulated and measured tile drainage for conventional drainage (DD) (top), controlled drainage (CD) (middle) and shallow drainage (SD) (bottom) for April through October for 2007-2015, as well as monthly precipitation (bar graph at top) and percent reduction in tile drainage in CD and SD systems.

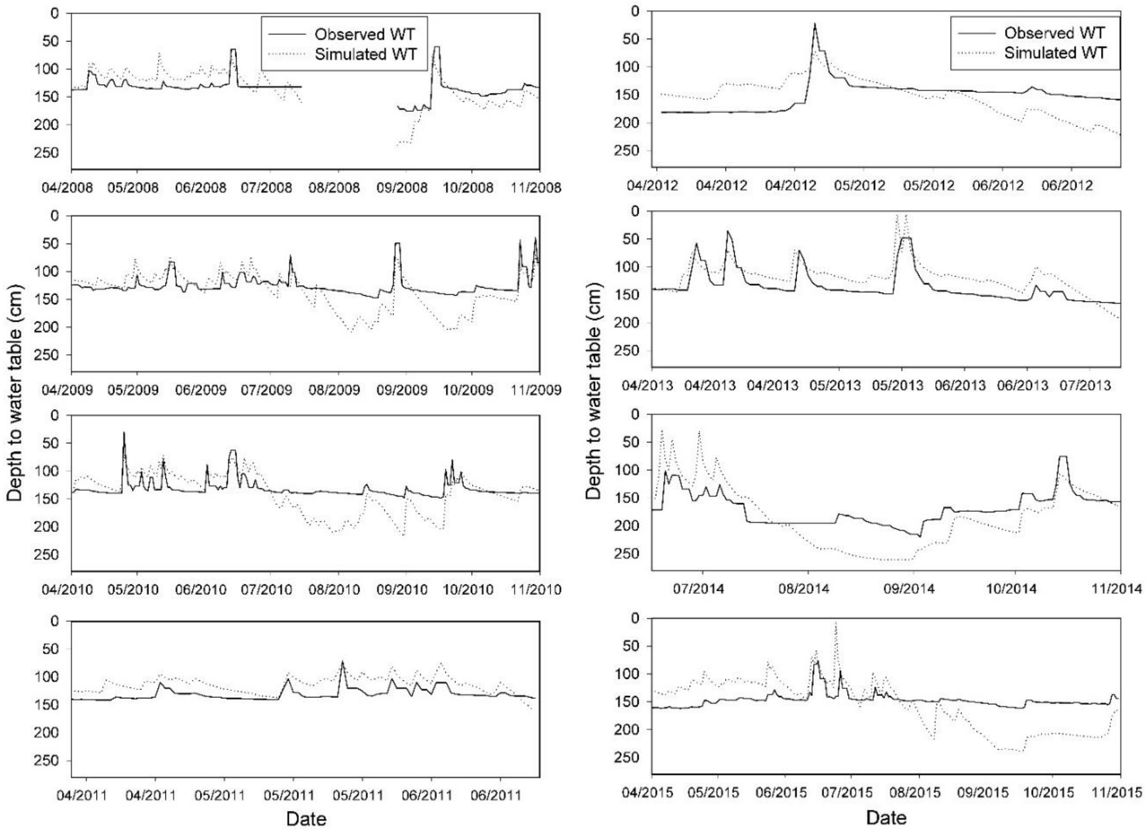

Figure 2.6. Daily average measured and simulated depth to water table for DD system.

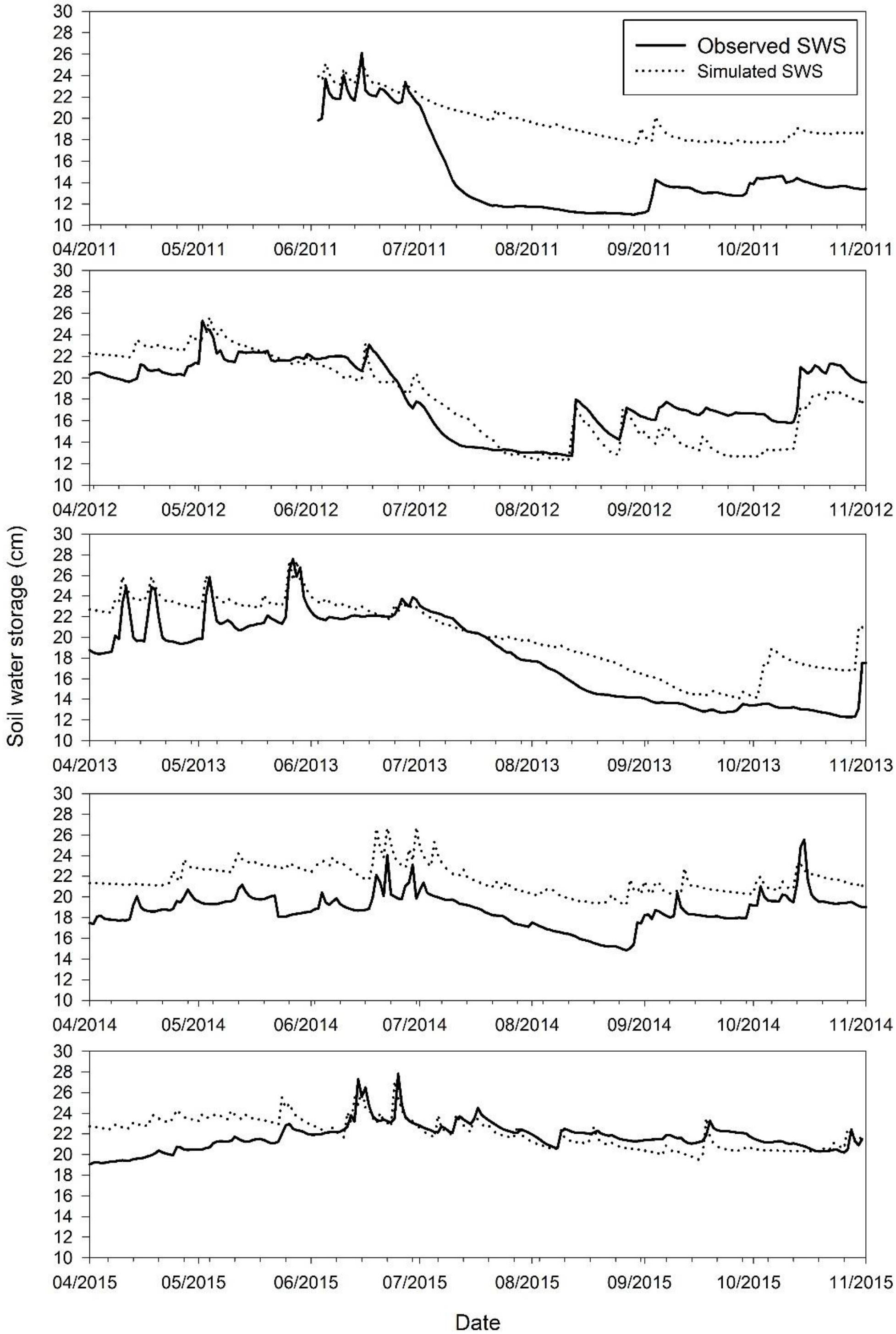

Figure 2.7. Daily average measured and simulated soil water storage (SWS) for conventional drainage (DD) from 2011 to 2015.

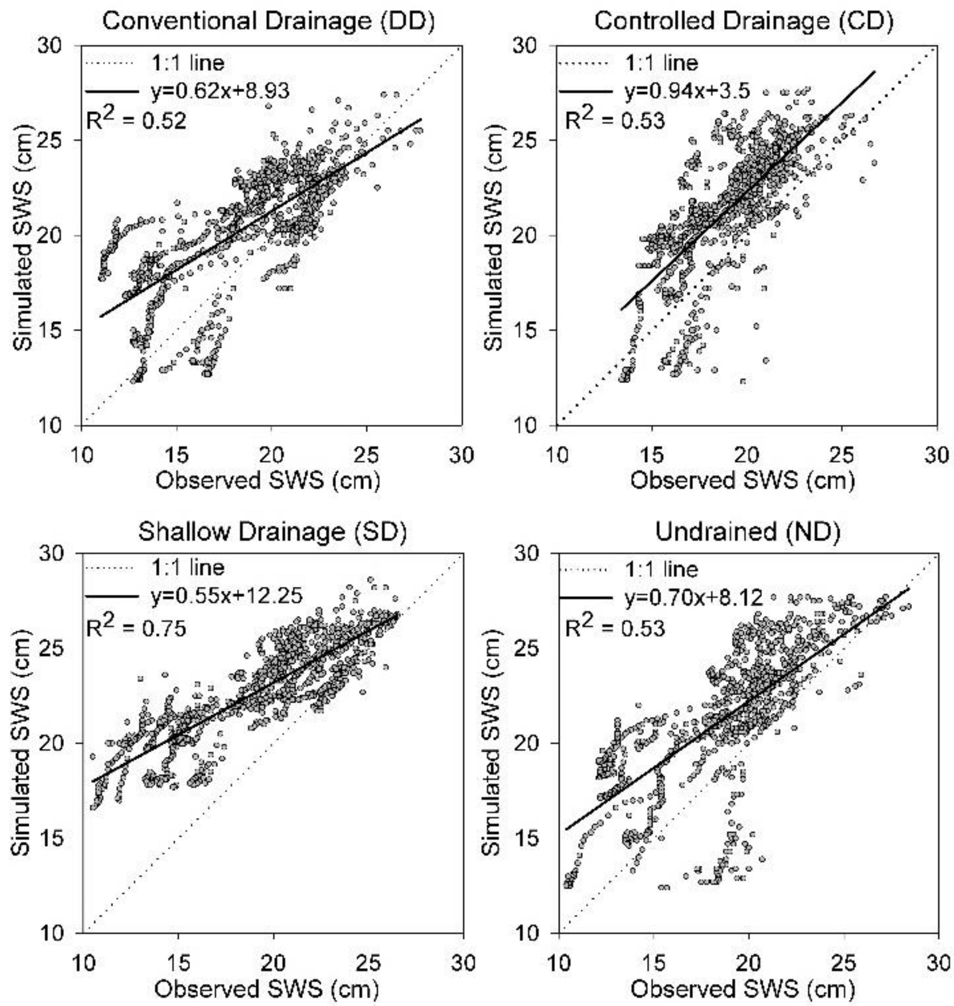

Figure 2.8. Daily average simulated versus measured 60 cm soil water storage (SWS) for conventional drainage (DD), controlled drainage (CD), shallow drainage (SD) and undrained (ND) with 1:1 line and R^2 value.

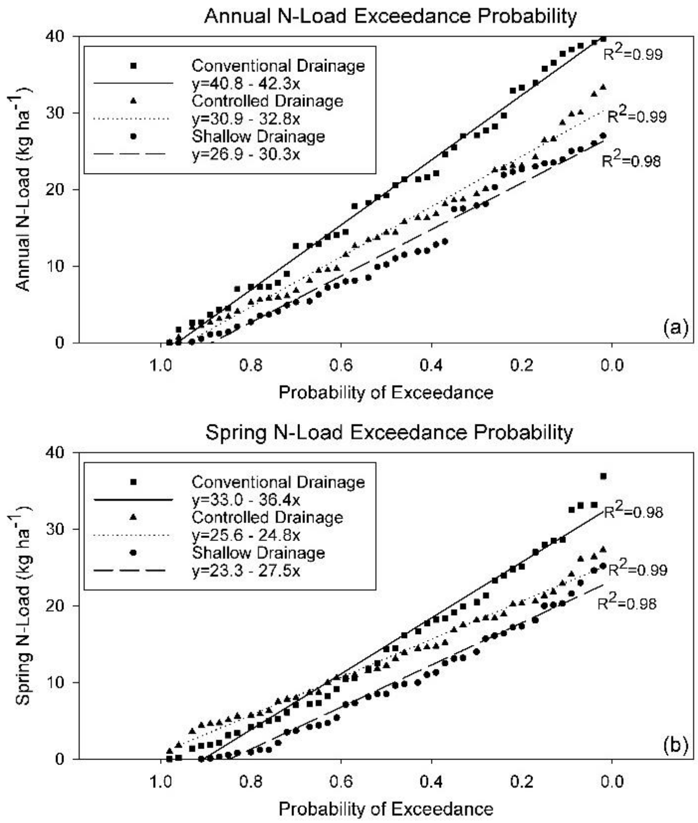

Figure 2.9. Annual (a) and spring (b) tile drainage N-load against the calculated probability of exceedance from the 45-year simulations of conventional drainage (DD), controlled drainage (CD) and shallow drainage (SD). Regression analysis equations and R^2 values are provided.

