2017

A Demonstration Study of Drainage Water Management in Eastern South Dakota

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A DEMONSTRATION STUDY OF DRAINAGE WATER MANAGEMENT IN

EASTERN SOUTH DAKOTA

BY

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A thesis submitted in partial fulfillment of the requirements for the

Master of Science

Major in Agricultural and Biosystems Engineering

South Dakota State University

2017

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This thesis is approved as a creditable and independent investigation by a candidate for the Master of Science in Agricultural and Biosystems Engineering degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidates are necessarily the conclusions of the major department.

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To my Father and Mother for their unconditional support and encouragement.

ACKNOWLEDGEMENTS

I would like to express sincere gratitude to my major advisor Dr. Laurent Ahiablame, without him this thesis could not have been completed. I sincerely appreciate Dr. Ahiablame for his sheer motivation, encouragement, guidance, support, and time during the completion of my degree. His invaluable suggestions, comments and constructive critics have helped me to complete my research work and thesis.

I would like to express gratitude to my committee member Dr. Christopher Hay for providing me the opportunity to study here in South Dakota State University as graduate research assistant. Dr. Hay's support and encouragement during his stay at South Dakota State University to me was immeasurable. I would also like to thank my other committee members Dr. Todd Trooien, Dr. George Langelett for their support, assistance and guidance. I would like to thank Scott Cortus for his immense support and guidance in field work. I would like to thank my colleagues Alex Boger, Utsav Thapa, Sami Bin Shokrana, Govinda Karki, and Shailendra Singh for their assistance in field work and research.

I would to thank U.S. Department of Agriculture, National Institute of Food and Agriculture for financial support. This project is part of a multi-state and multi-institutional effort, "Managing Water for Increased Resiliency of Drained Agricultural Landscapes". This material is based upon work that is supported by the National Institute of Food and Agriculture, U.S. Department of Agriculture, under award number 2015-68007-23193, "Managing Water for Increased Resiliency of Drained Agricultural Landscapes", http://transformingdrainage.org. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the U.S. Department of Agriculture.

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ABSTRACT

A DEMONSTRATION STUDY OF DRAINAGE WATER MANAGEMENT IN EASTERN SOUTH DAKOTA

ASHIK SAHANI

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Subsurface drainage is a common water management practice for improving crop production in proorly drained soils; however, the practice is associated with several environmental concerns such as nutrient losses to downstream surface waters. These environmental concerns from subsurface drainage have prompted interest in drainage water management strategies such as controlled drainage. This study assessed the agronomic and environmental impacts of drainage water management in eastern South Dakota by using two demonstration plots for controlled and conventional drainage. Drain flow, nitrate and dissolved phosphorous concentration in drain water, shallow groundwater, crop yield, residual soil nitrate, soil moisture and temperature, soil penetration resistance, bulk density, soil pH, and leaf area index (LAI) were measured from 2014 to 2016 from the two adjacent drainage plots. Soybean, oats, and corn were planted in 2014, 2015, and 2016, respectively with urea fertilizer applied during the corn year. Results showed that controlled drainage reduced drain flow by 58% compared to conventional drainage. Nitrate concentration in drain water increased and exceeded maximum contaminant level (10 mg/L) for drinking water in both controlled and conventional drainage plots during the second project year. Annual nitrate load was reduced by 55% with controlled drainage compared to conventional drainage. Nitrate concentration in shallow groundwater was slightly higher in the conventional drainage plot than in the controlled drainage plot, and generally higher than 10 mg/L for both plots. Dissolved phosphorous concentration in drain water and shallow groundwater exceeded the critical level of 0.03 mg/L for freshwater eutrophication. The dissolved phosphorous concentration in drain water was higher in controlled drainage compared to conventional drainage; but significantly higher in conventional drainage compared to controlled drainage in shallow groundwater samples ($p < 0.05$). Unlike nitrate load, controlled drainage increased dissolved phosphorous load by 35% compared to conventional drainage. Shallow groundwater table was significantly higher in the controlled drainage plot than in the conventional drainage plot.

The soil moisture content near the outlet and middle of plots was higher in the conventional drainage plot than in the controlled drainage plot at all depths, except for 20 cm depth in the middle of controlled drainage plot and 105 cm depth near the plot outlet in the conventional drainage plot. Soil temperature and penetration resistance showed no statistical difference in mean between the controlled and conventional drainage plots. However, the controlled drainage plot had slightly higher soil temperature than the conventional drainage plot, and slightly higher soil penetration resistance was measured in the conventional drainage plot. Mean residual soil nitrate content in the controlled drainage plot was significantly higher than in the conventional drainage plot. Controlled drainage showed 8% less yield for soybean, and 9% less yield for corn, while 5% increase in yield for oats was observed in controlled drainage compared to conventional drainage. Comparison of LAI between the controlled and conventional drainage plots was

statistically not significant. However, the controlled drainage plot had slightly higher LAI than the conventional drainage plot.

1 CHAPTER ONE: INTRODUCTION AND BACKGROUND

1.1 Subsurface drainage in South Dakota

Subsurface drainage is a common water management practice in the Midwest United States. The history of subsurface drainage installation dates back to the mid nineteenth century in the United States. Currently, about 25% of Midwest cropland is estimated to be drained (both surface and subsurface) (Pavelis, 1987). The practice of subsurface drainage has been widely adopted in neighboring states such as Minnesota and Iowa, where 25–30% of croplands are drained fields (Baker et al., 2004; Pavelis, 1987; Sands, 2010). In South Dakota, subsurface drainage has increasingly gained attention over the past several years (Figure 1.1). Crop prices especially for corn and soybean, were shown to outweigh installation and maintenance costs of subsurface drainage, thus making it economically feasible (Figure 1.2) (Dahlseng, 2013). Increase in price of non-irrigated cropland (Janssen et al., 2015) contribute to difficulty to acquire cropland, thus shifting attention to installation of subsurface drainage in fields where soils are poorly drained to maximize production profit (Figure 1.3). Moreover, there has been a shift in precipitation pattern around eastern part of South and North Dakota, southern Minnesota, and eastern Iowa (Hay et al., 2011). Precipitation increases of 51 to 127 mm have been reported during the past two decades (1991-2009) compared to previous years (1960–1990) in these areas (Hay et al., 2011). Kibria et al. (2016) also found increasing trends in rainfall and streamflow in eastern South Dakota during study period (1951-2013). Several areas in North and South Dakotas showed 10–50% increase in winter precipitation, leading to wetter springs and delayed crop plantating due to difficulties in field preparation and operation (Hay et al., 2011).

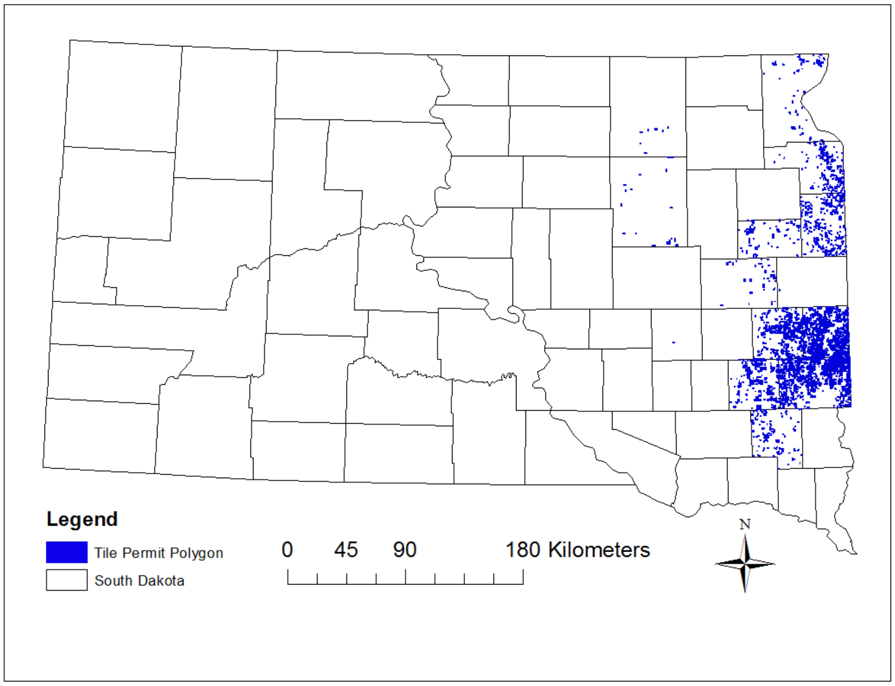

Figure 1.1 Agricultural subsurface drainage permits in South Dakota (Finnocchiaro, 2014)

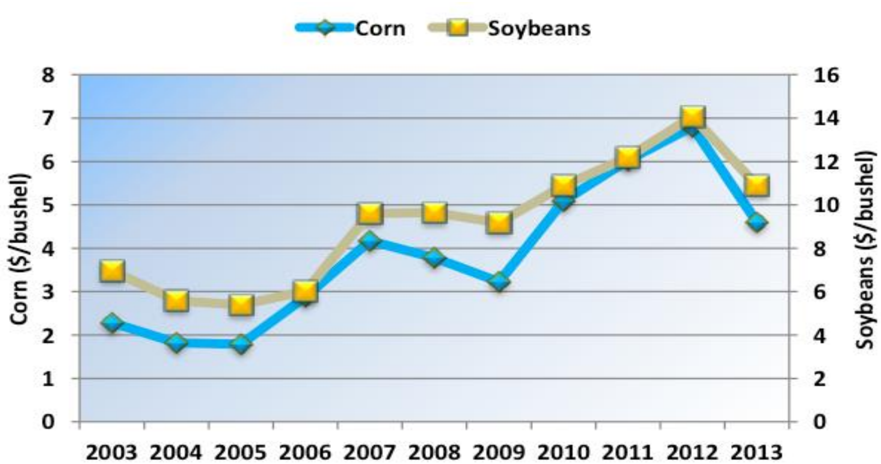

Figure 1.2 Corn and soybean price per bushel in South Dakota from 2003 to 2013 (Diersen, 2013)

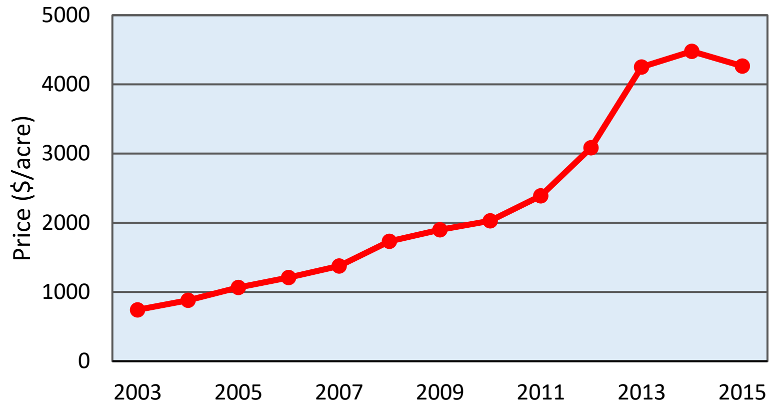

Figure 1.3 Price of non-irrigated cropland in South Dakota from 2003 to 2015 (Janssen et al., 2015)