2.6 Acknowledgements

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CHAPTER 3. QUANTIFYING THE IMPACTS OF A CEREAL RYE COVER CROP ON SOIL WATER CONTENT AND TEMPERATURE IN AN IOWA CORN-SOYBEAN ROTATION

Kristina Craft, Matthew Helmers, Michael Castellano, Rebecca Roberts, Ray Kruse, Carl Pederson

3.1 Abstract

A winter cover crop can reduce nitrate loss from annual grain cropping systems. In the Midwestern Corn Belt, cereal rye (*Secale cereal L.*) is commonly used due to winter hardiness and efficient nitrate retention. Managing rye for maximum nutrient reduction benefits without reducing corn and soybean grain production can be achieved by terminating rye immediately before soybean planting. However, rye is often terminated several weeks before soybean planting, either when rye in fields going to corn is termination for management simplicity or to avoid impacts on soybean yield. We quantified the effect of termination time on soil water content and temperature in a corn-soybean rotation at four depths within the soil profile. Three corn-soybean cropping systems were examined: winter-fallow, or no cover crop (NC), rye with early termination (EC) two weeks before the anticipated corn planting date regardless of the next crop, and rye with late termination (LC) 6-17 days before planting in soybean years and two weeks before planting in corn years. The delay in cover crop termination prior to soybeans led to significantly more rye biomass accumulation (4.5- and 2.6-times in 2015 and 2016, respectively). Despite rye water use, treatments with rye stored the same or more moisture in the 0-50 cm profile than no cover crop plots from mid-April to mid-

October. This likely indicates that the rye residue had a mulching effect that conserved water loss from the soil surface. From mid-April to mid-May, cover crop treatments generally had higher moisture content than NC treatments. The LC soybean treatment had 16% less moisture than the EC plots, likely due to greater transpiration during the 28 to 29 day-longer growing period. In both soybean and corn plots, LC plots were cooler than EC plots by 0.47 ˚C to 0.90 ˚C, potentially indicating a long-term effect of delayed planting. The cover crop treatments also reduced the daily temperature range (ST_Range) compared to NC. The differences in ST_Range were typically from a higher daily maximum temperature (ST_Max) in NC plots. From mid-May to Mid-June, moisture in soybean LC plots were the same as EC and NC plots, despite evidence of rye water use prior to LC termination. The NC corn plots were 0.70 to 1.4 ˚C warmer than the cover crop plots, indicating that the lack of cover allowed faster warming within May and June. From July 1 to mid-August, when corn and soybeans enter reproductive stages, LC soybean plots had higher VWC at 40 cm compared to EC and NC plots. A delay in cereal rye termination prior to soybeans reduced moisture content in the early spring, however this was quickly replenished and even promoted greater water content deeper in the soil profile during soybean flowering and grain fill. In years when water limits crop production, a delay in termination before soybeans may benefit yield. Every day within the week following 2015 corn planting the EC plots had higher moisture content than the LC plots and NC plots, on average by 0.061 $cm^3\ cm^{-3}$ and 0.093 $cm^3\ cm^{-3}$, respectively. In the weeks following corn planting, EC and LC plots were generally cooler than NC, by 1.1 ˚C, on average in 2015 and 2016. Cooler temperatures and wetter conditions from rye biomass could have a negative impact on corn yield. The LC treatment from the prior year may offset some of the wetness prior to corn planting.

3.2 Introduction

A multitude of agricultural best management practices (BMP) and nutrient reduction strategies will be required in order to address agricultural nutrient pollution throughout the Midwestern Corn Belt, (Dinnes et al., 2002). A winter hardy cover crop has been highly cited for success in reducing nitrate (NO_3) loss from agricultural systems across the Midwest, (Dinnes et al., 2002; Kaspar and Singer, 2011; Snapp et al., 2005). The loss of nitrate from agricultural systems is a function of the availability of soil nitrate and the timing of subsurface drainage and leaching in relation to the demand and use of water and nitrate, (Dinnes et al., 2002). The annual grain cropping systems that dominate Midwest land use typically have a fallow period of nearly eight months after cash crop harvest until planting in the following spring. The lack of plant nutrient demand during this time, paired with residual soil nitrate, nitrogen mineralization and excess soil moisture creates conditions that are susceptible to nitrate leaching. In Iowa, April through June is exceptionally conducive to nitrate leaching from fields due to a lack of water and nitrogen (N) demand paired with the majority of excess precipitation and drainage, (Helmers et al., 2005). A winter cover crop, such as Cereal rye (*Secale cereal L.*), can be practicably incorporated into an annual grain rotation. During this vulnerable spring period for leaching, the cover crop utilizes water by evapotranspiration and nitrogen by tying it up within its biomass as it grows. In this way, adding a cover crop into an annual grain system is creating competition for nitrate leaching through the soil profile during a typically fallow time-period without such competition.

Multiple research studies have found great success with cover crops for nutrient reduction, as was highlighted in a literature review by Meisinger et al. (1991), where cover crops were cited to reduce the mass and concentration of nitrogen in leachate below the root zone by 20% to 80%. Multiple others have found a high potential of cover crops for nutrient reduction, (Shipley et al., 1992). A study in southern Minnesota by Strock et al. (2004) found that rye reduced nitrate-nitrogen (NO_3-N) loss in subsurface tile drainage by 13% in a corn-soybean system. Long-term model predictions for northeast Iowa found a 38% reduction in NO_3-N loss in tile drainage with rye in a typical corn-soybean system by Malone et al. (2007). Across 41 locations throughout the Midwest region, a 42.5% reduction in NO_3-N loss was predicted by Malone et al. (2014). Experimental studies attribute reduction in nitrate leaching to rye water use and nitrogen uptake. Malone et al. (2014) found that greater simulated nitrogen uptake by rye biomass generally related to greater reduction in nitrate loss in tile drainage. Accumulated growing degree days (GDD) is often a limitation to the potential of cereal rye for nitrogen reduction. Potential GDD can be limited in northern climates with cooler temperatures. Additionally, management can impact accumulated GDD, based on the window of time between sowing and terminating the cover crop.

In addition to nutrient retention, Cereal rye has been found to provide a multiplicity of other benefits within an agroecosystem, such as minimizing soil erosion, increasing soil organic matter and carbon storage, building soil health and structure, among others, (Kaspar and Singer, 2011). Increasing solar energy harvest and the related return of organic carbon to the soil can aid in nitrogen recycling, (Dabney et al., 2001; Tonitto et al., 2006). Additionally, adding carbon material improves soil aggregate stability and water infiltration, (Letter et al., 2003; Roberson and Firestone, 1991). Cover crops grown before soybeans have also been found to suppress weeds by shading and reducing temperatures, (Liebl et al., 1992).

Cereal rye is either aerial seeded into a standing, often mature, cash crop or drilled after harvesting the cash crop in the fall. As cereal rye is winter-hardy, it persists through the winter in dormant state and begins actively growing again when the temperatures warm in the following spring. As a cereal grain crop, rye has the potential to produce a greater amount of biomass than many other cover crop species, even in a cooler northern climate, (Snapp et al., 2005). The living rye is controlled, or terminated, within a recommended range of time prior to planting the following cash crop. Termination is typically done using a chemical herbicide, however mechanical methods are also an option. Rye planting and termination date has been found to have a great impact on its nitrate reduction potential and greater rye biomass growth generally leads to greater nutrient retention and nitrate reduction, (Feyereisen et al., 2006; Li et al., 2008). Additionally, less-mature rye biomass has a lower carbon-to-nitrogen (C:N) ratio, allowing decomposition and conversion to inorganic nitrogen to occur faster than more mature rye after termination, (Balkcom et al., 2007). The decomposition of mature rye can cause microbial communities to immobilize additional soil N to decompose the residue, especially when the C:N is 25 or greater, (Fageria et al., 2005; Wyland et al., 1995; Zhang et al., 2008).

Rye termination is suggested at least 10 days before planting corn in the spring to avoid corn yield loss by allelopathic effects, however soybean yield is not negatively impacted this way and rye can be terminated just before planting soybeans, (Ruffo et al., 2004; Tonitto et al., 2006; USDA-NRCS, 2013). Based on 2015 National Agricultural Statistics Services (NASS) data, the average length of time in Iowa between corn planting and soybean planting is about 14 days, thus creating an additional window of about 24 days in which rye can accumulate biomass and take up residual soil nitrate prior to planting soybeans. This longer growth period before soybeans would occur every other year in a corn-soybean rotation. Managing rye for greater growth before soybeans would therefore correspond to managing rye for maximum nutrient reduction benefits.

Qi and Helmers (2010) experimentally found a 21% reduction in subsurface drainage with a rye cover crop compared to a bare soil, which was attributed to increased transpiration by the rye in the spring months. This transpiration has been found to reduce soil water content and storage, which may be harmful to the following cash crop in years when water deficit stress is a factor, (Campbell et al., 1984; Liebl et al., 1992; Unger and Vigil, 1998). Additionally, the biomass from cover crops can cause cooler temperatures in the soil profile which can impede germination and establishment of the cash crop, (Dabney et al., 2001). Hatfield et al. (2001) found a similar mulching effect with cover crops, as they described limited soil evaporation, cooler temperatures, decreased vapor diffusion and increased moisture absorption within cover crop biomass. It has generally been found with a more mature rye that the soil water content is depleted mostly due to the longer period with growing and transpiring rye, even with limited soil evaporation through rye biomass, (Liebl et al., 1992). Krueger et al. (2011) found that soil moisture wasn't depleted when rye was terminated two to four weeks prior to planting corn but it was depleted when terminated just a couple of days prior to planting corn. Most hypothesize that enhanced soil properties from long-term rye use will allow for greater soil water storage (SWS) capacity and soil moisture preservation in dry years due to increased organic material in the soil profile and residue on the soil surface, (Daigh et al., 2014; Kaspar and Singer, 2011; Morse, 1993; Williams and Weil, 2004).

The partner experiment for this analysis included an investigation of the impacts of rye and termination timing on carbon (C) and N dynamics and grain yield in a no-till system with a corn-soybean rotation from 2014 to 2015. There was no impact of rye or timing of rye termination found on corn or soybean yield, (Roberts, 2016). Experimental treatments include no cover crop (NC), rye terminated early at two weeks before the corn planting date (EC) and late terminated rye at a couple days before soybean planting and two weeks before corn planting (LC). This study found that the EC and LC treatments significantly decreased soil NO_3-N, by 31%, on average, compared to the NC treatment, (Roberts, 2016). In LC and EC plots in 2015, soil NO_3-N depletion persisted after termination for three weeks and one week, respectively, and the longer impact from LC plots was attributed to a higher C:N ratio (31:1 in LC plots compared to

17:1 in EC plots), likely prompting immobilization of NO_3-N by microbial communities for residue decomposition, (Roberts, 2016). Additionally, this study measured about 4.5-times more biomass accumulation in the LC plots in 2015, which corresponded to a 71% greater total NO_3-N immobilization in LC plots, (Table 3.1), (Roberts, 2016). In preliminary findings for rye biomass measurements in 2016, the biomass growth in LC plots, on average, were about 2.6-times greater than EC biomass growth, (Table 3.1). The late terminated (mature) rye persisted on the soil surface for much longer than the early terminated rye due to slower decomposition likely because of a higher C:N ratio, (Roberts, 2016). There was residual late terminated rye biomass visually observed on the soil surface of the plots even through the end of the year and into the following year. Knowing the additional benefits of nutrient reduction and soil health with a late termination management scheme before soybeans, we wanted to gain more information on the impacts on the soil system. For this analysis of soil moisture and temperature (SMT), the specific research questions included: 1) How does a rye cover crop and the termination date impact soil water storage in the soil profile and 2) how is water content and temperature impacted within important periods of the growing season?

3.3 Materials and Methods

3.3.1 Site description and experimental design

The field site in which this study was carried out is located at the Iowa State University Agricultural Engineering/Agronomy (ISU AEA) Research Farm in Central Iowa. The partner experiment measured rye biomass growth and carbon-to-nitrogen ratio, corn and soybean grain yield, soil NO_3-N and biomass decomposition was monitored at this site to study the effects of a rye cover crop and herbicide timing and source within no-till, corn-soybean rotation systems since the fall of 2013, (Roberts, 2016). Prior to the start of this study, the field was managed in a conventional tillage, continuous-corn cropping system. Within the field site, there are 32 experimental plots of 12.2 by 15.2 m, arranged within four randomized blocks, based on site variation in topography and soil type; the fourth block was not included in the SMT study design. Based on initial investigation of field soil characteristics made using the NRCS Web Soil Survey for the 0.97 ha field site, the field contains a 2-6% slope from west to east and soils include mainly Clarion loam (fine-loamy, mixed, superactive, mesic Typic Hapludoll), on 0.76 ha, and Canisteo silty clay loam (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquoll), on 0.21 ha, mainly found in the fourth block which is not used for this analysis, (Roberts, 2016). The SMT study design, therefore, included 18 experimental plots randomized within three blocks to account for spatial variability in topography and in soil type. A map of the field with soil type and the SMT study plot setup is provided in Figure 3.1. For the SMT study, analysis was done within 6.1 by 15.2 m plots, which were split within the 12.1 by 15.2 m plots for a separate herbicide type study. All plots included a corn-soybean rotation with or without a rye cover crop. Each plot contains eight rows of 76 cm spacing corn or soybeans, cropped in the east-west direction. The rye cover crop plots were terminated in the spring before cash crop planting with the chemical herbicide, Glyphosate. The three cover crop treatments include an early kill cover crop (EC) treatment in which rye is terminated about two weeks before corn planting date regardless of the following crop, a late kill cover crop (LC) treatment in which rye is terminated two weeks before corn planting in corn years, and 6-17 days before soybeans are planted in soybean years, and finally a no cover crop (NC) treatment which does not include a cover crop. The cropping rotations include corn-following-soybeans (C-s), with corn planted in even years, and soybeans-following-corn (S-c), with corn planted in odd years. Each cropping rotation and cover crop treatment combination has three replications within each year and complimentary cropping rotation treatment combinations ensure that both corn and soybeans are planted within a cover crop treatment within each year. Each of the three replications of cover crop treatment and cropping rotation were present every year within each of the three experimental blocks.

Cereal rye was hand-broadcast seeded at a rate of roughly 112 kg ha^{-1} on September 12, 2014, September 10, 2015, and August 26, 2016, into standing corn and soybeans. Harvest of both corn and soybeans occurred on October 27, 2014, November 2, 2015 and November 2, 2016. Termination for EC plots and LC plots going to corn occurred on April 16 in 2015 (15 days before corn planting on May 1 and 33 days before soybeans were planted on May 19) and April 19 in 2016 (17 days before corn planting on May 6 and 44 days before soybean planting on June 2). Termination for LC plots going to soybeans occurred on May 13 in 2015 (six days before soybeans were planted) and May 16 in 2016 (17 days before soybeans were planted). In 2016, there was a delay in soybean planting due to equipment availability. Plots going to corn were side-dressed with 168 kg-N ha^{-1} in the form of 32%-N UAN on June 5, 2015 and June 13, 2016. More information on agronomic management of the corn-soybean systems, including planting rate and herbicide applications, are presented in work by Roberts (2016).

3.3.2 Data collection

Volumetric water content (VWC) and soil temperature (ST) were measured from the center of each experimental plot at four depths into the soil profile: 10, 20, 40 and 60 cm below the ground surface. To measure VWC and temperature, 5TM sensors (Decagon Devices, Inc., Pullman, Washington USA) were used. The 5TM sensors make indirect soil moisture measurements using capacitance technology to record the dielectric permittivity constant of the soil which is converted to a volumetric water content, (Campbell, 2015). Decagon Em50 data loggers were used to log and store 5TM sensor recordings at five-minute intervals for each of the five sensors within a single plot. Measurement equipment was installed in July of 2014. A gas-powered auger with a roughly 20 cm-wide drill was used to excavate soil down to 100 cm. Within the excavated hole, sensors were inserted into the undisturbed soil profile at their designated depths, based on installation instructions provided by Decagon Devices, Inc., 2015. Five-minute recordings were aggregated to daily averages for both soil moisture and temperature. An estimation of soil water storage (SWS) was made by assigning representative soil layers for each sensor, including 0 to 15 cm for the 10 cm sensor, 15 to 30 cm for the 20 cm sensor, 30 to 50 cm for the 40 cm sensor and 50 to 80 cm for the 60 cm sensor, based on similar methods by Daigh et al. (2014). It was assumed that the VWC measurement was equal throughout the representative soil layer. The VWC value was multiplied by its representative layer height to get an estimate of cm of water held within one-unit of area, or one cm^2. This SMT analysis will summarize data from 2015 and 2016 and focus on the 30, 50 and 80 cm layers for SWS, and the 10, 20, 40 and 60 cm measurements for VWC and ST.

During the study time frame, precipitation and temperature were recorded at a nearby Iowa State University Soil Moisture Network weather station, located less than 2 km away from the field location, at the ISU AEA Research Farm in Boone, Iowa. Prior to 2013, weather data was available from a National Weather Service (NWS) Cooperative Observer Program (COOP) data network, also located at the ISU AEA Research Farm. Total precipitation, average, maximum and minimum temperature for months from September of 2014 through September of 2016 were summarized and are given in Table 3.2. Precipitation and average temperature were compared to 30-year averages, as shown in Figure 3.2.

Soil samples were collected in July of 2015 with 2.5 cm metal push probes to a depth of 60 cm and analyzed for soil texture in depth increments of 0-10, 10-20, 20-40 and 40-60 cm, (Kladivko et al., 2014). Texture analysis by the hydrometer method was completed for these samples by the Ward Laboratories, Inc. (Kearney, Nebraska) soon after sample collection. Results of texture within the field are consistent with the web soil survey texture information, which were defined in the site description, as soil type was found to be mostly loamy soils, Table 3.3. Undisturbed, 7.6 cm soil cores were collected in the spring of 2016 to a depth of 60 cm using a Giddings hydraulic soil sampler (Giddings Machine Company, Inc., Windsor, CO). The soil core was incremented into depth increments of 0-10, 10-20, 20-40 and 40-60 cm core for bulk density analysis. Three replicate samples were taken for each plot. The bulk density by depth increment was determined by oven drying each core to 105°C to aid in measuring the dry soil weight within the core volume, (Blake and Hartge, 1986).

3.3.3 Statistical Analysis

To evaluate treatment differences on soil bulk density, the general linear model (GLM) was used with three replications of each depth and plot. Treatment and depth were set as fixed effects while block was set as a random effect.

The VWC and ST dataset used for this analysis includes two years, 2015 and 2016. VWC and ST was analyzed over specific periods of the year that were of interest agronomically. SWS was analyzed over the bulk of the growing season, set from around April 15 to October 15. A generalized linear mixed model (PROC Glimmix; SAS software, Version 9, SAS Institute, Inc., 2011) was used to fit a model for treatment means within each depth and time period, separately. The moisture datasets show obvious pulses from precipitation, where all treatments increase together, which was causing an inflation in the daily variance. This variance was addressed by adding a daily fixed effect in the statistical model, which greatly improved AIC (Akaike information criteria). A fixed effect was also added for block to account for spatial differences in soil characteristics. Analysis of treatment means was done within the current or upcoming crop of the analysis year to focus the analysis on the impact within corn and soybeans separately. Statistical significance was assessed at $p<0.05$, however consideration was given to the $p<0.10$ significance level as well, as other soil moisture analysis have been conducted this way due to high measurement variability, (Basche et al., 2016b).

Specific periods of interest for VWC and ST include: P1) from around mid-April to mid-May, from about the time of early kill termination until around late kill termination, P2) from mid-May to Mid-June, from around late kill termination to about a week after soybean planting, and P3) from July 1 to mid-August, when corn is silking and soybeans are flowering, as both are entering into R1 reproductive stages and are most sensitive to stresses, (Claassen and Shaw, 1970; Licht, 2014; Licht et al., 2011). We broke the data up into these three periods to focus on the impact of rye at different stages throughout the year which are hypothesized to have differing impacts on the soil profile. In P1, rye in EC plots and LC plots going to corn have been terminated, while rye in LC plots going to soybeans are still actively growing and transpiring. In P1, therefore, we expect to find a difference in plots with rye that may still be using water (LC plots going to soybeans) and those plots with dead rye biomass on the soil surface. In P2, rye in all plots have been terminated, however, there are varying amounts of rye biomass covering the soil between the LC plots going to soybeans, with the greatest amount of biomass, and the EC plots and LC plots going to corn. In P3, during the reproductive stages of corn and soybeans, we wanted to examine if the dead rye biomass, with varying levels between EC and LC treatments, are impacting the conditions within the soil profile. Additionally, we observed differences in treatments means for the weeks following corn planting and soybean planting each year, as well as individual days of interest, such cash crop planting.

3.4 Results and Discussion

Compared to the 30-year average precipitation, the March through September rainfall was generally average or slightly above average in 2015 and 2016. The 30-year average March through September rainfall at the site is 73.0 cm, while that of 2015 and 2016 were 82.7 and 76.1 cm. In 2015, spring precipitation (March – May) was 7.9 cm below average and summer precipitation (June – August) was 13.4 cm above average which included 7.2 cm above average in August. In 2016, spring and summer precipitation was nearly average, at 22.7 cm, however precipitation in the month of June was 10.6 cm below average and the month of September was 10.0 cm above average.

Within the soil moisture analysis, it was important to note that the measured 40-60 cm soil bulk density was significantly lower ($p<0.05$) in the EC treatment plots than the NC plots (Table 3.2), which added some challenges in interpreting soil moisture data below 40 cm. With a lower bulk density, there is a greater amount of pore space, which could potentially allow for greater VWC in the EC plots than NC plots at depths lower than 40 cm into the profile. For this reason, minimal analysis was carried out with the 60 cm soil VWC measurement.

3.4.1 Soil Water

The wilting point and field capacity are estimated for loamy soils around 0.12 cm^3 cm^{-3} and 0.26 cm^3 cm^{-3}, respectively, which gives somewhat of a reference for the degree of deficit or excess water within the following VWC results, (Or, 2011). The results of the statistical comparison in treatment means in SWS and VWC are provided in Table 3.4.

Soil water storage

Over most of the growing season, from mid-April until mid-October, EC plots held statistically the same or more moisture than the NC plots in the upper 30, 50 and 80 cm soil profiles (Table 3.4). When EC plots held significantly more moisture than NC plots (2015 corn plots), EC and LC plots were statistically the same, while LC and NC plots were statistically the same. It's important to note that cover crop water use, or transpiration in the spring, within EC plots is likely much less than LC plots due to significantly less growth in EC plots. The differences in SWS may indicate that the cover crop is conserving moisture within the soil profile because even though there is transpiration in the spring, cover crop plots maintained the same or higher SWS throughout the growing season. This can also be visually observed in Figure 3.3. Daily 50 cm SWS over the growing season shows that cover crops plots are generally similar to NC plots and often seem to be greater than NC plots later in the year. This water conservation may be due to a mulching effect of the residue covering the soil surface and limiting soil evaporation.

Volumetric water content

Period 1 (P1) (Figure 3.4) includes the time just after the early termination date, up until LC soybean plots are terminated, from around mid-April to mid-May. It was important to note that, though not significant, there was an observable depletion in VWC from EC and LC plots around day 110, or early termination, which is likely evidence of rye water use. During P1, LC plots going to soybeans are actively growing and transpiring rye but the LC plots going to corn have been termination just as the EC plots have. The LC corn plots, however, have more residual residue than EC plots from the late-killed rye growth from the year prior.

For this reason, LC corn plots are analyzed separately than EC corn plots even though they are terminated on the same date. It is important to note that P1 is typically when producers are planting corn and moisture could have a great impact the seed-to-soil contact and germination.

During P1, VWC in EC plots was statistically the same or higher than the LC and NC plots. The significantly higher VWC in EC plots occurred at 10 cm in the corn plots in 2015, when EC plots had nearly 40% more moisture than NC corn plots. Within this same depth, the LC corn plots were statistically the same as NC corn plots. At 10 cm, there was 16% less moisture in LC soybean plots compared to EC plots in 2015 and 10% more moisture in EC plots compared to NC plots in 2016 ($p < 0.1$). Also at 10 cm, there was 7% less moisture in LC soybean plots compared to EC plots in 2016, but this was not statistically significant ($p = 0.14$). Though not significant at $p < 0.05$, in 2015, at 10 and 20 cm, LC soybean plots had 16% ($p < 0.10$) and 15% ($p = 0.14$) less moisture than the EC plots and at 40 cm had 18% ($p = 0.10$) more moisture than EC plots. Also in 2015, at 10 and 20 cm, LC soybean plots had 15% less ($p = 0.12$) and 7% ($p = 0.40$) less moisture than NC plots and 10% ($p = 0.32$) more moisture than NC at 40 cm, though not significant at $p < 0.10$. Similar depletion in LC soybean plots compared to EC plots was also found at 10 and 20 cm in 2016, but LC soybean plots did not decrease VWC compared to NC plots at 10 and 20 cm in 2016.

This consistent, moisture depletion during P1 in LC soybean plots compared to EC plots is likely due to greater transpiration of rye that grew an additional 28 and 29 days before soybean planting in 2015 and 2016, respectively.

Additionally, it was valuable to note that LC soybean plots did not deplete VWC to significantly less levels than NC soybean plots. A study by Basche et al. (2016b) found statistically lower moisture (10-15%) in cover crop plots managed similar to LC plots in this study, compared to no cover crop plots in the spring before cash crop planting, which was attributed to rye transpiration. Transpiration of rye has been estimated by modelers to be on average around 2.7 cm yr^{-1} and as much as 5 cm yr^{-1}, (Malone et al., 2007). The higher VWC estimates for EC plots during this period may also be somewhat attributed to reduced soil evaporation through the dead EC biomass. April and May rainfall totals in 2015 and 2016 were very similar, with 8.4 and 10.5 cm in 2015 and 8.8 and 9.7 cm in 2016, both respectively. Rainfall in March, however, was much less in 2015 at less than 1 cm, compared to 4.2 cm in 2016. This likely caused the lower VWC found in 2015 compared to 2016 within P1 as well as the greater reductions in VWC within LC soybean plots in 2015 compared to 2016.

Within period 2 (P2) (Figure 3.5), from mid-May to Mid-June, VWC was either statistically similar or greater in EC plots than LC and NC plots. Significant differences ($p < 0.10$) were found at 10 cm in corn plots in 2015, when EC plots had 43% more moisture than NC plots and 38% more than LC plots, likely a carryover of the higher moisture found in P1. The higher moisture found in EC corn plots during P2 may again indicate reduced evaporation through the dead EC rye residue. The rye in the LC soybean plots during P2 had just been terminated and the plots planted with soybeans. In soybean plots, LC plots in 2015 were about 10% drier than EC at 10 and 20 cm, were about 9% and 4% drier than NC plots at

10 and 20 cm, however, at 40 cm, LC plots had about 14% and 9% more moisture than EC and NC plots, respectively, though none of these reductions were significant at $p < 0.05$. These findings were similar in 2016, though there was less of a reduction in moisture compared to the NC plots. This depletion in LC plots compared to EC plots may be a residual impact of the higher transpiration of LC rye in P1, as LC rye was killed just before the start of P2. It can be seen in Figure 3.5 that the depletion from rye water use at 10 cm in the LC soybean plots seems to be replenished to similar levels as NC plots after a couple of rainfall events, post LC termination.