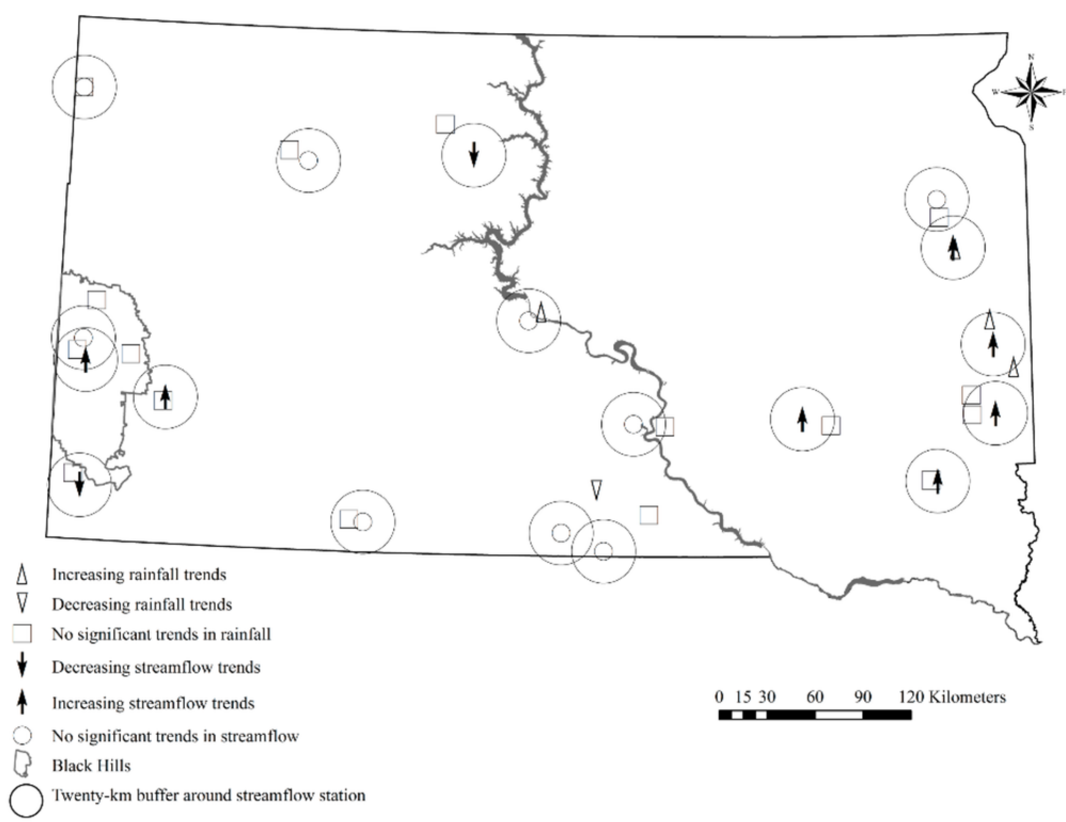

Figure 1.4 Trend of annual streamflow and rainfall in South Dakota (Kibria et al., 2016)

1.2 Transforming drainage project

The United State Department of Agriculture National Institute of Food and Agriculture (USDA-NIFA) funded a multi-state and multi-institutional project, "Managing Water for Increased Resiliency of Drained Agricultural Landscapes" in 2015. The project is commonly referred to as the Transforming Drainage by the project team members and is implemented across nine states including South Dakota, North Dakota, Minnesota, Iowa, Indiana, Missouri, Illinois, Ohio, and North Carolina. This team involves 35 researchers and extension specialists made up of drainage researchers, agricultural engineers, hydrologists, soil physicists, soil scientists, agronomists, environmental scientists, and agricultural economists. The project aims at minimizing crop production loss due to seasonal variation in precipitation and water quality concerns from subsurface drained landscapes with innovative drainage management practices. These practices include controlled drainage, saturated buffers, and drainage water recycling with a total of 29 field research sites across the nine states (Figure 5). The primary objectives of the project are to (Reinhart et al., 2016);

1. Strengthen and broaden the network of drainage researchers and stakeholders to advance and coordinate research, extension, and implementation of drainage water storage systems.
2. Determine economic and environmental benefits and costs of storing drainage water at field sites across the region.
3. Extend estimates of benefits and costs both temporally, accounting for future climate change, and spatially across the region through modeling.

4. Develop strategies and tools to apply the research findings to decision-making on the farm, in watersheds, and in state and to national policy.
5. Extend the strategies and tools to agricultural producers, the drainage industry, watershed managers, agencies, and policy makers to bring about transformation of drainage strategies.
6. Educate the next generation of engineers and scientists to design drainage systems that include drainage water storage in the landscape.

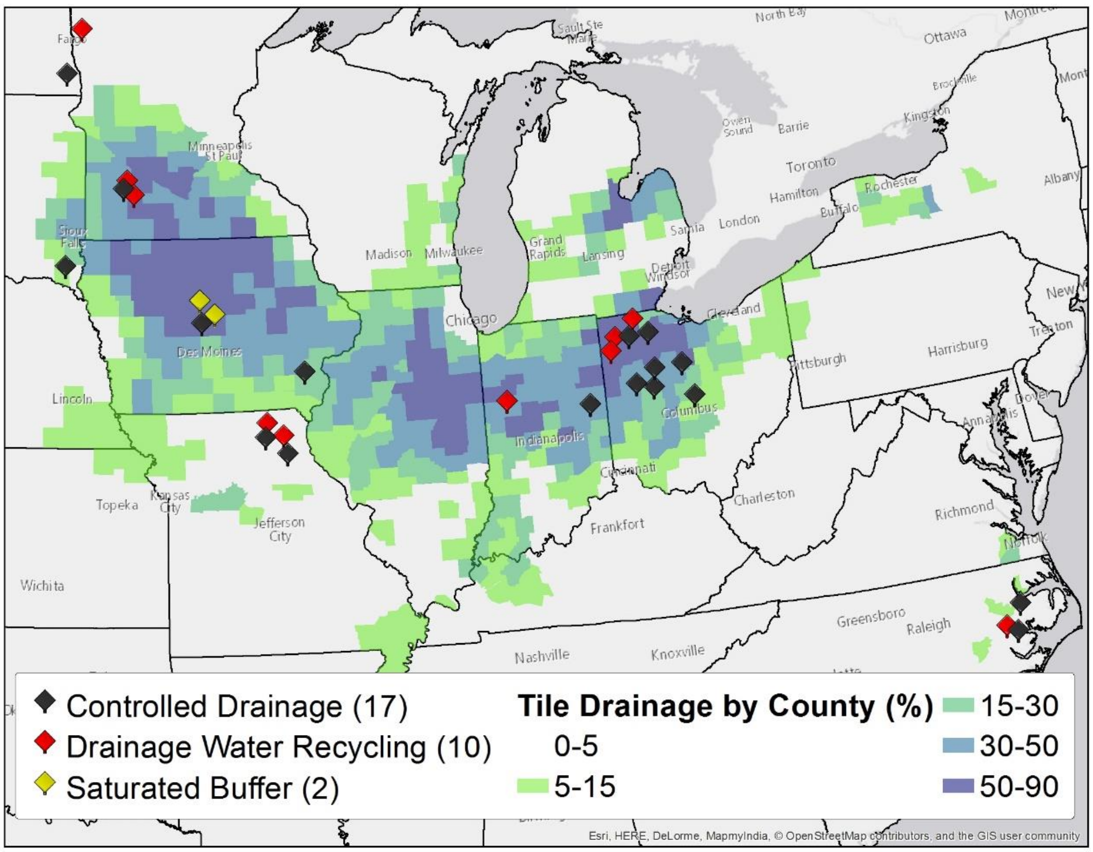

Figure 1.5 Transforming drainage project field research sites (Reinhart et al., 2016)

Several measurements such as drain flow, nutrient concentration and loading, crop yield, soil moisture, shallow groundwater table, soil nitrate, evapotranspiration, bulk density, LAI, and surface runoff are collected at the project field sites. These measurements will be useful to assess the economic and environmental impacts of drainage management practices.

1.3 Problem Statement

With the primary purpose of enhancing crop productivity, subsurface drainage benefits, both agronomic and environmental, are widely documented in the literature (Drury et al., 1993; Fraser et al., 2001; Hatfield et al., 1998). However, subsurface drainage has been linked to downstream water quality problems (Alexander et al., 2000; Petrolia and Gowda, 2006; Schindler, 1977). Studies showed that high influxes of nutrient enriched water from the Midwest agricultural drained fields within the Mississippi/Atchafalaya basin are a major contributor of nonpoint source pollution to the hypoxic zone in Gulf of Mexico (Ahiablame et al., 2011; Goolsby et al., 1999; Rabalais et al., 2002). Environmental concerns from subsurface drainage have prompted interest in drainage management strategies such as controlled drainage for water quality conservation. Controlled drainage is a technique of controlling the drainage outflow and nutrient loss from agricultural fields by adjusting the field drainage outlet elevation. (Frankenberger et al., 2004; Robert O. Evans, 1995; Strock et al., 2010). Controlled drainage practices are shown to reduce nutrient loading at different locations (Skaggs et al., 2010). While research on drainage water management practices has been conducted for many years, continued field observations to understand location-specific environmental impacts of agricultural drainage, are needed to improve agricultural water management based on local conditions.

1.4 Research Objectives

The goal of this study was to determine drainage water management impacts on hydrology and water quality using field measurements from demonstration plots in eastern South Dakota. The specific objectives of the study were:

1. To quantify the impacts of drainage water management on crop growth and yield.
2. To compare hydrology and water quality from controlled and conventionally drained fields.

1.5 Significance of Study

The practice of controlled drainage to address water quality issues from drained agricultural fields is relatively well documented in the literature (Singh et al., 2007; Skaggs et al., 2012; Williams et al., 2015b); however, it has not been widely adopted in South Dakota. This study seeks to demonstrate the feasibility of controlled drainage practices in eastern South Dakota. The study compared field hydrology, crop yield, and water quality from controlled and conventional drainage plots located in eastern South Dakota. Results from this study would be useful to producers, local community, and decision makers for developing a better understanding of drainage water management practices. Furthermore, this study is part of the Transforming Drainage project (see section 1.2), and would add data to understanding of the economics and environmental benefits of controlled drainage in the Midwest United States.

2 CHAPTER TWO: LITERATURE REVIEW

2.1 Overview of Subsurface Drainage

Subsurface drainage is the practice of installing perforated pipe beneath the soil surface generally at a depth of 1 to 1.5 m with the aim of removing excess water from the soil profile in agricultural fields. Subsurface drainage is generally installed in the soils which are somewhat very poorly drained soils. These soils remain wet or submerged in water for several days after precipitation events, causing stress in the plant by creating insufficient aeration for optimal crop root development. Subsurface drainage removes gravitational water from the soil profile thereby creating a favorable environment for crop growth (Sands, 2001).