Period 3 (P3) (Figure 3.6), from July 1 to mid-August, involves a critical growth stage for both corn and soybeans. State-level NASS data for corn silking (R1) date and soybean blossoming (R1 and R2) date was used to designate this key period. The data indicated that corn R1 stage occurred mostly between July 12 and August 9 in 2015 and between in July 10 and August 7 in 2016, and soybean entering R1 and R2 stages occurred mostly between July 5 and August 9 in 2015 and between July 3 and August 14 in 2016, (NASS USDA, 2016). In P3, a significant finding for soybean plots included higher VWC estimates for LC plots at 40 cm, compared to EC plots in 2015 and compared to NC plots in 2016 ($p < 0.10$). This was also found at 60 cm in soybean plots, as LC plots had higher VWC than NC plots ($p < 0.05$). This may be an indication of greater water infiltration through decayed root channels in the LC plots with significantly more biomass production than EC plots. Mean 10 cm VWC varied little over all six treatments throughout 2016 corn and soybean plots. It was interesting, however, that in the soybean plots at 10 cm, the LC plots were about 10.7% wetter than EC and 10.1% wetter than NC, though treatment means were not statistically different, $p = 0.37$ and $p = 0.44$, respectively. Slightly less increases in VWC were found in 2015 LC soybean plots, with VWC 3.9% greater than EC and 4.5% greater in NC, $p = 0.37$ and $p = 0.31$. This may give an indication of a reduction in soil evaporation from the upper soil profile, which has been found to be a measurable impact of rye biomass. Reduction in soil evaporation from cover crop residue was predicted at around 3.3 cm yr^{-1} for long-term estimates made by Malone et al. (2007) and estimates by Basche et al. (2016a) were around 2 to 18% reduction in evaporation by a cover crop. Furthermore, increased residue is expected to exaggerate the mulching effect by reducing soil evaporation and conserving moisture in the upper profile, (Clark et al., 1997; Mulumba and Lal, 2008).

The weeks following corn and soybean planting dates for 2015 and 2016 were analyzed for treatment effects. In corn plots, every day within the week after 2015 corn planting the EC plots were significantly wetter than the LC plots and the NC plots, on average by 0.061 cm^3 cm^{-3} and 0.093 cm^3 cm^{-3}, respectively. In 2015, precipitation within the months of March, April and May was 7.9 cm below average, including 4.5 cm below average in March. With low spring precipitation, the rye biomass may have conserved more moisture in the upper soil profile, compared to the NC plots. There may have been differences in the total residual biomass between the EC and LC corn plots during this time which may have caused EC corn plots to be wetter than LC corn plots during the 2015 corn planting week, however this wasn't specifically measured. Within each day of the week following

2016 corn, 2015 soybean and 2016 soybean planting, there were no statistically significant differences between treatments. Moisture in the upper soil profile is very important for corn germination, as sufficient water is needed to allow for the seed to absorb enough water to germinate. Water uptake of up to 35% of the seed's weight is needed, however, conditions that are overly saturated can inhibit germination as well, (Licht et al., 2011). The increased VWC in EC plots found in this study may indicate positive impacts of the cover crop on corn germination in a dry year. In years with much wetter springs than 2015 and 2016, however, this increased VWC may be detrimental to corn germination. Soybean germination requires water absorption equal to 50% of the seed weight, making it similarly sensitive to germination VWC conditions (Licht, 2014).

3.4.2 Soil Temperature

Treatment impact on soil temperature variables, such as soil temperature (ST) daily mean (ST_Mean), ST daily range (ST_Range), ST daily minimum (ST_Min) and ST daily maximum (ST_Max) are provided in Table 3.5. Soil temperature was only summarized for the 10, 20 and 40 cm measurements, due to very little variation below the 40 cm sensor. P1, P2, P3 and the weeks following corn and soybean planting were examined for differences in treatments for soil temperature responses. Figures 3.7 and 3.8 show ST_Mean estimates of the upper profile using 10 cm measurements for P1 and P2, respectively. P3 is not graphically shown, however differences in treatments in P3 were similar to that of P1 and P2.

Within the soybean plots in P1, there were many occasions when the presence of a cover crop impacted soil temperature. In soybean plots, ST_Mean was often significantly cooler in the LC plots compared to EC plots; these differences were minimal, between 0.47 ˚C to 0.90 ˚C. EC plots in soybeans were also sometimes slightly warmer than NC plots, but this was only significant in 2016 at 10 cm with 0.60 ˚C warmer. The increased rye biomass in the LC plots may be causing these plots to be cooler than EC plots, as the mulching effect of the LC residue may be holding in cooler spring soil temperatures and minimizing light penetration to the soil surface. In the corn plots, there were no differences found with statistical significance. This may be due to the less residue in the plots going to corn, as they hosted soybeans the year prior and have less residual cash crop residue on the soil surface. The higher residue in the plots going to soybeans may be amplifying the mulching effect of the rye biomass in soybean plots.

In P1, the ST_Range was influenced by the rye cover crop. In 2015 soybeans, LC plots had a significantly smaller range than NC at 10, 20 and 40 cm and at 40 cm in 2016 soybeans ($p<0.05$). In soybean plots, the EC plots had a greater ST_Range than LC plots ($p<0.10$) at 10 cm and 20 cm in 2016. EC rye had a smaller impact than LC rye on reducing daily ST_Range, as EC was only greater than NC at 10 cm in 2015 soybeans and 2016 corn as well as 40 cm corn in 2016. There was residual late-killed rye residue visually observed in the LC corn plots from the previous year, which may have caused a smaller ST_Range compared to NC corn plots at 10 cm in 2016, at 40 cm in 2015 and 2016 ($p<0.05$). This was also true ($p<0.10$) at 10 cm in 2015 and 20 cm in 2015 and 2016. There were more differences in ST_Max between treatments than ST_Min. The ST_Max was highest in NC plots generally, and this difference was most pronounced between LC and NC than between EC and NC. This indicates that in the spring period, when soils are warming from increasing ambient temperature and sunlight penetration, it may be that the covered plots aren't getting quite as warm as plots without a cover because the light can't penetrate to the soil surface.

In P2, soil temperature responses were variable. The magnitude of soil temperature differences dissipated with increasing depth, thus most significant differences were generally found closer to the top of the soil profile. The NC corn plots were often warmer than the cover crop plots, as seen at 10 cm and 40 cm in 2016 at $p<0.05$, as well as at 20 cm in 2016 at $p<0.10$; these differences are within a 0.70 to 1.4 ˚C increase in NC plots. In a couple cases, EC soybean plots were warmer than LC soybean plots, such as at 10, 20 and 40 cm in 2016. Similar to the findings in P1, this may indicate that the high biomass in LC soybean plots have inhibited soil surface warming by light penetration.

In P2, the LC soybean plots had a smaller ST_Range than NC plots at 10 cm and 20 cm in 2015 and at 40 cm in 2015 and 2016, with a difference of 2.0 ˚C at 10 cm, 0.90 ˚C at 20 cm and 0.25 ˚C at 40 cm. EC plots also decreased ST_Range compared to NC plots but always less than LC plots did and only significant in a couple cases. There were few differences in ST_Min responses in P2, similar to P1; most of the differences in ST_Range from cover crop plots were due to a decrease in ST_Max.

During P3 in 2016 soybean plots, LC plots were cooler than EC plots, consistently by around 1 ˚C at the 10, 20 and 40 cm depths. At 40 cm in 2015 soybean plots, LC plots were 0.7 ˚C cooler than NC plots. It is possible that the rye residue may still be having an impact on temperature by limiting light penetration to the soil surface. At 40 cm in 2016 corn plots, the NC plots were again warmer than LC and EC plots by 1.4 ˚C and 1.1 ˚C, respectively. Impacts on ST_Range in P3 were consistent with other periods, as NC plots generally had the highest daily range due to a higher ST_Max value.

In the weeks following corn planting in the corn plots at 10 cm, NC plots were generally warmer than cover crop plots. In 2015, NC was warmer, on average, by 0.38 ˚C and 0.63 ˚C compared to EC and LC plots, respectively, and these differences were 0.41 ˚C and 0.71 ˚C in 2016, respectively. In 2015, LC was cooler than NC in three of the seven days ($p<0.05$ and $p<0.10$) and in 2016, this was found in six of the seven days ($p<0.001$, $p<0.05$ and $0<0.10$). In 2015, EC was cooler than NC in one day ($p<0.05$) and in 2016, this was found in four days ($p<0.05$). On the planting date in 2015, ST was 0.78 ˚C cooler in LC plots than NC plots ($p<0.10$). In 2016, the differences on planting date were similar, as EC plots were 0.63 ˚C warmer ($p<0.10$) than LC plots, EC plots were 1.13 ˚C cooler ($p<0.05$) than NC plots and LC plots were 1.75 ˚C cooler ($p<0.001$) than NC plots. These findings are significant, as cooler temperature can inhibit corn germination, (Licht et al., 2011). The cooler soil temperatures found in the cover crop plots may indicate that the rye biomass is holding in cool early-spring temperatures or limiting soil surface warming. The cooler soil temperatures sometimes found in LC plots compared to EC plots in 2016 may indicate that the higher residue from the late-killed rye in the year prior has amplified this effect.

During the week of soybean planting, temperature responses were more variable. In 2015, ST_Mean was similar between EC and NC plots, with no significant differences. In 2015, LC plots were warmer than NC plots on the day of and two days after planting, up to 1.48 ˚C. EC plots were cooler than LC plots on the day of and the day after planting, up to 1.07 ˚C. These differences in the first couple of days after soybean planting in 2015 were significant at $p<0.05$. In 2016, however, EC plots were warmer than LC plots the day after planting and through the rest of the week, on average by 1.51 ˚C but up to 2.4 ˚C six days after planting. LC plots were cooler than NC plots three days, on average by 0.82 ˚C but up to 1.92 ˚C six days after planting. EC plots were not significantly different than NC plots.

Soybean temperature for germination has been reported at very low temperatures, 2 ˚C to 4 ˚C, however, germination is generally improved at warmer temperatures, or around 18 ˚C, (Licht, 2014). The 10 cm soil temperatures during the week following soybean planting was cooler in 2015 than in 2016, possibly because of a colder winter and a 15-day earlier planting date. On the day of soybean planting in 2015, NC plots were 12.1 ˚C, significantly cooler than both EC plots at 12.4 ˚C and LC plots at 13.5 ˚C, compared to 2016 when all treatments were similar at 19.6 ˚C, 20.0 ˚C and 19.5 ˚C for NC, EC and LC, respectively. In 2015, there was a drop in ambient and soil temperature between the corn and soybean planting dates. The higher temperatures at soybean planting in cover crop plots compared to NC plots in 2015 likely indicate that the rye biomass held in the warmed soil temperatures during that cooling period, unlike the NC plots. The differences between 2015 and 2016 may also be due to less of a difference between EC and LC growth in 2016 compared to 2015, as LC plots accumulated 4.5-times more biomass in 2015 and closer to 2.5-times more in 2016. It may be possible that once soils had warmed in 2016 the effect of the cover crop biomass was minimal.

3.5 Summary and Conclusions

In two years with nearly average rainfall, there were occasions when cover crop plots were slightly cooler and wetter during the week of corn planting, which can be detrimental to seed germination and may lead to increased soil-borne diseases or harm by insects. In the early spring, the late-terminated rye in soybean plots dried out the soil compared to the dead rye plots, but did not deplete moisture compared to the plots without a cover crop. This depletion from late-terminated rye was replenished after a couple of rainfall events. Despite the observed evidence of rye water use when alive, the water stored within the 30 and 50 cm profiles were not impacted by the cover crop treatments over the season, likely due to a mulching effect of the residue or increased infiltration from decaying root channels. During the soybean reproductive stage, late-terminated rye plots usually had extra moisture at 40 cm compared to early-terminated rye plots and plots without a cover crop, which could be useful for the growing soybean crop.

In a long-term study, we would expect to see higher soil water storage capacity with cover crops due to increasing soil organic matter, especially when rye growth is promoted with later termination before soybeans. In addition to a potentially more resilient soil profile with greater moisture storage capacity, a late-termination rye system has been found to have a greater impact on N-retention. To advance our understanding of the impacts cover crops and termination date have on moisture and temperature within the soil, we must examine them over a range of weather conditions and soil types. The field site within this study was new to cover crop, therefore the long-term impacts of cover crops were not yet observable. It is likely that these early and late termination systems will have differing impacts in dry or excessively wet years as well as over the long-term.

Tables

Table 3.1. Spring rye biomass growth for early termination rye (EC) and late termination rye (LC) at their respective termination dates in 2015 and 2016, all values in kg ha^{-1}.

	2015	*Standard Error*	2016	*Standard Error*
EC	1397	*75*	1947	*136*
LC	5846	*758*	5059	*1106*

Table 3.2. Monthly weather conditions near the field site[a].

Month-Year	High (°C)	Low (°C)	Avg. (°C)	Precip. (mm)
Jan-15	0.0	-9.7	-4.8	3.8
Feb-15	-4.5	-15.8	-10.1	1.3
Mar-15	11.0	-3.0	4.0	6.4
Apr-15	17.4	4.8	11.1	83.6
May-15	21.1	10.9	16.0	105.4
Jun-15	26.7	16.4	21.5	163.6
Jul-15	28.0	17.3	22.7	145.3
Aug-15	26.2	15.7	21.0	197.9
Sep-15	26.7	14.5	20.6	124.5
Oct-15	17.9	6.0	12.0	31.5
Nov-15	11.0	0.2	5.6	60.2
Dec-15	4.1	-3.2	0.5	121.2
Jan-16	-3.1	-10.7	-6.9	6.4
Feb-16	1.9	-6.1	-2.1	9.4
Mar-16	12.0	0.5	6.3	42.4
Apr-16	16.7	4.5	10.6	88.1
May-16	22.3	10.2	16.2	97.0
Jun-16	30.2	17.3	23.7	21.3
Jul-16	28.2	17.8	23.0	136.9
Aug-16	27.8	17.5	22.7	191.8
Sep-16	26.3	14.5	20.4	182.9

[a] The high temperature (High) low temperature (Low) average temperature (Avg.) and total precipitation (Precip.) is provided by month for the study period

Table 3.3. Soil characteristics by treatment and depth.

Treatment	Depth	Sand (%)	Silt (%)	Clay (%)	Bulk Density (g cm^{-3})
NC	0-10	47.7	32.2	20.2	1.35
	10-20	47.0	33.0	20.0	1.48
	20-40	45.0	31.5	23.5	1.48
	40-60	45.2	31.0	23.8	1.59
EC	0-10	46.8	31.8	21.3	1.32
	10-20	47.0	30.7	22.3	1.47
	20-40	40.3	32.7	27.0	1.45
	40-60	41.2	32.5	26.3	1.49*
LC	0-10	49.5	30.7	19.8	1.32
	10-20	47.3	30.5	22.2	1.48
	20-40	43.3	31.2	25.5	1.41
	40-60	42.3	31.5	26.2	1.54

*Statistically significant differences between the treatments within same depth at $p<0.05$ level

Table 3.4. Comparison in treatments, early-killed cover crop (EC), late-killed cover crop (LC) and no cover crop (NC), within corn or soybean for soil water storage (SWS) over the growing season and for volumetric water content (VWC) over period 1, 2 and 3.[a][b]

			Corn			Soybeans		
Time frame	Response	Year	EC	LC	NC	EC	LC	NC
Seasonal SWS	30 cm SWS	2015	**8.6 a**	**7.8 ab**	**7.1 b**	8.2 a	8.0 a	7.9 a
		2016	7.8 a	8.0 a	8.2 a	8.7 a	8.4 a	8.0 a
	50 cm SWS	2015	**14.4 a**	**13.5 ab**	**12.3 b**	13.6 a	14.1 a	13.6 a
		2016	12.9 a	13.4 a	14.1 a	14.4 a	14.2 a	12.9 a
	80 cm SWS	2015	**24.8 a**	**22.9 ab**	**21.1 b**	22.5 a	23.6 a	22.3 a
		2016	21.1 a	22.6 a	23.0 a	24.8 a	23.2 a	20.7 a
P1) mid-April to mid-May	10 cm SM	2015	**0.293 a**	**0.232 b**	**0.209 b**	0.260 a	0.218 a	0.256 a
		2016	0.278 a	0.276 a	0.283 a	0.300 a	0.277 a	0.270 a
	20 cm SM	2015	0.263 a	0.274 a	0.229 a	0.274 a	0.233 a	0.251 a
		2016	0.259 a	0.249 a	0.272 a	0.301 a	0.275 a	0.271 a
	40 cm SM	2015	0.280 a	0.286 a	0.257 a	0.258 a	0.304 a	0.278 a
		2016	0.262 a	0.290 a	0.274 a	0.289 a	0.291 a	0.271 a
	60 cm SM	2015	**0.321 a**	**0.300 ab**	**0.275 b**	0.289 a	0.297 a	0.285 a
		2016	0.279 a	0.302 a	0.284 a	**0.359 a**	**0.310 b**	**0.275 c**
P2) mid-May to mid-June	10 cm SM	2015	**0.300 a**	**0.217 b**	**0.210 b**	0.265 a	0.238 a	0.262 a

Table 3.4. continued

		2016	0.296 a	0.303 a	0.292 a	0.311 a	0.288 a	0.287 a
	20 cm SM	2015	0.270 a	0.267 a	0.233 a	0.276 a	0.246 a	0.255 a
		2016	0.274 a	0.272 a	0.280 a	0.307 a	0.278 a	0.273 a
	40 cm SM	2015	0.287 a	0.293 a	0.264 a	0.269 a	0.306 a	0.281 a
		2016	0.273 a	0.303 a	0.281 a	0.297 a	0.296 a	0.275 a
	60 cm SM	2015	**0.338 a**	**0.310 ab**	**0.281 b**	0.294 a	0.305 a	0.288 a
		2016	0.289 a	0.307 a	0.286 a	**0.369 a**	**0.310 b**	**0.278 b**
P3) July 1 to mid-August	10 cm SM	2015	**0.286 a**	**0.246 b**	**0.229 b**	0.263 a	0.273 a	0.261 a
		2016	0.242 a	0.255 a	0.242 a	0.264 a	0.292 a	0.265 a
	20 cm SM	2015	0.275 a	0.250 a	0.239 a	0.277 a	0.265 a	0.260 a
		2016	0.241 a	0.226 a	0.236 a	0.297 a	0.264 a	0.253 a
	40 cm SM	2015	0.290 a	0.275 a	0.271 a	0.269 a	0.310 a	0.287 a
		2016	0.230 a	0.262 a	0.238 a	0.281 a	0.303 a	0.259 a
	60 cm SM	2015	**0.363 a**	**0.311 b**	**0.291 b**	0.299 a	0.323 a	0.293 a
		2016	**0.251 b**	**0.288 a**	**0.276 ab**	0.377 a	0.330 a	0.261 b

[a] within the same crop and row, means with the same letter are statistically the same at p<0.05
[b] Period 1 (P1): mid-April to mid-May; Period 2 (P2): mid-May to mid-June; Period 3 (P3): July 1 to mid-August

Table 3.5. Comparison in daily values for treatments, early-killed cover crop (EC), late-killed cover crop (LC) and no cover crop (NC), within corn and soybeans for soil temperature mean (ST_Mean) and soil temperature range (ST_Range) within periods 1, 2 and 3.[a][b]

				Corn			Soybeans		
				EC	LC	NC	EC	LC	NC
P1) mid-April to mid-May	ST_Mean	10 cm	2015	14.80 a	14.49 a	15.07 a	14.69 a	13.79 a	14.78 a
			2016	12.96 a	12.70 a	12.97 a	**13.08 a**	**12.60 b**	**12.49 b**
		20 cm	2015	14.20 a	13.91 a	14.03 a	14.18 a	13.33 a	14.14 a
			2016	12.90 a	12.52 a	12.75 a	**12.90 a**	**12.32 b**	**12.25 ab**
		40 cm	2015	12.70 a	12.35 a	12.57 a	**12.65 a**	**11.98 b**	**12.64 a**
			2016	12.13 a	11.92 a	12.23 a	12.02 a	11.67 a	11.63 a
	ST_Range	10 cm	2015	4.26 a	4.41 a	6.54 a	**4.48 ab**	**3.53 b**	**6.35 a**
			2016	**2.90 b**	**2.35 b**	**4.79 a**	3.32 a	2.34 a	2.87 a

Table 3.5 continued

		20 cm	2015	2.37 a	2.27 a	3.11 a	**2.34 ab**	**1.94 b**	**3.14 a**
			2016	1.79 a	1.32 a	2.45 a	2.47 a	1.43 a	2.06 a
		40 cm	2015	**0.61 ab**	**0.54 b**	**0.78 a**	**0.58 ab**	**0.48 b**	**0.76 a**
			2016	**0.57 b**	**0.51 b**	**0.86 a**	**0.62 ab**	**0.47 b**	**0.71 a**
P2) mid-May to mid-June	ST_Mean	10 cm	2015	17.66 a	17.36 a	17.70 a	17.27 a	16.96 a	17.39 a
			2016	**17.55 b**	**17.27 b**	**18.66 a**	**18.03 a**	**17.05 b**	**17.46 ab**
		20 cm	2015	17.09 a	16.71 a	16.83 a	16.47 a	16.91 a	16.90 a
			2016	17.27 a	16.78 a	18.02 a	**17.56 a**	**16.53 b**	**17.28 ab**
		40 cm	2015	15.64 a	15.12 a	15.58 a	**15.47 ab**	**14.89 b**	**15.59 a**
			2016	**15.87 b**	**15.57 b**	**16.96 a**	**15.95 a**	**14.93 b**	**15.72 ab**
	ST_Range	10 cm	2015	4.29 a	4.69 a	5.47 a	**4.43 ab**	**3.46 b**	**5.50 a**
			2016	**3.49 b**	**3.01 b**	**6.19 a**	4.11 a	3.05 a	3.68 a
		20 cm	2015	2.43 a	2.49 a	2.74 a	**2.31 ab**	**2.00 b**	**2.86 a**
			2016	2.05 a	1.59 a	3.01 a	2.86 a	1.78 a	2.46 a
		40 cm	2015	**0.69 ab**	**0.63 b**	**0.82 a**	**0.66 ab**	**0.53 b**	**0.79 a**
			2016	**0.57 b**	**0.54 b**	**0.82 a**	**0.60 b**	**0.52 b**	**0.75 a**
P3) July 1 to mid-August	ST_Mean	10 cm	2015	17.66 a	17.36 a	17.70 a	17.27 a	16.96 a	17.39 a
			2016	17.55 a	17.27 a	18.66 a	**18.03 a**	**17.05 b**	**17.46 ab**
		20 cm	2015	17.09 a	16.71 a	16.83 a	16.90 a	16.47 a	16.91 a
			2016	17.27 a	16.78 a	18.02 a	**17.56 a**	**16.53 b**	**17.28 ab**
		40 cm	2015	15.64 a	15.12 a	15.58 a	**15.47 ab**	**14.89 b**	**15.59 a**
			2016	**15.87 b**	**15.57 b**	**16.96 a**	**15.95 a**	**14.93 b**	**15.72 ab**
	ST_Range	10 cm	2015	4.29 a	4.69 a	5.47 a	**4.43 ab**	**3.46 b**	**5.50 a**
			2016	**3.49 b**	**3.01 b**	**6.19 a**	4.11 a	3.05 a	3.68 a
		20 cm	2015	2.43 a	2.49 a	2.74 a	**2.31 ab**	**2.00 b**	**2.86 a**
			2016	2.05 a	1.59 a	3.01 a	2.86 a	1.78 a	2.46 a
		40 cm	2015	**0.69 ab**	**0.63 b**	**0.82 a**	**0.66 ab**	**0.53 b**	**0.79 a**
			2016	**0.57 b**	**0.54 b**	**0.82 a**	**0.60 b**	**0.52 b**	**0.75 a**

[a] within the same row, means with the same letter are statistically the same at p<0.05
[b] Period 1 (P1): mid-April to mid-May; Period 2 (P2): mid-May to mid-June; Period 3 (P3): July 1 to mid-August

Figures

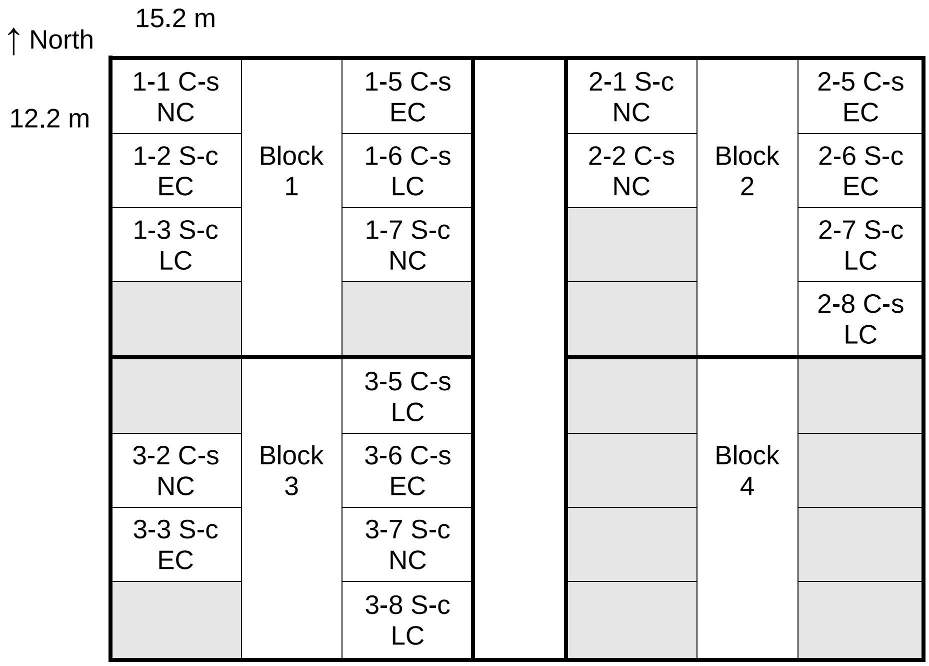


Figure 3.1. Map of field including 18 experimental plots with no cover crop (NC), early termination cover crop (EC) and late termination cover crop (LC).