2.1.1 Agronomic benefits of subsurface drainage

With the goal of improving productivity in poorly drained soils, subsurface drainage holds several agronomic and economics benefits (Fraser and Fleming, 2001; Hatfield et al., 1998; Pavelis, 1987). Subsurface drained fields enormously improve soil trafficability which allows farm machinery to operate smoothly during operations (Aldabagh, 1971). Higher load bearing capacity has been reported with subsurface drained soils than on undrained soils in North Dakota during planting and harvesting periods (Kandel et al., 2013). A well-drained soil has higher soil temperature during late winter to early summer (Jin et al., 2003), providing the ability to promote early planting (Evans et al., 1995; Plamenac, 1988). Better aerated soils overall support soil microbial activities and soil physical properties such as tilth and porosity (Gardner et al., 1994; Hillel, 1998). Subsurface drainage promotes optimal plant root growth in the soil profile enhancing access to water and nutrients which allow healthier crop growth (Skaggs et al., 1994). Poorly drained soils with high water table tend to accumulate soluble salts (Fraser and Fleming, 2001). Subsurface drainage reduces salt build ups by leaching excess soluble salts (Fausey et al., 1987).

Previous studies reported yield increase for different crops in subsurface drained systems (Buscaglia et al., 1994; Plamenac, 1988; Poole et al., 2013). For example, yield increase of as high as 35% and 32% for corn and soybean were reported in Ontario and Quebec regions of Canada with subsurface drained fields (Cowell, 1978). Research in subsurface drainage in combination with different drainage management practices such as crop rotation, cover crop, fertilizer rate and timing, and controlled drainage has also reported increase in crop yield (Kanwar et al., 2005; Randall et al., 1997; Robert et al., 2016).

2.1.2 Hydrologic impacts of subsurface drainage

Drainage plays a crucial role in the field water budget, as drainage removes water from the plant's root zone, altering different components of the field water balance (Sands, 2001). Soil is composed of solids and pores (comprised of both air and water). Generally, soil pore space varies with soil type and structure (Hillel, 1998; Scott, 2000) and ranges between 35–55 % of soil total space (Sands, 2001). Water in soil exists in three different forms, hygroscopic water, plant available water, and drainable water (Hillel, 1998). Hygroscopic water is the water which is strongly held by soil particles and is not available to plants (Hillel, 1998). Plant available water is water held between the pore spaces and is readily available for crop use (Hillel, 1998). Drainable water is the excess water which is not held against gravitational forces, and is available for drainage (Hillel, 1998). The point at which water is not available for plant use is termed wilting point while the point at which gravitational drainage ceases is termed field capacity. The field capacity typically range from 15–45% water by volume while wilting point ranges from 5–25% water content by volume for a given soil (Sands, 2001). Water is applied to the soil either by precipitation, irrigation, or capillary rise from ground water (Sands, 2001). For example, when there is precipitation the soil began to get wetter, the proportion of air filled pores decreases and water filled pores increase until the soil is filled with water, which is saturation (Sands, 2001). Any further addition of water to the soil does not change air-water dynamics in the soil profile. The process reverses once precipitation stops. Evapotranspiration (ET) begins to dry the soil, and the proportion of air filled pores gradually increase and water filled pores gradually decrease. The rate at which water filled pores change to air filled pores depends on soil texture and soil structure (Hillel, 1998). When the soil is poorly drained, it remains saturated for longer period, which means there is more water filled pores than air filled pores in the soil. This condition hinders the crop root development due to lack of sufficient aeration in the soil profile (Skaggs et al., 1994), making drainage an important practice for these types of soil.

Research shows that lowering seasonal high water tables in subsurface drained fields offers temporary storage space for water in the soil profile (Moore and Larson, 1979; Natho-Jina et al., 1987; Skaggs et al., 1994). This increased in storage capacity is often referred to as the “sponge effect” and is greatly influenced by the soil type, amount of rainfall, crop type, time of the year, and antecedent soil moisture conditions (Sands, 2001). Improved temporary storage space allows water to infiltrate more easily in the soil and consequently reduces surface runoff volume (Konyha et al., 1992; Stillman et al., 2006). In general, subsurface drainage improves soil permeability, allowing more storage of water in the soil, thereby attenuating downstream peak flows (Fraser and Fleming, 2001); even though studies have showed that subsurface drainage may increase or decrease downstream peak flows (Robinson, 1990). Impacts of subsurface drainage on peak flows depend on soil type, precipitation characteristics, drainage design, topography and soil water storage (Robinson, 1990; Robinson and Rycroft, 1999). Robinson (1990) in a field study with five different plots reported that subsurface drainage can reduce peak flows in clay and silty soils, but increase peak flows in sandy soils. Subsurface drainage in clayey and silty soil improves soil permeability. Water is retained more in these soils during precipitation events. Research showed that subsurface drainage increases total annual outflow from fields (Konyha et al., 1992; Robinson, 1990). For example, Konyha et al. (1992) reported that subsurface drainage outflow was 10% (40 mm/year) higher than from surface drainage alone. ET is another important component of field water balance. Generally, cumulative daily ET from subsurface drained fields are higher than ET in undrained fields (Khand et al., 2014; Rijal et al., 2012; Yang et al., 2017). However, Rijal et al. (2012) showed that ET during spring and fall season are greater in undrained plots compared to drained plots in a corn-soybean rotation study. The increase in ET in undrained plots was predominantly due high water table resulting from winter snowmelt, and spring and fall precipitations while ET was higher during growing season in drained plots compared to undrained plots. The high ET in drained plots during summer season can be attributed to higher ET rates from the crop due to better crop growth (Kjaersgaard et al., 2014; Rijal et al., 2012).

2.1.3 Water quality impacts of subsurface drainage

While subsurface drainage is beneficial for crop production, it is also associated with off-site environmental impacts especially, nutrient (nitrate and dissolved phosphorus) loading to receiving water bodies such as lakes and rivers(King et al., 2015; Skaggs et al., 1994) . Agricultural fields with subsurface drainage systems reduce the drainage flow path to surface water bodies (Dinnes et al., 2002). The excessive use of fertilizer and discharge of nutrient enriched water from drained agricultural lands from the Midwest to Mississippi/Atchafalaya river basin have been the major cause for eutrophication in the Gulf of Mexico (Alexander et al., 2007; Goolsby et al., 2001). Eutrophication is the occurrence of algal blooms due to excess amounts of nutrients present in water (Kelly, 2008; Ryther and Dunstan, 1971; Smith et al., 1999) which decreases dissolved oxygen content in the water bodies (Rabalais et al., 2002)

Total annual nitrate load from subsurface drained fields generally ranges from 0 to > 100 kg/ha from dry to wet years, respectively (Randall and Goss, 2008). Nitrate concentration in drain water is even higher during wet years when a wet year follows by a dry year (Randall and Iragavarapu, 1995; Randall et al., 1997). This is mainly due to soil organic mineralization processes when more soil nitrogen mineralization occurs but sufficient nitrogen uptake by the crop does not occur in the dry year (Randall and Goss, 2008). An extension report from North Carolina reported nitrogen and dissolved phosphorus losses from 14 different locations and 125 drainage study sites (Evans et al., 1991). The report highlighted that nitrogen loss from subsurface drainage was six times higher than nitrogen loss from undrained plots and three times higher from surface drainage. A long term water quality monitoring study in the Little Vermillion River watershed in Illinois reported 15, 17, 19 and 20 mg/L nitrate concentrations in drain flow at four different sites (Kalita et al., 2006). A study over a 2005-2012 period in Ohio showed that subsurface drainage contributes 44 to 82% of annual watershed nitrate loading while subsurface drainage accounted for 56% of annual streamflow discharge from the study watershed (Williams et al., 2015a).

While nitrate loading has been acknowledged as a major contributor of downstream water quality problems associated with subsurface drainage systems, there is growing concerns over dissolved phosphorous from the subsurface drainage and its impact on freshwater ecosystems (King et al., 2015). Dissolved phosphorus in surface water acts as the limiting nutrient for algae blooms in freshwater (King et al., 2015). Evans et al. (1995) reported that there was no difference in total phosphorous loss between drained and undrained sites. A field study in Wisconsin conducted on four subsurface drained fields with four different management practices (chisel plowed [two different types], no-till, and grazed pasture) during 2005–2009 showed that overall subsurface drained flow contributed 17–41% of cumulative total phosphorous loads and 16 to 58% of dissolved reactive phosphorous (Ruark et al., 2012). A field study in Ontario reported 95-97% total phosphorous loss from subsurface drainage while 3-5% was accounted for by surface runoff (Tan and Zhang, 2011). Controlled drainage practice is one management approach that can be used to address water quality impacts of subsurface drainage.

2.2 Conventional Drainage versus Controlled Drainage

Controlled drainage is a water management practice for conserving drainage water in the soil profile by seasonally adjusting the drainage outlet elevation with the assistance of riser boards at one or more outlet control structures (Evans et al., 1995; Frankenberger et al., 2004; Strock et al., 2010). Controlled drainage is generally installed in fields with slope < 1% so that single outlet control structures can be used to manage water in the soil profile for larger areas (Strock et al., 2010). Conventional subsurface drainage can be installed on steeper slopes (Wright and Sands, 2001). In recent decades, controlled drainage practices were deemed important to address water quality concerns associated with subsurface drainage (Skaggs et al., 2012).

Raising the outlet depth with the controlled drainage practice reduces drainage outflow (Evans et al., 1991; Skaggs et al., 1994). Research reported 20% to 80% drain flow reduction compared to conventional drainage practice (Cooke and Verma, 2012; Skaggs et al., 2012; Williams et al., 2015b). A five-year field experiment in Iowa reported 60% reduction in drainage outflow with the controlled drainage practice compared to conventional drainage (Schott et al., 2017). While drain flow is reduced in controlled drainage practice, surface runoff subsequently increases (Riley et al., 2009). A field experiment in Ontario, Canada showed that controlled drainage with sub-irrigation and no-cover crop yielded 34% higher surface runoff compared to conventional drainage with no-cover crop during 5-year study period while cover crop reduced surface runoff from controlled drainage with sub-irrigation to 13% compared to conventional drainage installations (Drury et al., 2014). A modeling study on North Carolina soils showed that controlled drainage increased ET, surface runoff, and seepage (both vertical and horizontal) while reducing drainage volumes Skaggs et al. (2010).

Controlled drainage is an effective practice in addressing water quality concerns from agricultural drained lands. Reduction in drainage volume is the driving factor for nitrate reduction in drain flow (Gunn et al., 2015; Jaynes, 2012). Controlled drainage retains more water in soil profile, creating an anaerobic environment which promotes denitrification of soil nitrate and leads to lower nitrate leaching than in conventional drainage (Dinnes et al., 2002; Tyndall and Bowman, 2016). While studies reported 20% to 80% of nitrate load reduction with controlled drainage compared to conventional drainage, there was no difference in nitrate concentration between these two practices (Skaggs et al., 2012; Sunohara et al., 2010; Wesström et al., 2001). Cooke and Verma (2012) reported mean annual nitrate loss of 61% from controlled drainage fields compared to conventional drainage fields during a two-year study in Illinois.