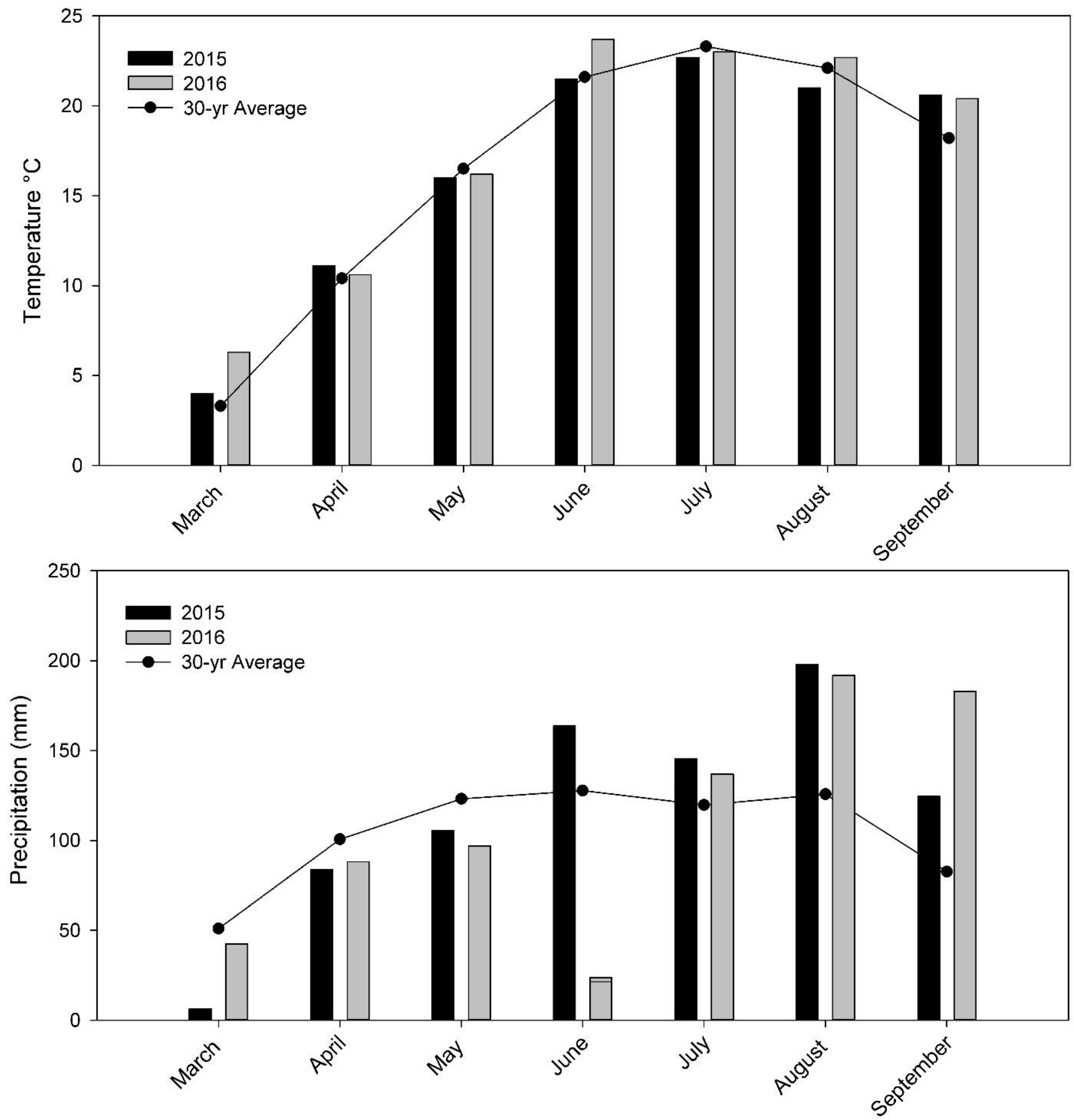


Figure 3.2. Average temperature and total precipitation for months of March through September for 2015 and 2016 along with the 30-year averages.

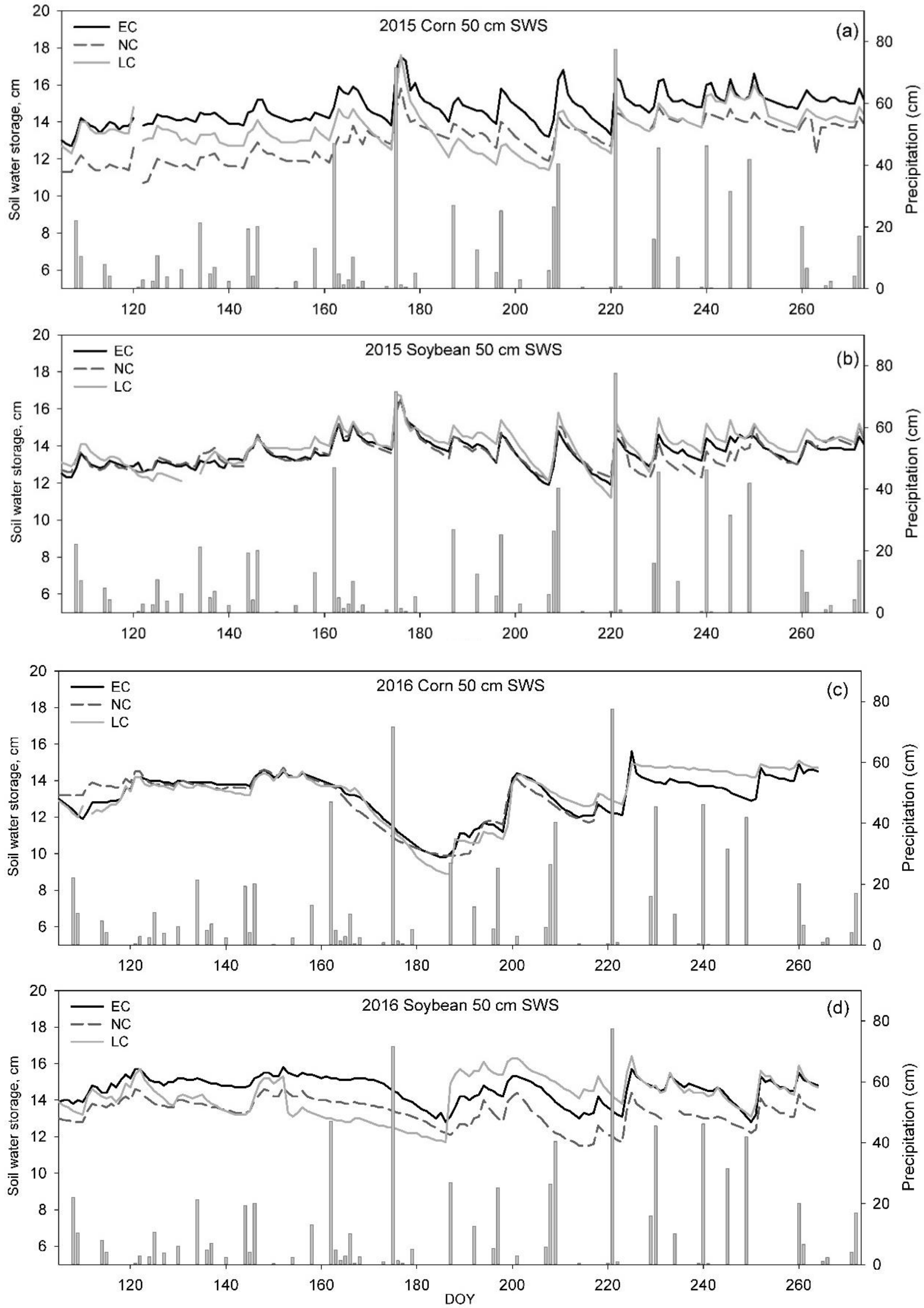


Figure 3.3. Soil water storage (SWS) within the 50 cm soil profile for (a) corn plots in 2015 (b) soybean plots in 2015 (c) corn plots in 2016 and (d) soybean plots in 2016. SWS was analyzed over the whole season from mid-April to the end of September.

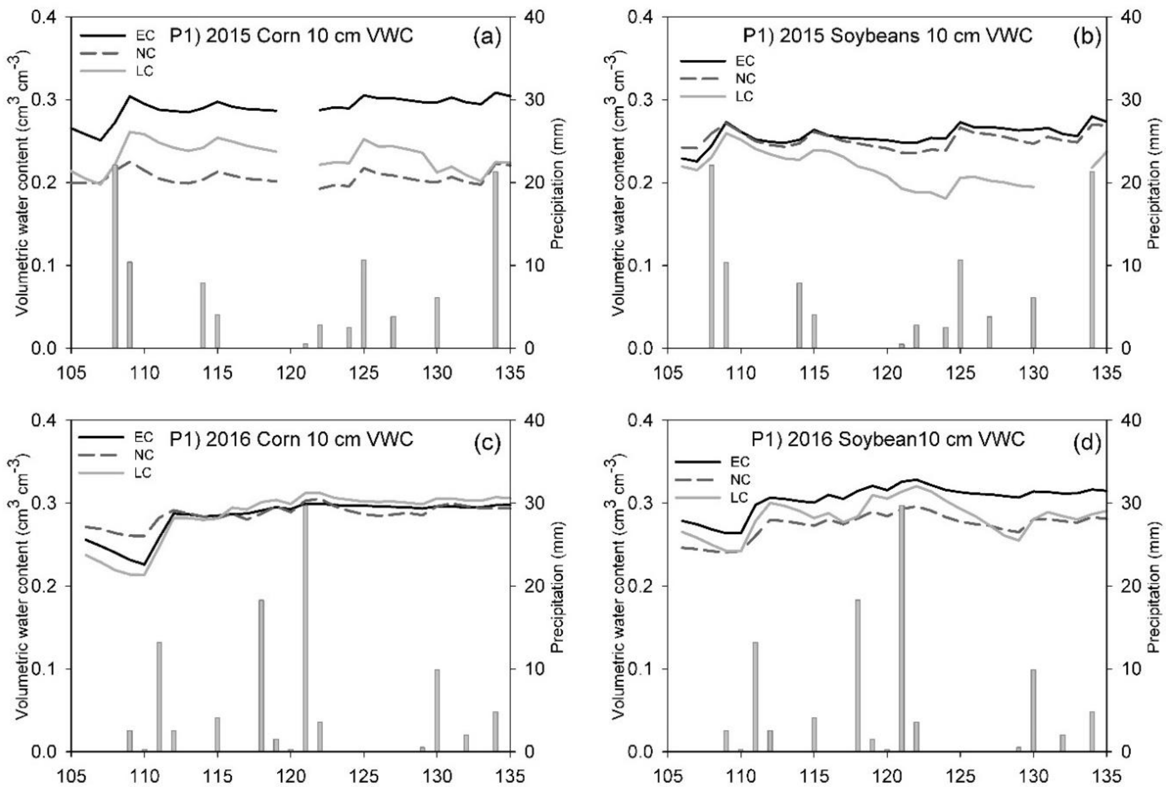
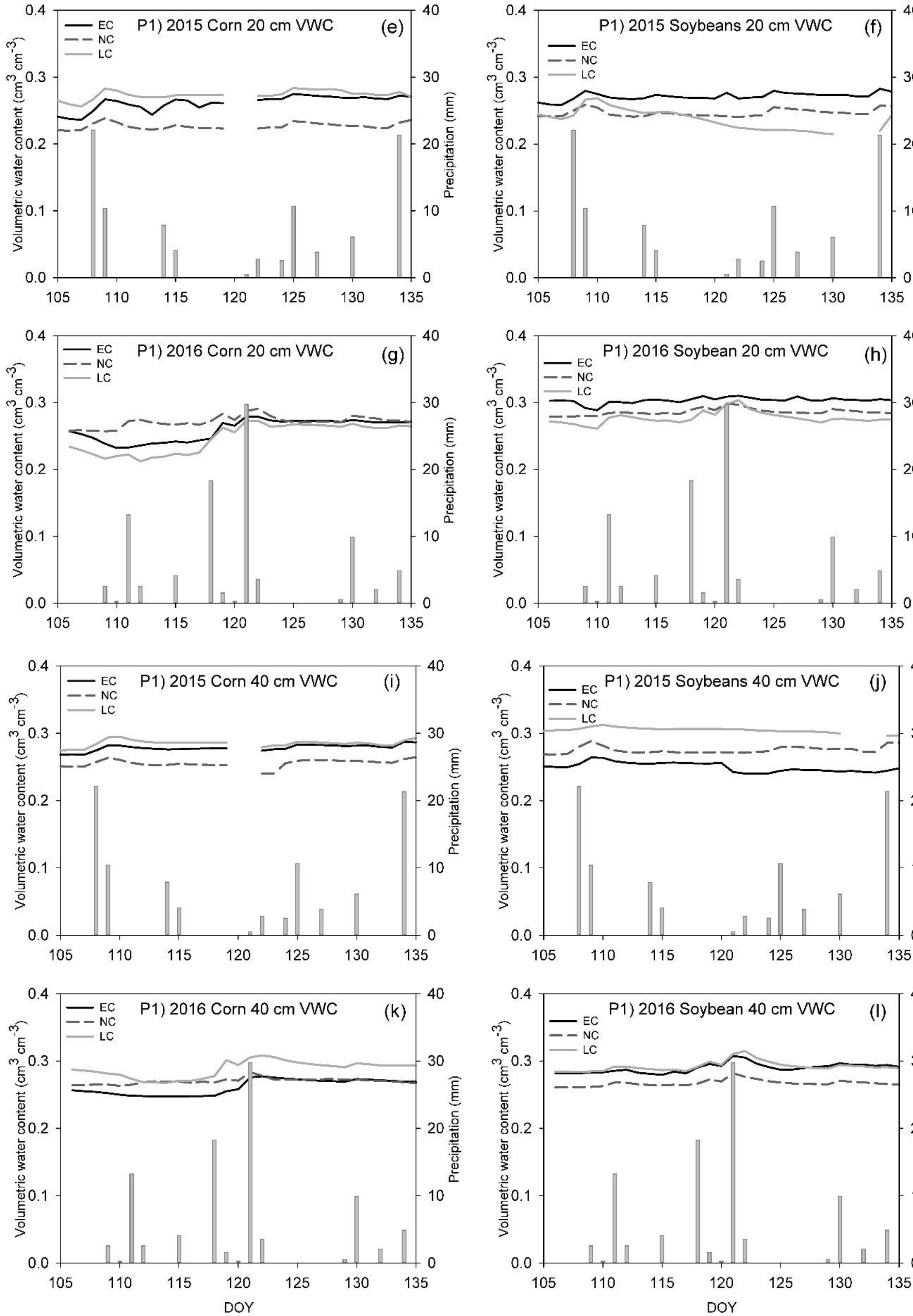


Figure 3.4. Volumetric water content (VWC) for period 1 at 10 cm in (a) corn plots, 2015 (b) soybean plots, 2015 (c) corn plots, 2016 and (d) soybean plots, 2016, at 20 cm in (e) corn plots, 2015 (f) soybean plots, 2015 (g) corn plots, 2016 and (h) soybean plots, 2016 and at 40 cm in (i) corn plots, 2015 (j) soybean plots, 2015 (k) corn plots, 2016 and (l) soybean plots, 2016; period 1 includes data from mid-April to mid-May.