Research showed higher dissolved phosphorous concentration in controlled drainage plots compared to conventional drainage plots; while higher drain flow from conventional drainage will eventually yield high dissolved phosphorus load compared to controlled drainage (Feser et al., 2010; Wesström and Messing, 2007). A field experiment in Ontario, Canada reported 64% higher dissolved reactive phosphorus concentration in controlled drainage fields compared to conventional drainage fields while total phosphorous concentration was 58% higher in controlled drainage fields compared to conventional drainage fields (Sanchez Valero et al., 2007). Controlled drainage has also been reported to address dissolved phosphorous loss from drain flow by reducing phosphorous load by 25% to 35% compared to conventional drainage (Strock et al., 2010). In Sweden, higher reduction in total phosphorous load was reported in controlled drainage plots compared to conventional drainage plots during a four year study (Wesström and Messing, 2007).

The effects of controlled drainage on crop yield are still not clear. Varying results in crop yield have been reported in several studies (Helmers et al., 2012; Sunohara et al., 2010). This variation in yield may be due to soil type, precipitation, drainage design, and management plan (Skaggs et al., 2012). Skaggs et al. (2012) explained that the benefits of controlled drainage effects on yield can be observed when excess water from spring rainfall is retained in the soil profile and used later to satisfy crop needs during dry summer, leading to more yield. In contrast, the excess water of spring rainfall in conventional drainage is flushed and water stress may during the dry season, leading to decrease in crop yield (Frankenberger et al., 2004; Skaggs et al., 2012). A field research in North Carolina reported 11% and 10% increase in corn and soybean yields with controlled drainage as compared to conventional drainage fields over seven year study period (Poole et al., 2013). Similarly, 8% increase in soybean yield was observed for controlled drainage compared to conventional drainage while no yield differences were observed for corn in Iowa (Jaynes, 2012). Other studies also reported varying yield results when comparing controlled and conventional drainage fields (Cooke and Verma, 2012; Skaggs et al., 2012).

3 CHAPTER THREE: MATERIALS AND METHODS

3.1 Study Area

Two adjacent demonstration plots with silty loam soils (Egan–Chancellor Complex) and 0–2% slope were installed in November 2013 at the South Dakota State University, Southeast Research Farm (SDSU SERF) in Clay County, South Dakota. The area of the plots is 3.6 ha of which 1.6 ha is operated as a conventionally drained plot and 2 ha was operated as a controlled drained plot (Figure 3.1). The plots were installed with 10 cm lateral subsurface drain at a depth of 1.22 m from the ground surface and 12.2 m spacing to achieve a drainage coefficient of 1 cm/day. The laterals are further connected to 15 cm mains. The plots were outfitted with control structures (Agri Drain Cooperation, Adair, Iowa) to enable water sampling and management of water depth (controlled drainage plots). The depth of the control structures is 1.4 m below the ground surface. The plots were planted with soybeans in 2014 and oats in 2015 before adopting a corn-soybean rotation, starting with corn in 2016. The study period for this research is from July 2014 to December 2016.

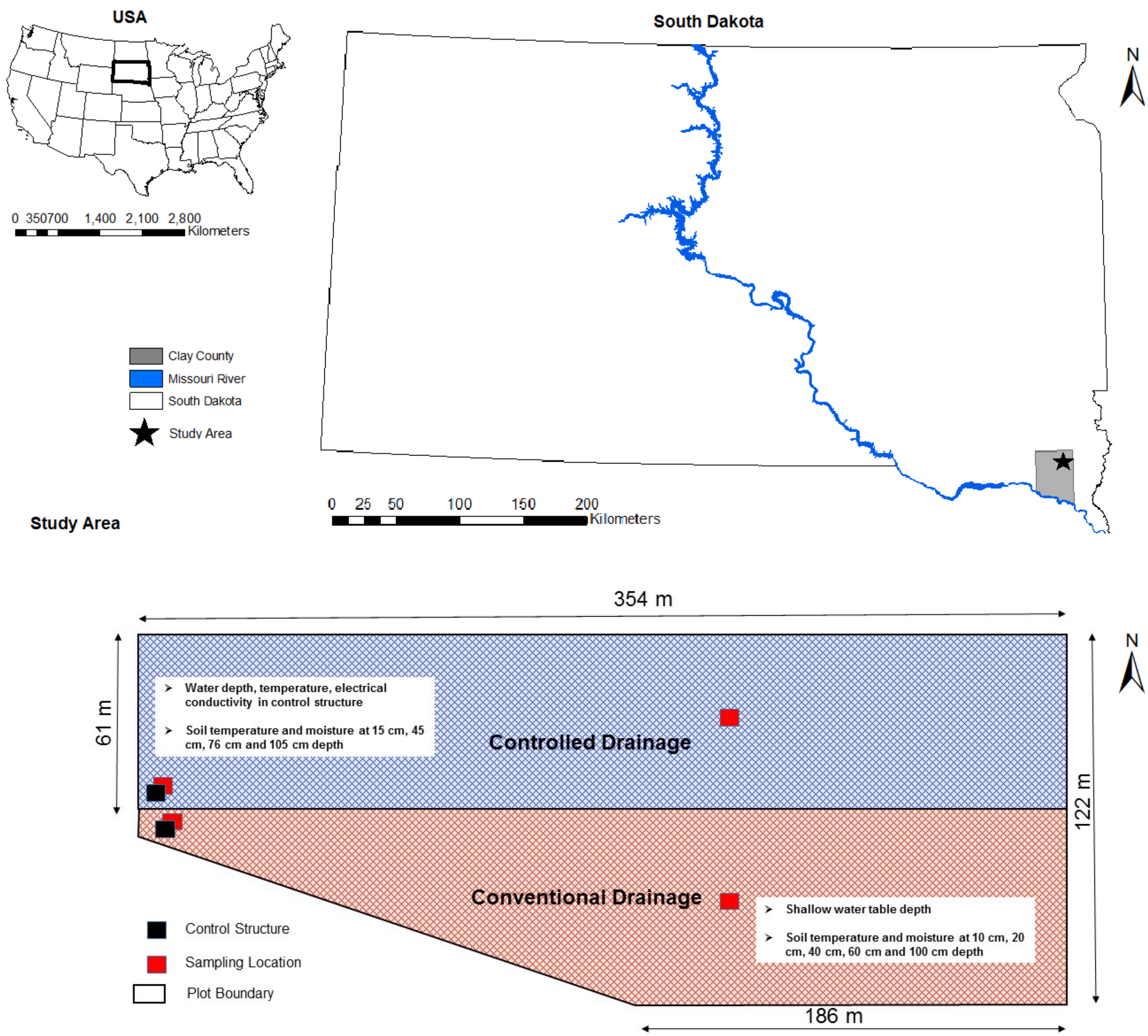

Figure 3.1 Study area and schematic layout of demonstration drainage plot at South Dakota State University, Southeast Research Farm near Beresford, South Dakota

3.2 Field operations and management

The operation and management of the demonstration plots during the study period (2014 -2016) include information on tillage, planting, fertilizer application, and herbicide application during the growing season as shown in Table 3.1.

Table 3.1 Field operation and management in demonstration of conventional and controlled drainage plots at South Dakota State University, Southeast Research Farm near Beresford, South Dakota

Crop	Date	Operation	Details	Remarks
Soybean	11/22/2013	Fertlize	Monoammonium phosphate applied @ 90 lb/ac	Fall fertlizer application
	5/6/2014	Tillage	Disk till	
	5/20/2014	Herbicide	Roundup @ 32 oz/ac Authority AMZ @ 12oz/ac COC @ 1.5%	
	5/23/2014	Plant	Soybean P24T19R	
	5/27/2014	Herbicide	Roundup @ 32 oz/ac Authority AMZ @ 12oz/ac COC @ 1.5%	
	7/3/2014	Herbicide	Roundup @ 32 oz/ac Select @ 10 oz/ac COC @ 1% UAN 1%	
	7/9/2014	Herbicide	Roundup @ 32 oz/ac Select @ 10 oz/ac COC @ 1% UAN 1%	
	10/20/2014	Harvest	Harvest two strip IH combine	
Oats	3/20/2015	Fertlize	Urea @ 100 lb/ac	
	3/23/2015	Herbicide	Roundup as burndown @ 40 oz/ac mix @ 2% 28%; 12 - 15 g/ac	
	3/23/2015	Plant	Hayden Oats i@ 90 lbs/ac 11,654 seeds/lb	
	5/22/2015	Herbicide	Roundup @ 1 qt/ac 40 gal 28% per 200 gal H20	
	6/1/2015	Herbicide	Round up @ 1 qt /ac Select plus 28% to SW Corn 90 X 200	
	6/4/2015	Fungicide	Prolimax @ 4 oz/ac	
	8/6/2015	Harvest	Oats @ 84 bales/ac	
	8/12/2015	Harvest	Harvest Canary 6 bales	
	8/13/2015	Herbicide	Round up @ 1 qt/ac AMS@ 1%	Oat stubble
	8/26/2015	Manure		

	9/14/2015	Tillage	Chisel plow	Oat stubble
	9/15/2015	Tillage	Disk till	Oat stubble
	9/16/2015	Tillage	Disk till	Oat stubble
Corn	4/14/2016	Fertilize	Urea @ 350 lb/ac	
	5/17/2016	Tillage		
	5/18/2016	Herbicide	Rounduo @ 32 oz/ac Dual @ 1-1/3 pt/ac Metribuzen 4 oz/ac Sharpen @ 1 oz/ac	
	5/18/2016	Tillage		
	5/18/2016	Plant	Channel 207 & DK46-36 @ 32,000 seed/ac	
	10/21/2016	Harvest		

The riser boards in the control structure of the outlet of the controlled drainage plot were adjusted based on drainage requirements and field operations (i.e. planting and harvesting) (Table 3.2). During the year 2014, the riser board in the controlled drainage plot was adjusted at a shallow depth (at 73.1 cm from ground surface) since water depth sensor was installed in the growing season (July 14, 2014). Field operations with shallow depth continued during the year 2015. Because of dry weather conditions, riser boards were not adjusted for planting and harvesting operations. Beginning of the year 2016, the riser boards were removed to a depth equal to conventional drainage during planting and harvesting period to allow excess water to drain from the soil profile to facilitate field operations.

Table 3.2 Riser board depth management in the control structure at the outlet of drainage plots in South Dakota State University, Southeast Research Farm near Beresford, South Dakota

Period		Number of days	Depth from soil surface (cm)	
Start Date	End Date		Controlled	Conventional
7/14/2014	10/30/2014	108	71.3	132.2
10/30/2014	4/5/2016	523	71.9	132.8
4/5/2016	5/26/2016	51	132.8	132.8
5/26/2016	9/23/2016	121	64.3	132.8
9/23/2016	10/31/2016	8	132.8	132.8
10/31/2016	12/31/2016	62	27.7	132.8

3.3 Field data collection

3.3.1 Water

Decagon CTD 10 (Decagon Inc., Pullman, WA) sensors were installed in the control structures at the outlet of both controlled and conventional drainage plots for continuous measurement of water temperature and electrical conductivity. Water temperature and electrical conductivity were not discussed in this thesis. The sensors were placed at the bottom of the control structure and measure the data every 15 min which are then recorded by the CR1000 data logger (Campbell Scientific, Inc. Logan, UT). The sensors are removed during the winter months to avoid damage due to freezing temperature. The CTD 10 sensors consist of vented differential pressure transducers which measure water level in the control structure (Decagon Devices, 2016b). Each control structure was outfitted with a v–notch weir to estimate the drain discharge. The flow rate is computed with the water level over the v–notch weir using the following equation (Partheeban, 2014):

$$Q = 1.7406 * H^{1.9531} \quad (3.1.)$$

where Q is drain flow rate through v-notch weir (L/min), H is depth of water flowing over the v-notch weir (cm). The spillway discharge rate when the v-notch weir is under submerged condition is estimated using the following equation (Chun and Cooke, 2008):

$$Q = 0.027 * H^{1.2} \quad (3.2.)$$

where Q is drain flow rate above the v-notch weir (L/sec), H is depth of water flowing above the v-notch weir (cm). The flow rate from both v-notch weir and spillway (above v-notch weir) were added to calculate the total flow rate from each plot. The total daily drainage volume from each plot is calculated, and divided with plot areas to determine drainage flow in depth (mm).

Shallow groundwater monitoring wells were installed on October 20, 2015 in the middle of both drainage plots (Figure 3.1.). These monitoring wells were installed at a depth of 1.5 m below the ground surface to collect water samples for water quality analysis and measure shallow groundwater table depth. HOBO U20 water level loggers (Onset Computer Cooperation, Bourne, MA) installed in the wells allowed measurement of the water table depth in the wells at 10-min intervals. During the study period, the water level loggers were removed during the winter months to avoid damage due to freezing temperature.

Grab water samples from the control structures and groundwater monitoring wells were collected during flow events in 2015-2016 every week from both controlled and conventional drainage plots. Water samples were collected in pre-labeled 120 mL nalgene bottle and stored in a cooler with ice until transported to the laboratory.

3.3.2 Soil

3.3.2.1 Soil Texture, pH, and Nitrate

Soil samples were collected from both drainage plots to assess the soil texture, soil pH and soil nitrate. The soil samples for texture, residual soil nitrate, and pH tests were collected on October 31, 2016. The samples were collected from seven random locations in each plot at 0 – 10 cm, 10–20 cm, 20-30 cm and 30-45 cm depth. A hand auger was used to collect the soil sample at each location. The soil samples were collected in a paper bag and stored in a cooler with ice until transported to laboratory. The samples were kept frozen until sent to SDSU Soil Testing Laboratory for further analysis.

Nitrate-nitrogen in the soil was analyzed using an Orion 930700 nitrate ion sensitive electrode (Thermo Fisher Scientific Inc., Beverly, MA). pH was analyzed using Orion pH electrode (Thermo Fisher Scientific Inc., Beverly, MA), and soil texture was determined using ASTM 152 Bouyoucos Scale hydrometer (Thermo Product, Inc., Lafayette, NJ).

3.3.2.2 Bulk Density

Bulk density soil sampling kit (AMS, Inc., American Falls, ID) was used to collect soil samples for bulk density measurement. The sampling kit consists of core sampler cup and cap, hammer head or slide hammer, auger (regular and planer), extension rod and accessories such wrench. Sample rings of 90.59 cm^3 were used to collect the undisturbed soil core. The samples were taken at six random locations in each study plot on June 23, 2016. At each location, samples were collected at 2.5 cm, 13 cm, 28 cm, and 48 cm depth. The regular auger was used to dig the hole to a specific depth where the soil sample was taken. The undisturbed soil cores once collected, were closed with caps at both ends, stored in a cooler, and brought back to the laboratory for further analysis.

In the laboratory, the undisturbed soil sample was placed in a disposable aluminum tray and oven dried at 105 ℃ for 24 hours. The weights of the sample rings and disposable aluminum trays were deducted from the total weight to obtain the weight of oven dry soil. The weight of oven dry soil was then divided by the volume of sample (i.e. 90.59 cm^3) to obtain the dry bulk density.

3.3.2.3 Soil Moisture and Temperature

Decagon 5TM sensors (Decagon Inc., Pullman, WA) were used to measure soil moisture and temperature in the plots. The sensor measures soil dielectric permittivity to determine the water content while thermistor in sensor prongs determines the soil temperature (Decagon Devices, 2016a). The soil dielectric permittivity is converted to VWC in the soil using Topp equation (Topp et al., 1980):

$$VWC = 4.3 * 10^{-6} \varepsilon_a^3 - 5.5 * 10^{-4} \varepsilon_a^2 + 2.92 * 10^{-2} \varepsilon_a - 5.3 * 10^{-2} \quad (3.3.)$$

where VWC is volumetric water content (cm^3/cm^3) and, ε_a is dielectric permittivity (dS/m).

The 5TM sensors were installed at two separate locations in the drainage plots (Figure 3.1.). The sensors were installed at 15 cm, 45 cm, 75 cm, and 105 cm depths from the soil surface about 6 m from the outlet (i.e. location of control structures) into the field. Another set of sensors were installed at 10 cm, 20 cm, 40 cm, 60 cm, and 100 cm depths from the soil surface in middle of the plots. The sensors collected data continuously at 15-min time intervals and recorded by CR 1000 data loggers.

3.3.2.4 Soil Penetration Resistance

Cone penetrometer (RIMIK, Toowoomba, QLD, Australia) was used to measure soil bearing capacity at six random locations in each drainage plots. The penetrometer records on-site penetration resistance of the soil every 25-mm depth up to 500 mm. The measurement was performed every week during the growing season from pre-planting to post-harvest.

3.3.3 Crop

3.3.3.1 Leaf Area Index

Leaf Area Index (LAI) measurement was taken to assess crop canopy coverage and biomass. LAI is defined as the area of leaves per unit area of the soil surface. AccuPAR LP 80 Ceptometer (Decagon Devices, Inc., Pullman, WA) was used to measure LAI. The measurements were taken at six random locations in each drainage plot. At each location, six separate readings were taken to capture the variability of measurements. The measurement was carried out every week during the growing season from early leaf stage to senescence stage.

3.3.3.2 Crop yield

Crops in the drainage plots were generally harvested during the month of October except during the year 2015 when oats were planted and harvested earlier (see Table 3.1.). Soybean and corn were planted in 2014 and 2016, respectively. The crops were harvested using an International Combine Harvester (CNH Industrial American LLC., NV). Grain samples were collected to run through a Steinlite SL95 Grain Tester (Steinlite Corporation, Atchison, KS) for moisture content (%) measurement.

3.4 Water Quality Analysis

Water samples were manually filtered with 30 mL plastic syringes and 0.45-micron nylon filter membranes of 25 mm diameter into 60 mL nalgene bottles. Filtered water samples were labelled properly and frozen in refrigerator until analyzed (within 28 days of sampling). In 2015, the samples were analyzed for nitrate using Dionex IC Analyzer (Thermo Fisher Scientific Inc., Sunnyvale, CA) by Ion Chromatography with EPA 300.1 method in Water and Environmental Engineering Research Center for analysis in Civil Engineering at South Dakota State University. In 2016, the samples were analyzed for nitrate using AQ2 discrete analyzer (Seal Analytical Inc., Milwaukee WI) in water quality laboratory at South Dakota State University, Agriculture and Biosystems Engineering. Nitrate plus nitrite were analyzed using copperized cadmium coil reduction method followed by sulfanilamide reaction in presence of N-(1-napahthyl)-ethylenediamine dihydrochloride (EPA- 114-A). Cadmium coil reduction was omitted in the above procedure to separately obtain nitrite (EPA- 115-A). Nitrate was reported at the end after deduction of nitrite from nitrate plus nitrite. Dissolved phosphorous were analyzed using the acidic molybdate/antinomy with ascorbic acid reduction with EPA 365.1 method.

3.5 Statistical Analysis

Analysis of variance (ANOVA) was used to relate water, soil, and crop variables to drainage effect (controlled and conventional drainage) using R statistical programming software (RStudio, Inc., Version 1.0.143). One-way ANOVA was used to determine differences in means of drain depth and flow, nutrient concentrations and loads, soil characteristics, and crop variables between the controlled and conventional drainage plots.

4 CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Precipitation

Figure 4.1 shows total monthly precipitation with long-term mean monthly precipitation during the three-year study period (2014 to 2016). Total annual precipitation ranged from 641 mm to 724 mm during the 2014-2016 period. Total annual precipitation during growing season (i.e. May to October) was 254 mm in 2014 (precipitation after installation of sensors in July 2014), 570 mm and 608 mm in 2015 and 2016, respectively. Monthly precipitation varied from 7 mm in February 2015 to 184 mm in August 2015 during the study period (July 2014–December 2016). Precipitation was below the 13-year normal after July 2014 when sensors were installed indicating dryer fall in 2014. Precipitation was below normal during spring 2015, while above normal precipitation was recorded during fall 2015, spring 2016 and, fall 2016. Research has showed correlation between precipitation amount and drain flow events (Jin and Sands, 2003; Skaggs et al., 1994), and nitrate losses from drain water (Dinnes et al., 2002; Randall and Mulla, 2001).

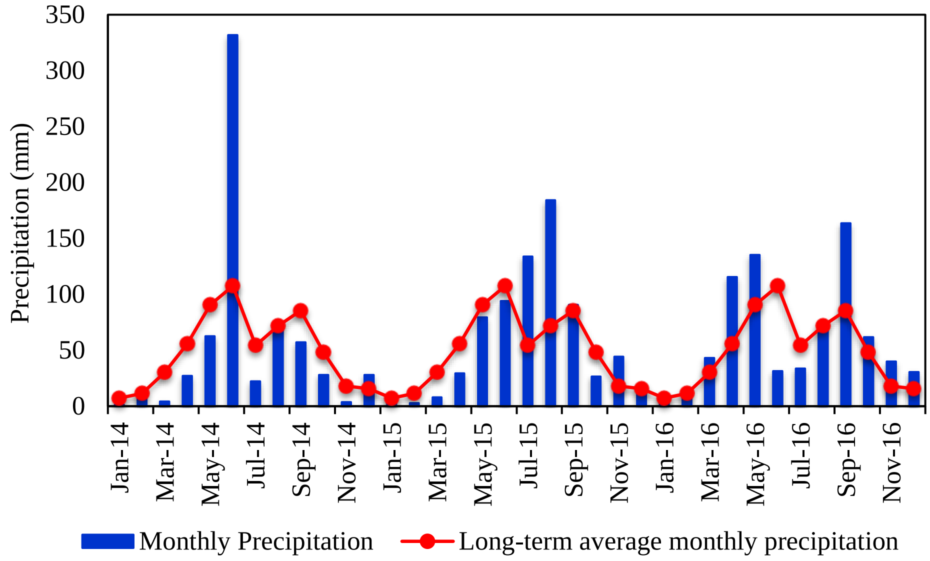

Figure 4.1 Monthly precipitation and long-term mean monthly precipitation (2014-2016) recorded at South Dakota State University, Southeast Research Farm, South Dakota.

4.2 Water Depth at the Plot Outlet

Water level in outlet control structures was generally measured from April to October except in 2014 when measurement started in July. The daily mean water depth at outlet of the conventional drainage plot ranged from 0 to 1192 mm with an overall mean of 98 mm, while in the controlled drainage plot the mean daily water table depth ranged from 15 to 1087 mm with an overall mean of 188 mm. The water depth at outlet of the controlled drainage plot was consistently higher than water depth in the conventional drainage plot. Water level fluctuation at outlets of both drainage plots seems not to be always affected by the timing and amount of precipitation (Figure 4.2). For example, on July 6, 2015, 60 mm precipitation did not cause any changes in water table depth in both drainage plots. This is likely due to crop evapotranspiration demand (Khand et al., 2014) and low soil moisture content during the month of July (Jin et al., 2003).