Figure 3.4 continued



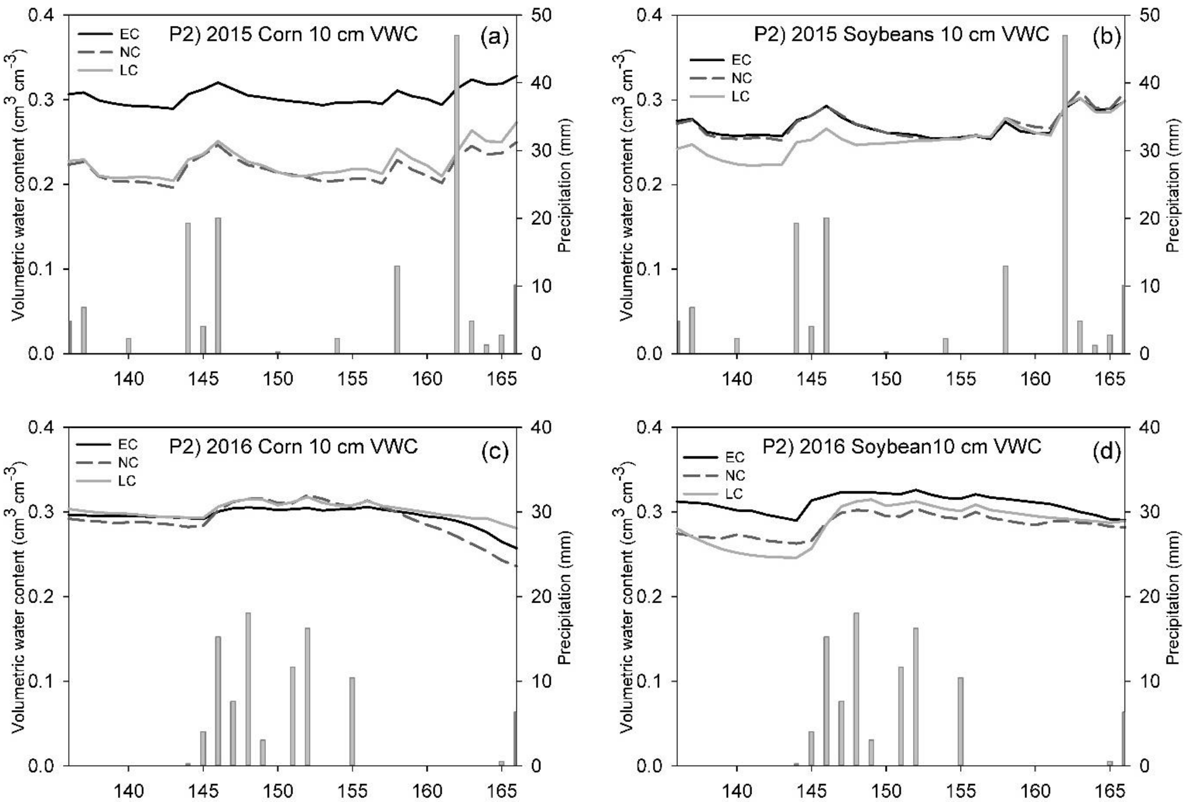
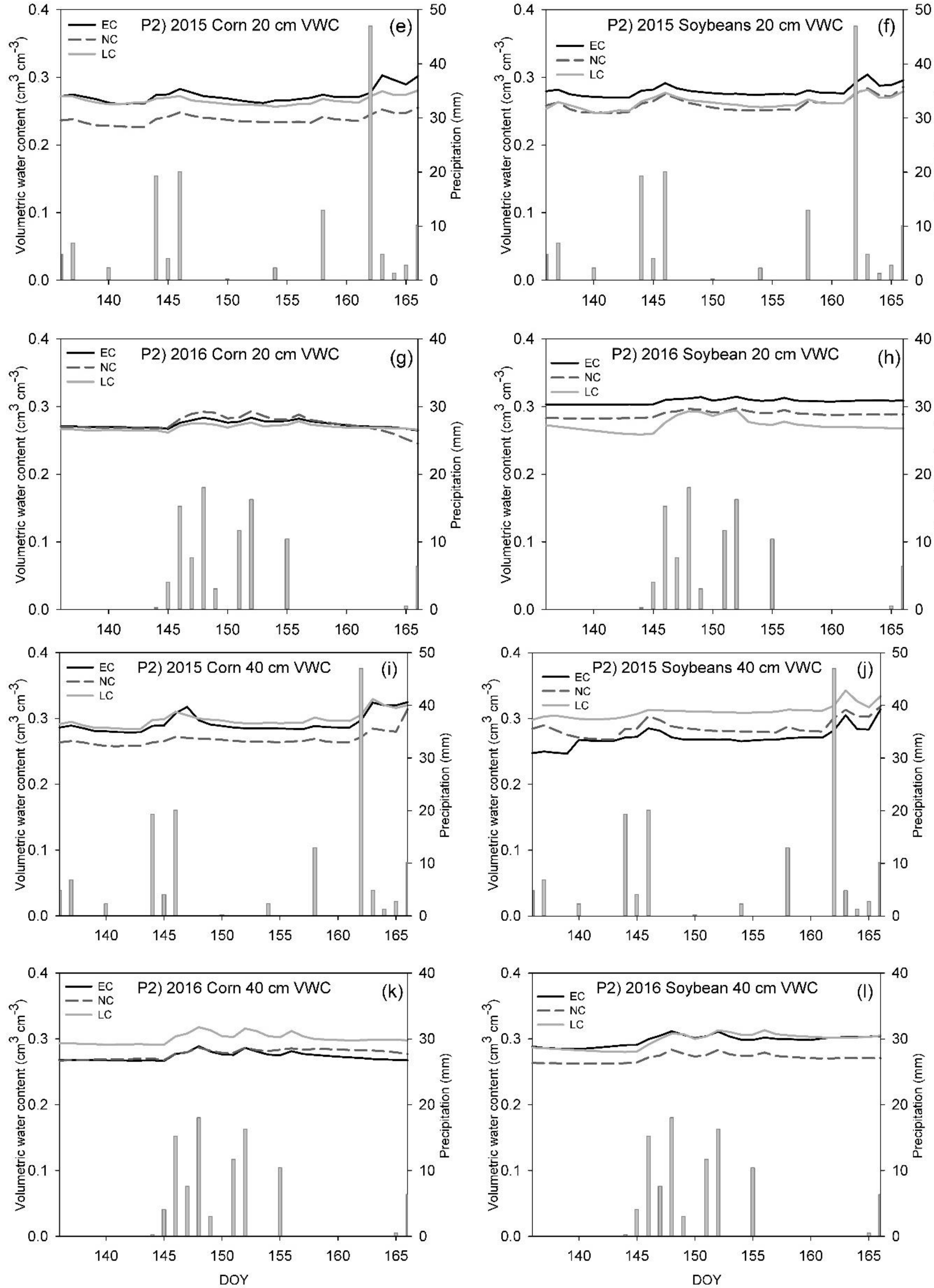


Figure 3.5. Volumetric water content (VWC) for period 2 10 cm in (a) corn plots, 2015 (b) soybean plots, 2015 (c) corn plots, 2016 and (d) soybean plots, 2016, at 20 cm in (e) corn plots, 2015 (f) soybean plots, 2015 (g) corn plots, 2016 and (h) soybean plots, 2016 and at 40 cm in (i) corn plots, 2015 (j) soybean plots, 2015 (k) corn plots, 2016 and (l) soybean plots, 2016; period 2 includes data from mid-May to mid-June.

Figure 3.5 continued



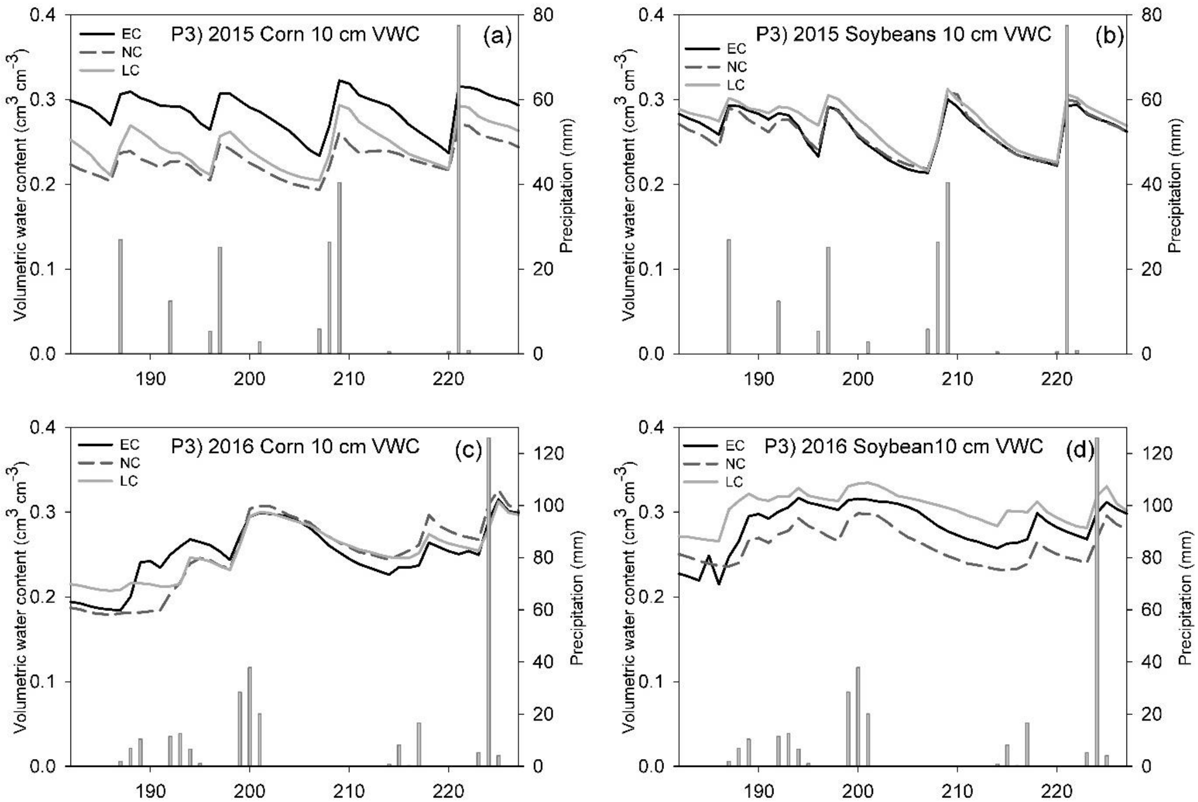
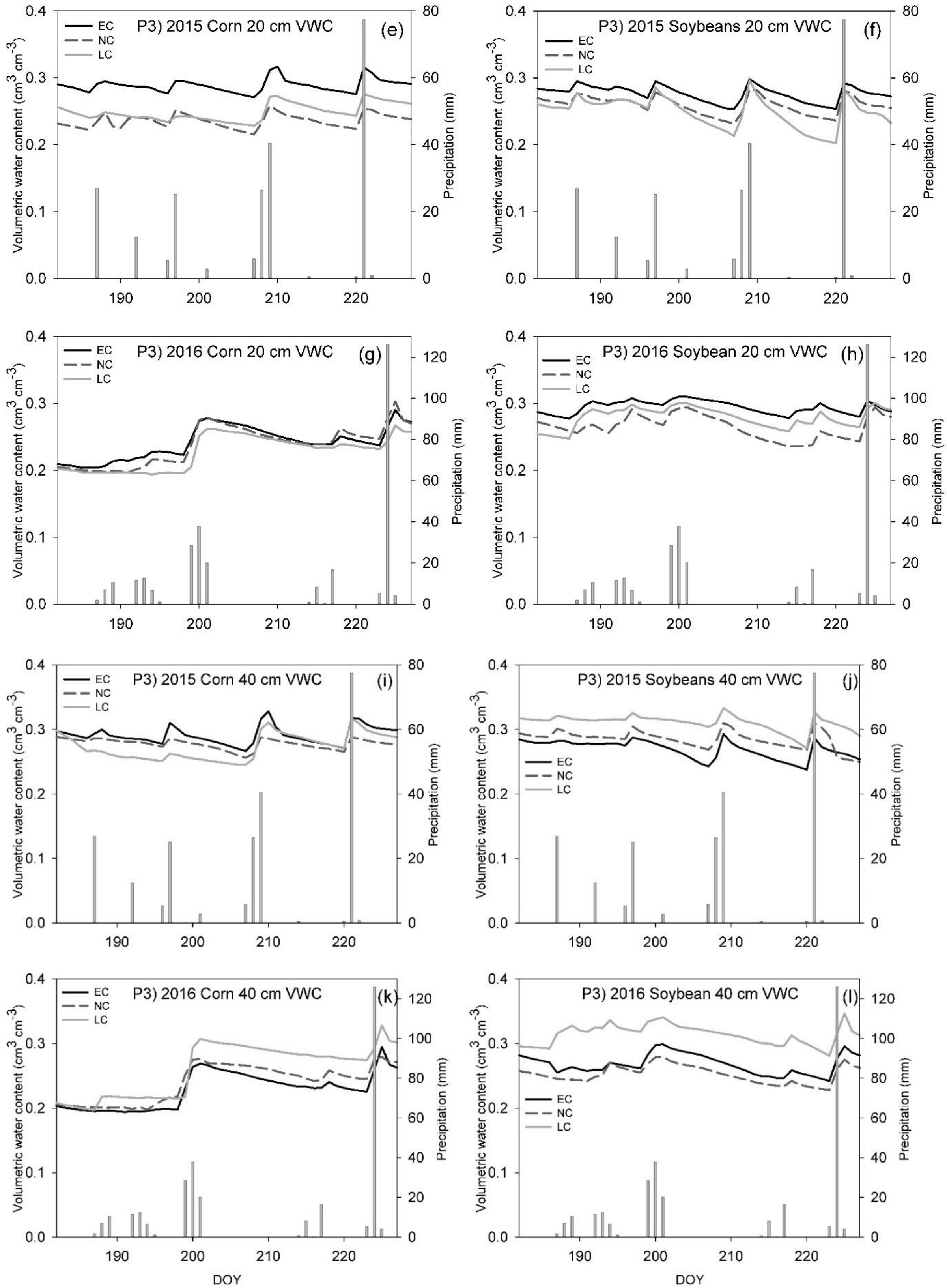