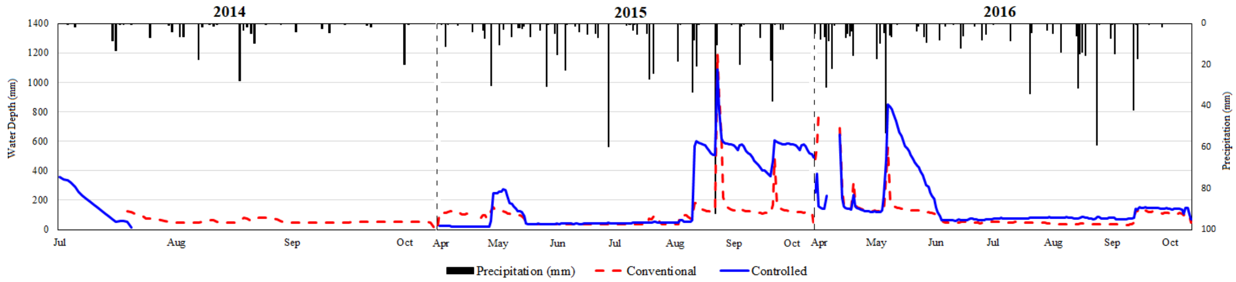

Figure 4.2 Daily mean water depth at the outlet of drainage plots at South Dakota State University, Southeast Research Farm near Beresford, South Dakota.

Seasonal variation in water depth was not consistent during the study period. Drainage water depth in 2014 remained below 100 mm in the conventional drainage plot while sensors in the controlled drainage plot did not measured any data past last week of July due to malfunctioning. In 2015, drainage water depth rise was noticeable during the month of August, September, and October indicating a wet fall season. In 2016, drainage water depth was high during April, and May indicating a wet spring. Mean daily drainage water depth per year in the conventional drainage plot ranged from 14 to 31% of the total annual precipitation while it ranged from 24% to 92% of the total annual precipitation for the controlled drainage plot during the study period.

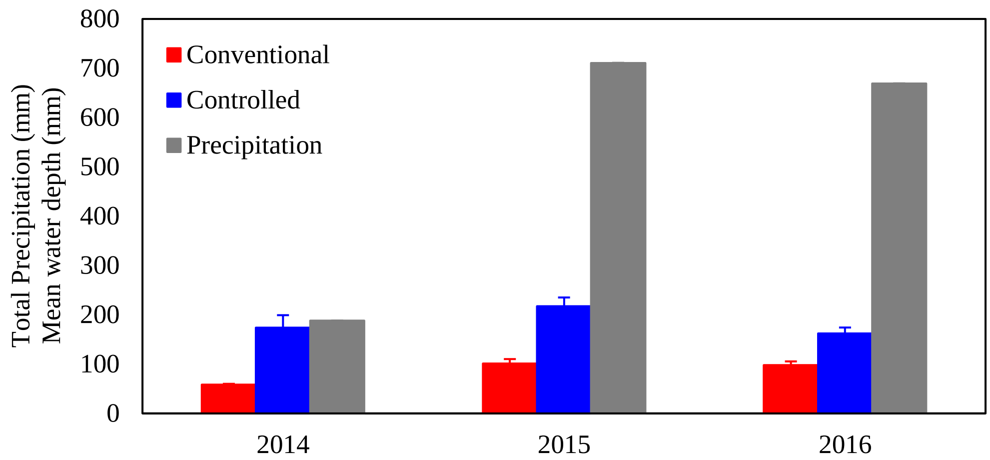

Figure 4.3 Annual precipitation and mean daily water depth per year at the outlets of drainage plots at South Dakota State University, Southeast Research Farm near Beresford, South Dakota.

4.3 Drain Flow

Some issues were detected in the drain flow data, likely due to the malfunctioning of the Decagon CTD sensors especially under submerged conditions (Table 4.1). The data must therefore be interpreted with caution.

The majority of drain flow in eastern South Dakota is generally observed during April through October and no drainage or minimal drainage is observed during November to March when temperature is below freezing point (Jin and Sands, 2003). During all three years (2014 to 2016), drainage outflow varied with the timing and amount of rainfall. Figure 4.4 shows daily total drain flow and precipitation in both controlled and conventional drainage plots. In 2014, less drainage (11 mm) was observed in the conventionally drained plot while no drainage was observed in the controlled drainage plot. This was due to lower precipitation than normal in 2014 (see Table 3.2). During 2015, more than 80% of drain flow from conventionally drained plot was observed during August, September, and October while 100% of drain flow occurred during the month of August in the controlled drainage plot. In 2016, most of drain flow in both controlled and conventionally drained plots occurred in April, May, and June. During the study period, monthly drain flow in the controlled drainage plot ranged from 0 to 134 mm and from 0 to 225 mm for conventional drainage. The mean daily drain flow in the conventional drainage plot were 0.11 mm, 2.17 mm, and 2.10 mm during 2014, 2015, and 2016, respectively during flow events. The mean daily drain flow in controlled drainage plot were 0 mm, 0.18 mm, and 1.22 mm for controlled drainage plots during 2014, 2015, and, 2016, respectively.

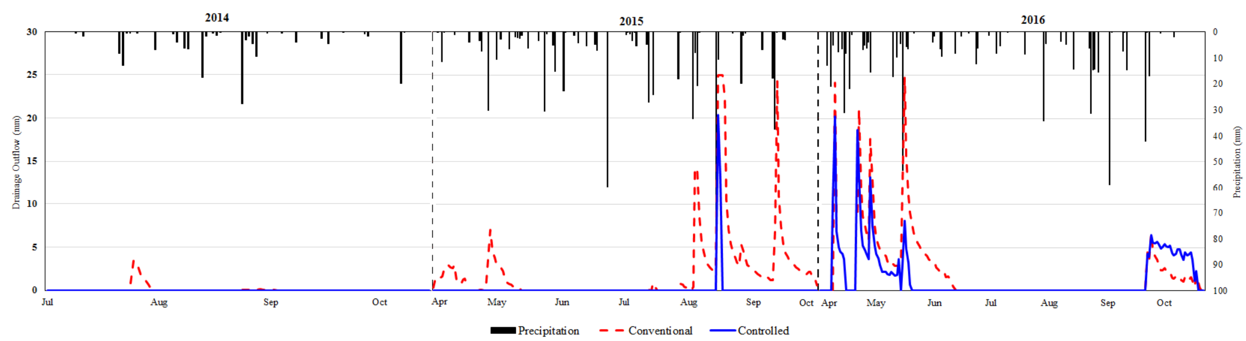

Figure 4.4 Daily drain flow and precipitation at South Dakota State University, Southeast Research Farm near Beresford, South Dakota.

The difference in daily mean drain flow between the controlled and conventional drainage plots was statistically significant ($p < 0.05$) for the combined three years of study (2014 to 2016). The controlled drainage plot showed 24 to 100% reduction in annual drain flow compared to the conventional drainage plot, with an overall reduction of 58% of drain flow. Schott et al. (2017) also reported a similar (58%) reduction in drain flow in controlled drained plots compared to conventional drained plots in southeast Iowa. Other researchers reported 18 to 96% of drain flow reduction for controlled drainage (Cooke and Verma, 2012; Skaggs et al., 2012; Williams et al., 2015b). Drain flow reduction examined with the controlled drainage in this study falls within the range mentioned above.

Table 4.1 Monthly drain flow from the controlled and conventional drainage plots at South Dakota State University, Southeast Research Farm near Beresford, South Dakota.

	Drain flow (mm)					
Year →	2014		2015		2016	
Month ↓	Conventional	Controlled	Conventional	Controlled	Conventional	Controlled
April	-	-	28.8	0.0	32.8	54.5
May	-	-	35.1	0.0	225.7	134.7
June	-	-	0.0	0.0	89.1	0.7
July	0.0	0.0	1.4	0.0	0.0	0.0
August	10.9	0.0	163.8	33.4	0.0	0.0
September	0.5	0.0	138.3	0.0	0.0	0.0
October	0.0	0.0	31.5	0.0	63.6	121.7
November	-	-	-	-	2.4	0.0

4.4 Water Quality

4.4.1 Nitrate Concentration and Load in Drain Water

The daily nitrate concentration in drain water and mean load during 2015 and 2016 are presented in Figure 4.5. The nitrate concentration ranged from 1.6 to 35.8 mg/L with mean of 9.3 mg/L for the conventional drainage plot and from 1.7 to 34.3 mg/L with an overall mean of 8.3 mg/L for the controlled drainage plot during the two-year sampling period. Similar mean nitrate concentration was reported in Iowa, Minnesota, and Indiana with controlled and conventional drainage field studies (Adeuya et al., 2012;

Feser et al., 2010; Helmers et al., 2012). In Ohio, nitrate concentration ranged from 0.1 to 60.2 mg/L for controlled and conventional drainage fields during seven-year study period (2006 to 2012) (Williams et al., 2015b) There was no statistical difference in mean nitrate concentration between controlled and conventional drainage plots for both years. While majority of studies in the region reported no statistical differences in mean nitrate concentration between controlled and conventional drainage plots (Helmers et al., 2012; Jaynes, 2012; Schott et al., 2017), a few studies showed statistical significant difference in nitrate concentration. For example, a study in Ohio showed a statistical significant difference in mean nitrate concentration between controlled and conventional drainage plots (Williams et al., 2015b).

Nitrate concentration was measured only during the spring season, not summer or fall, in 2015. The 2015 nitrate concentration was lower than the 10 mg/L USEPA maximum allowable limit for nirate concentration in drinking water (Pontius, 1993). In 2016, nitrate concentration exceeded 10 mg/L in spring while nitrate concentration dropped below 10 mg/L in fall. This is likely due to the impact of spring fertilizer application on nitrate loss. In fall, less nitrate is available after losses during spring and crop nitrate uptake during the growing season, leading to reduced nitrate transport. In Iowa, a field study with varying rate of nitrogen fertilizer (low, medium and high) in a subsurface drained field with corn-soybean rotation showed that high application rate of nitrogen fertlizer (172 to 202 kg/ha) resulted in high nitrate concetration in drain water compared to medium (114 to 135 kg/ha) and low (57 to 67 kg/ha) rates of nitrate fertlizer application (Jaynes et al., 2001). The results obatined in this study also showed a correlation between precipiation amount and timing in nitrate loss in drain flow. For example, low precipitation during spring 2015 and fall of 2016 resulted in low nitrate concentration in drain flow while high precipitation in spring 2016 led to higher nitrate concentration in drain flow. Similar corelation between nitrate concentration and precipitation amount and timing were reported in Iowa, Minneosta, Indiana, and Ontario with subsurface drianage field studies (Bakhsh et al., 2002; Drury et al., 1993; Kladivko et al., 2004; Randall and Iragavarapu, 1995).

Daily mean nitrate load for conventional drainage was 0.1 kg/ha/day and 0.7 kg/ha/day, and 0 and 0.6 kg/ha/day for for controlled drainage in 2015 and 2016, respectively (Figure 4.5). The total annual nitrate load from the conventional drainage plot ranged from 15 to 60 kg/ha/year with an overall mean of 38.7 kg/ha/year and from 0 to 47.7 kg/ha/year with an overall mean of 23.8 kg/ha/year for the controlled drainage plot during 2015 and 2016 respectively. Controlled drainage reduced nitrate load by 89% in 2015 and 21% in 2016 with an overall mean of 55% reduction compared to conventional drainage. Skaggs et al. (2012) reported a similar range (18% to 89%) of nitrate load reduction with controlled drainage compared to conventional drainage with 20 different field studies. Other field studies in Illinois, Iowa, and Sweden have also reported similar similar reductions with controlled drainage practice compared to conventional drainage (Cooke and Verma, 2012; Schott et al., 2017; Wesström et al., 2001).

The increase in nitrate fertlizer application rate from 2015 to 2016 (see Table 3.1) resulted in increased nitrate concentration in drain water. Similary, increase in preciptation amount also increased the nitrate concentration in drain water. However, the nitrate concentration between controlled and conventional drainage plot was not statistically significantly different. Nitrate load reduction in controlled drainage plots is primarly achieved by reduction in drainage volume, which decreases nutrient enriched water discharge to stream and rivers and potentially improves downstream water quality (Evans et al., 1995; Skaggs et al., 2012; Wesström et al., 2001).

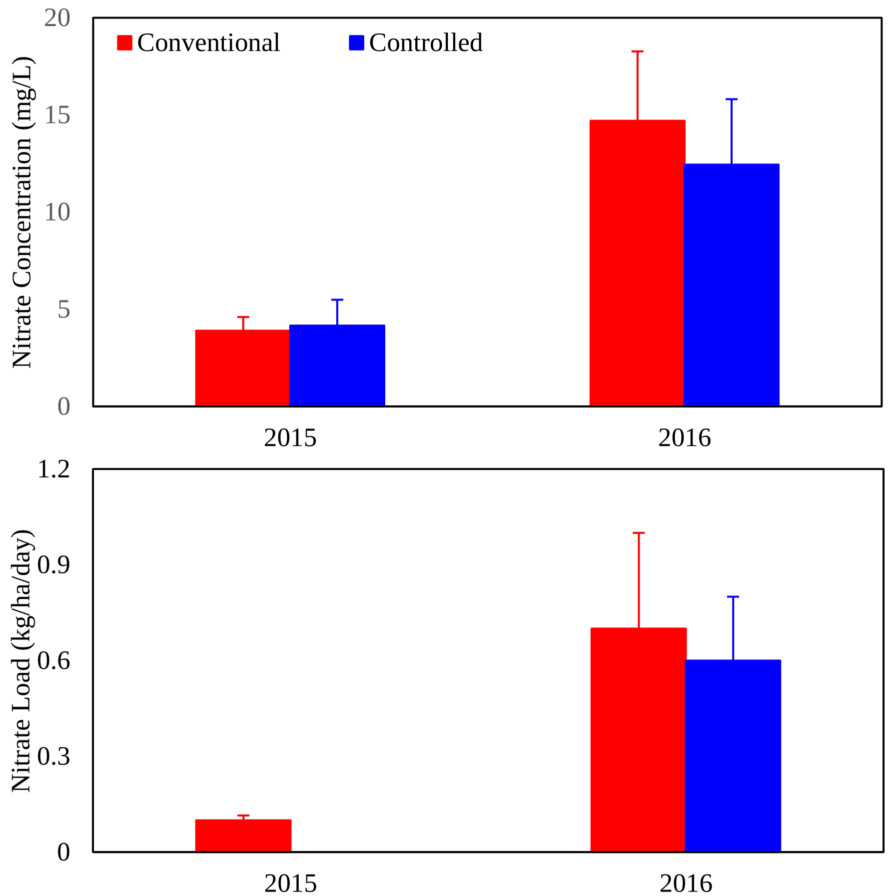

Figure 4.5 Mean nitrate concentration (a) and daily mean nitrate load (b) in controlled and conventional drainage plot at South Dakota State University, Southeast Research Farm near Beresford, South Dakota.

4.4.2 Dissolved Phosphrous Concentration and Load in Drain Water

Water quality analysis for dissolved phosphorous concentration was performed in 2016. Daily dissolved phosphorous concentration and mean load is presented in Figure 4.6. The dissolved phosphorous concentration in conventional drainage ranged from 0.027 to 0.095 mg/L with a mean of 0.048 mg/L during the study period. In the controlled drianage plot, concentration ranged from 0.040 to 0.127 with a mean of 0.081 mg/L. Mean dissolved phosphrous concentrations from both controlled and conventional drainage plots were about two to three times higher than the critical level of 0.03 mg/L for eutrophication (Daloglu et al., 2012; King et al., 2015), indicating a risk for water quality problems in downstream water bodies. While there was no seasonal pattern in dissolved phosphorus in the year 2016, dissolved phosphorous concentration was consistently higher in controlled drainage than in conventional drainage. The mean dissloved concentration of drain water in the controlled drainage plot was slighly higher than concentration in the conventional drainage plot; but was not statistically different ($p > 0.05$).

In Quebec, Canada, a comparative study reported a range of 0.011 – 0.054 mg/L for conventional drainage, and 0.031 to 0.0113 mg/L for controlled drainage/subirrigation. These ranges were slightly lower than the the concentrations measured from both controlled and conventional drainage plots in this study.

Daily mean dissolved phosphrous load from conventional and controlled drainage was 0.002 kg/ha/day and 0.005 kg/ha/day respectively (Figure 4.6), and the total annual dissolved phosphorous load was 0.198 kg/ha and 0.309 kg/ha during 2016. A field study in Ohio reported 0.029 kg/ha daily mean dissolved phosphorous loss from controlled drainage fields and 0.014 kg/ha from conventional drainage fields (Pease et al., 2017). The dissolved phosphorous load reported in the Ohio study was higher than the load from both controlled and conventional drianage plots measured in this study. Controlled drainage in this study increased dissolved phosphorous load by 35% compared to conventional drainage. Other studies from the region found similar higher dissolved phosphorus loads from controlled drainage compared to conventional drianage (Feser et al., 2010; Sanchez Valero et al., 2007; Sunohara et al., 2010).

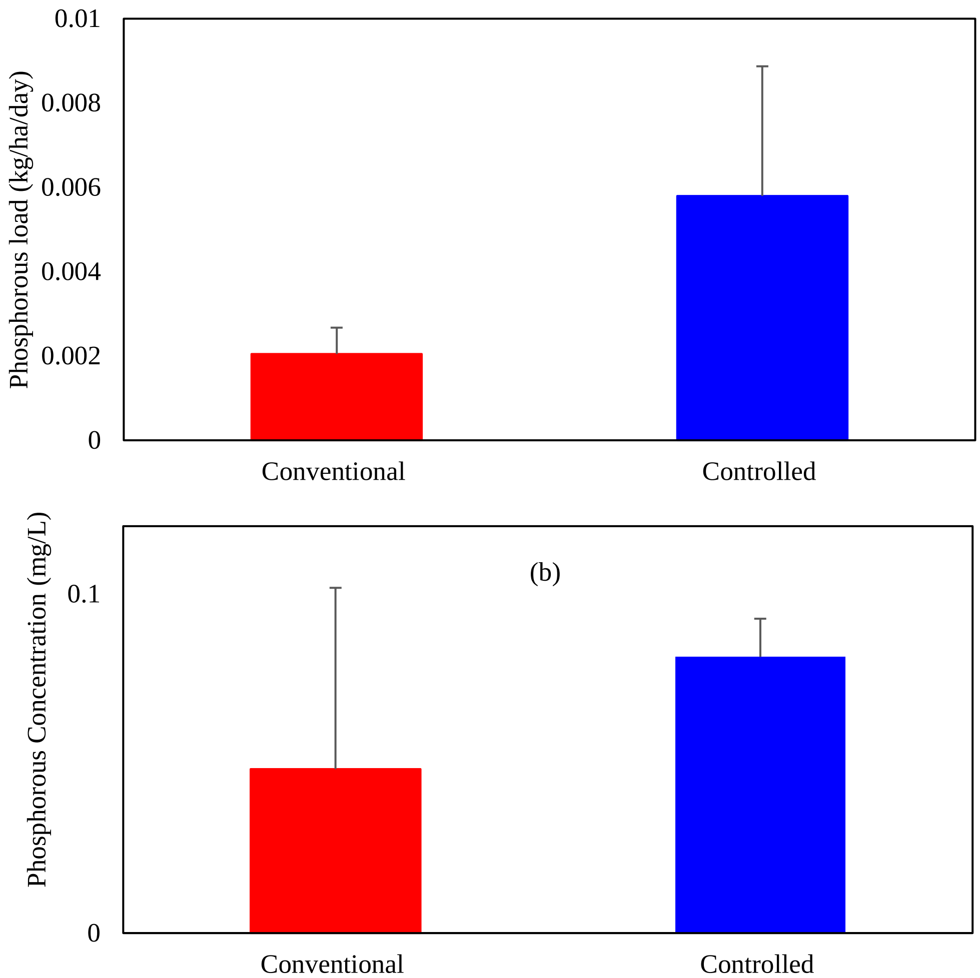

Figure 4.6 Mean dissolved phosphorous concentration (a) and daily mean load (b) at the outlet of drainage plots in South Dakota State University, Southeast Research Farm near Beresford, South Dakota.

This increased dissolved phosphrous concentration in the drain water may be due to several contributing factors such as macropore flow, drainage design, and management practices (King et al., 2015). In addition, the study drainage plots have no boundary between, suggesting the possibility of lateral flow and nutrient movement between the two plots.

4.5 Shallow Groundwater Table

Shallow groundwater table was measured at the middle of both controlled and conventional drainage plots from spring 2016. The shallow groundwater table depth for the coventional drainage plot varied from 0 to 1.372 m with an overall mean of 1.168 m, while the water table depth for the controlled drainage plot varied from 0.081 to 1.372 m with an overall mean of 1.098 m. There was a statistically significant difference in mean shallow groundwater table depth between controlled and conventional drainage plots ($p < 0.05$). The water table in the controlled drainage plot was consistently higher than the water table in the conventional drainage plot during the measurement period. Field studies in Iowa also reported significantly higher shallow water table depth in the controlled drainage plot compared to the conventional drainage plot (Helmers et al., 2012; Schott et al., 2017).

Shallow groundwater table showed similar patterns as outlet drainage water depth and drain flow (Figures 4.7, 4.2, and 4.4). Water table rise was generally observed during spring (April and May), and fall (September and October) seasons when precipitation was high during the study period (Figure 4.7). Water table in the conventional drainage plot dropped faster than water in the controlled drainage plot, sugessting that water is being held in controlled drainage plot for longer period of time. Water level was below the depth of the monitoring wells for both controlled and conventional drainage plots from mid-June to mid-September in 2016, which was due to water loss via drianage, lateral or vertical seepage, and evapotranspiration. The shallow groundwater table fluctuation is driven by precipitation, soil type, and drainage design. At the study site, shallow groundwater table is generally close to the ground surface during spring season following precipitation and spring snow melt events but draws down during summer before rising in fall with precipitation events. Similar seasonal variation in shallow groundwater table was observed in Iowa with controlled and conventional drainage plots (Helmers et al., 2012; Schott et al., 2017).