Figure 3.6. Volumetric water content (VWC) for period 3 at 10 cm in (a) corn plots, 2015 (b) soybean plots, 2015 (c) corn plots, 2016 and (d) soybean plots, 2016, at 20 cm in (e) corn plots, 2015 (f) soybean plots, 2015 (g) corn plots, 2016 and (h) soybean plots, 2016 and at 40 cm in (i) corn plots, 2015 (j) soybean plots, 2015 (k) corn plots, 2016 and (l) soybean plots, 2016; period 3 includes data from July 1 to mid-August.

Figure 3.6 continued



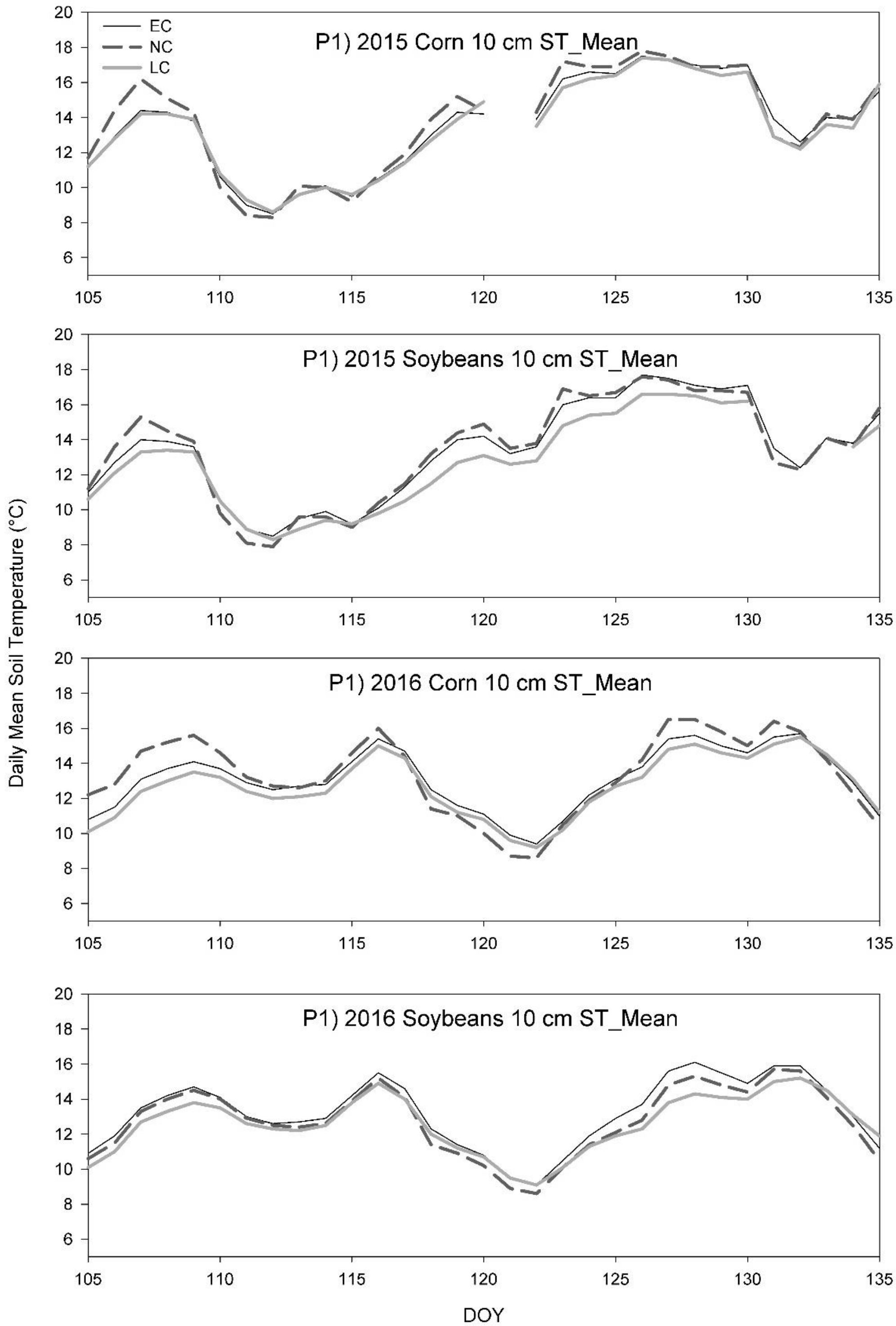


Figure 3.7. Mean daily soil temperature at 10 cm in (a) corn plots and in (b) soybean plots, at 20 cm in (c) corn plots and in (d) soybean plots and at 40 cm in (e) corn plots and in (f) soybean plots; includes data from period 1.

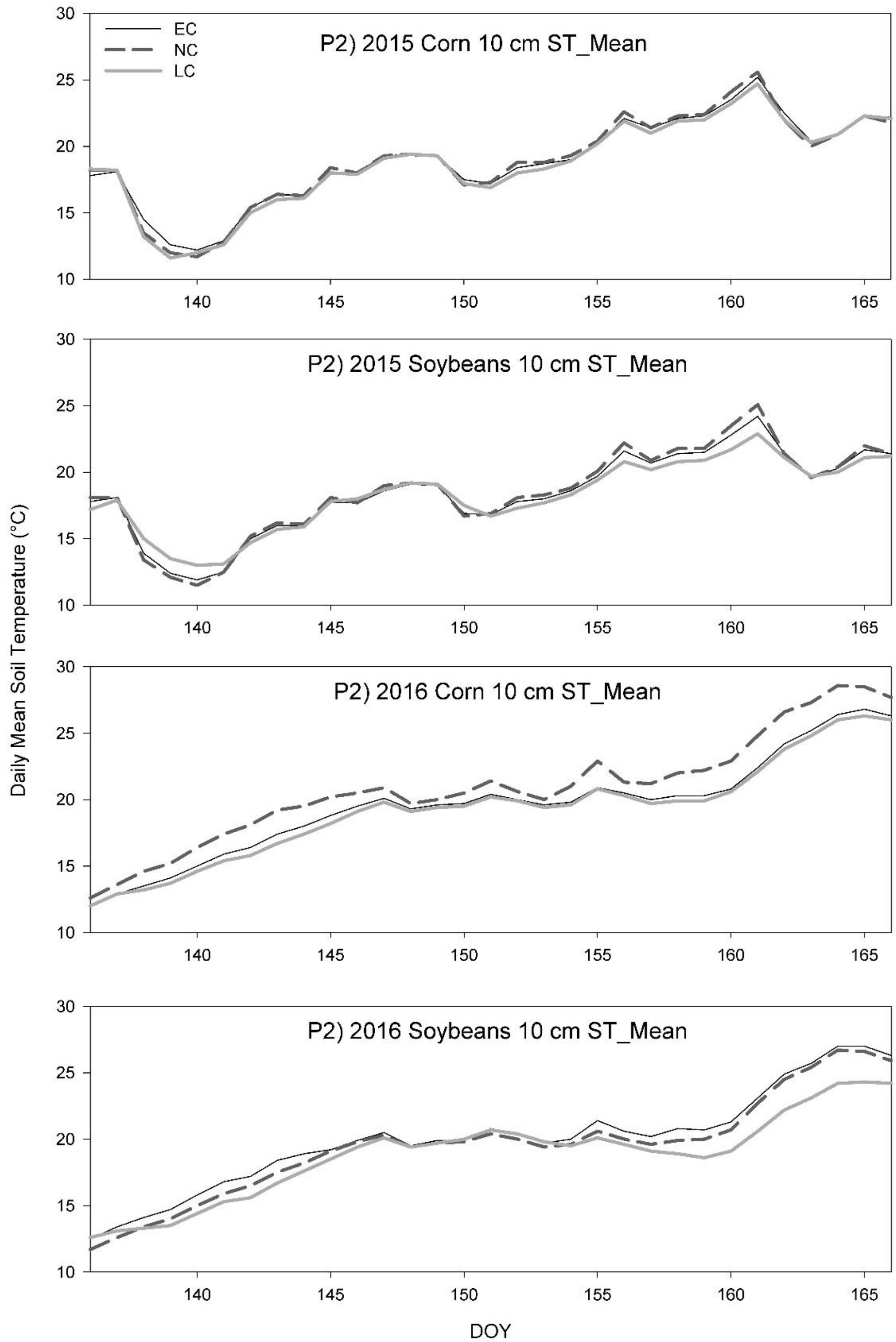


Figure 3.8. Mean daily soil temperature at 10 cm in (a) corn plots and in (b) soybean plots, at 20 cm in (c) corn plots and in (d) soybean plots and at 40 cm in (e) corn plots and in (f) soybean plots; includes data from period 2.

3.6 Acknowledgements

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CHAPTER 4. GENERAL CONCLUSIONS

4.1 General Discussion

The first study demonstrated that the RZWQM can be successfully calibrated and field-tested to simulate nutrient reduction data from alternative drainage systems, such as controlled drainage and shallow drainage. This study simulated long-term impacts of such systems in southeast Iowa, which included 1.2 to 2.2% yield reduction in alternative drainage systems as well as a naturally poorly system without artificial drainage, mostly attributed to higher water tables. Long-term, RZWQM predicted a reduction in annual nitrate lost via tile drainage of 26% in a controlled drainage system and 40% in a shallow drainage system. During the spring months, when N-loading makes the most impact on hypoxia in the Northern Gulf of Mexico, controlled drainage was found to be less effective (11% nitrate-loss reduction) than shallow drainage (35% nitrate-loss reduction). The second study found that a rye cover crop did not deplete soil water storage within 50 cm over two average-rainfall years, even though the rye treatments demonstrated water use in the spring. Additionally, it was found that there were times throughout the year, such as during planting, that the cover crop treatments were cooler and wetter, which could negatively impact cash crop germination.

Understanding the interrelated hydrologic and nutrient components of the corn and soybean agroecosystems across the Midwest is essential to ensure environmental sustainability as well as productivity into the future. With a more thorough understanding of these processes and how they differ among climates and soil types, researchers can aid producers in better managing their operations for viability as well as for improved water quality.

4.2 Future Research Recommendations

Based upon the findings in this research and the literature cited within this thesis, future research recommendations may include:

1. Additional agricultural subsurface drainage field studies with robust datasets are needed to aid model developers in improving the descriptions of the physical, chemical and biological processes within models
2. Long-term studies of the soil water and temperature impacts of cover crops should be conducted, as impacts are expected to change due to the accrued soil organic matter and changes in soil structure that are expected to occur from many years of cover crop use
3. Soil water and temperature dynamics should be studied over a range of soil types and climate regions, as these two greatly influence the way cover crops impact the soil system
4. Policy development is needed to increase adoption of alternative drainage practices and cover crop use, as there are management concerns and economic burdens associated with both nutrient reduction strategies