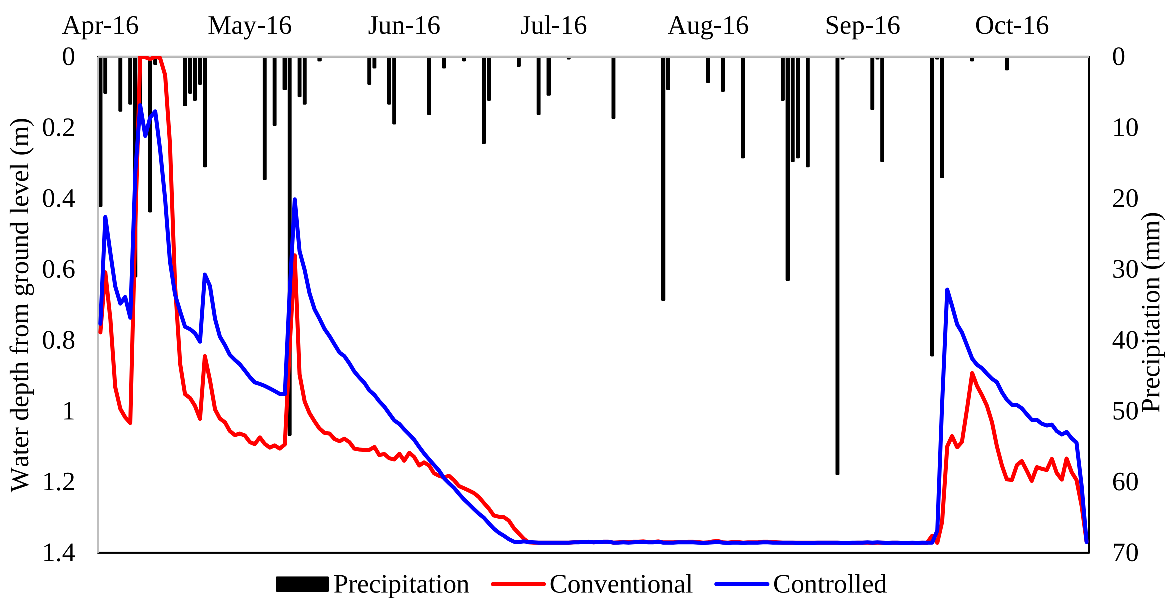

Figure 4.7 Daily shallow groundwater table and precipitation at the controlled and conventional drainage plots at South Dakota State University, Southeast Research Farm near Beresford, South Dakota.

4.6 Nitrate and Dissolved Phosphorous Concentrations in Shallow Groundwater

Water samples for nitrate and dissolved phosphorous concentrations from the monitoring wells were collected in 2016 growing season. Nitrate concentration in the conventional drainage plot ranged from 2.9 to 31.3 mg/L with an overall mean of 19.4 mg/L. In the controlled drainage plot, concentration ranged from 5.2 to 30.9 mg/L with an overall mean of 13.6 mg/L (Figure 4.8). There was no statistical significant difference in mean nitrate concentrations between the contolled and conventional drainage plots ($p > 0.05$).

Dissolved phosphorous concentration in the conventional drainage plot ranged from 0.088 to 0.441 mg/L with a mean of 0.257 mg/L, and from 0.032 to 0.202 mg/L with a mean of 0.091 mg/L for the controlled drainage plot plot (Figure 4.8). The mean dissolved phosphorous concentration in the contolled drainage plot was statistically significantly lower than that of the conventional drainage plot during the sampling period ($p < 0.05$).

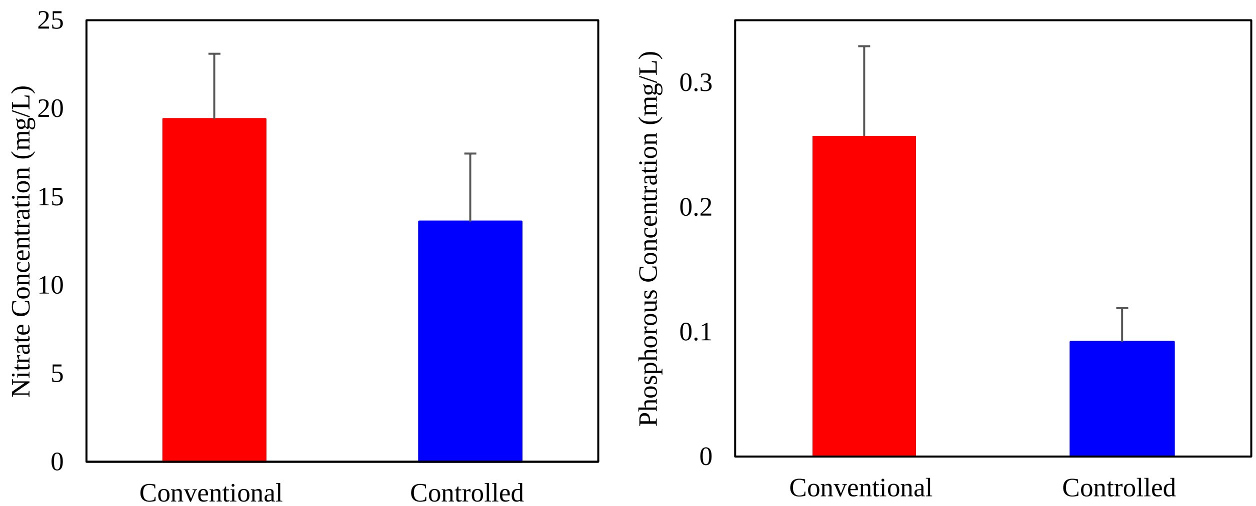

Figure 4.8 Nitrate (a) and dissolved phosphrous concentrations (b) in shallow groundwater in conventional and controlled drainage plots located at South Dakota State University, Southeast Research Farm near Beresford, South Dakota.

Both nirate and dissolved phosphorous concentrations showed similar seasonal variation at the outlet and middle of plots, except for the conventional drainage plot outlet. Nitrate and dissolved phosphorus concetrations in both controlled and conventional drainage plots depends on nitrate fertilizer application rates and precipitation events. Nutrient concetrations were generally high during spring (May to June) when spring fetilizer was applied under frequent spring rainfall events, while low concentrations were measured during fall when there was less precipitation.

4.7 Soil Texture

Soil samples were collected in fall 2016 to assess texture at four different depths (0 - 10 cm, 10 – 20 cm, 20 – 30 cm, and 30 – 45 cm). The mean percent of sand, silt, and clay for all four depths in conventional and controlled drainage plots is presented in Figure 4.9. The overall mean percent sand, silts and clay for the conventional drainage plot was 11.6%, 42.5%, and 45.9%, respectively and 14.9%, 45.8%, 39.3% for the controlled drainage plot. Using soil textural classification (Gee and Bauder, 1986; Hillel, 1998), soils in the conventional drianage plot were classified as as silty clay at depths 0 to 10 cm, 10 to 20 cm, and 20 – 30 cm, and as silty clay loam at 30 to 45 cm depth. In the controlled drainage plot, soils was classified as silty clay at 0 to 10 cm depth, clay at 10 to 20 cm, and sility clay loam at 20 to 30 cm and 30 to 45 cm depths. Overall, the soils in the conventional drianage plot was classified as silty clay and silty clay loam for the controlled drianage plot. The texture analysis conducted in this study revealed moderatly fine textured and fine textured soils in controlled and conventionally drained plots, respectively, which is similar to the soil texture group reported by USDA (2017) for these fields. These soils are somewhat poorly drained to very poorly drained, which supports the need for subsuface drainage to increase crop growth.

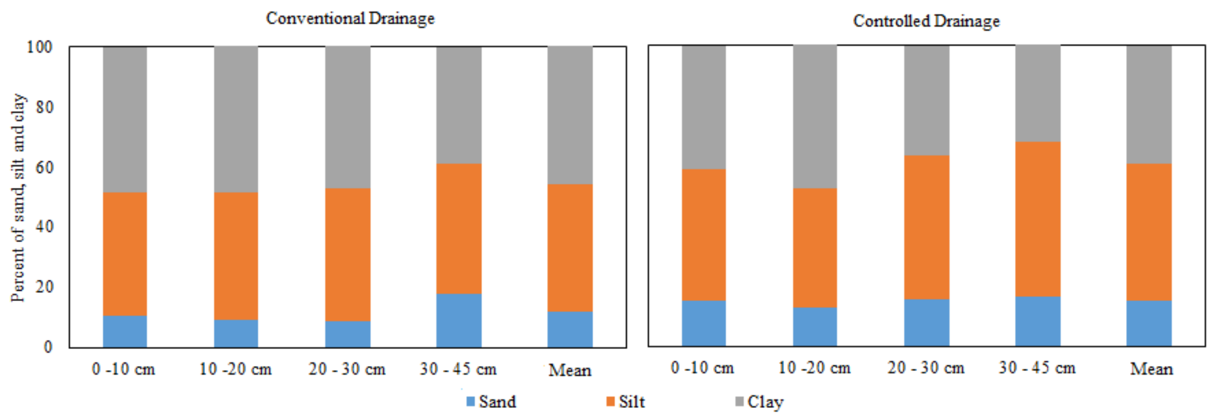

Figure 4.9 Soil texture of controlled and conventional drainage plots at South Dakota State University, Southeast Research Farm near Beresford, South Dakota.

4.8 Soil Bulk Density

Soil samples were collected during summer 2016 for dry bulk density analysis at four different depths (2 cm, 12 cm, 28 cm , and 48 cm). Soil dry bulk density in the conventional drainage plot ranges from 1.19 to 1.49 g/cm^3 (2 cm depth), 1.37 to 1.48 g/cm^3 (12 cm depth) , 1.46 to 1.62 g/cm^3 (28 cm depth), and 1.43 to 1.63 g/cm^3 (48 cm depth). For the controlled drainage plot, the soil dry bulk ranges from 1.15 to 1.51 g/cm^3 (2 cm depth), 1.35 to 1.54 g/cm^3 (12 cm depth), 1.31 to 1.62 g/cm^3 (28 cm depth), and 1.31 to 1.60 g/cm^3 (48 cm depth). The mean dry bulk density of soil at all four depths for the controlled and conventional drainage plot is presented in Figure 4.10. While there was no statistical significant difference in means of bulk density at all four depths between controlled and conventional drainage plots, dry bulk density of the conventional drainage plot appears slightly higher than dry bulk density in the controlled drainage plot.

Research found inverse relationship between bulk density and soil pore space; i.e. bulk density tends to decrease with increase in soil pore space (Chaudhari et al., 2013; Daddow and Warrington, 1983). As silty clay loam soil (controlled drainage plot) have larger pore space compared to silty clay soil (conventional drainage plot), the conventional drainage plot thus has higher bulk density than the controlled drainage plot. Beside soil texture, other contributing factors such as soil organic content, soil mineral density and their packing arrangements, and management practices (Lal and Shukla, 2004) may also affect soil bulk density.

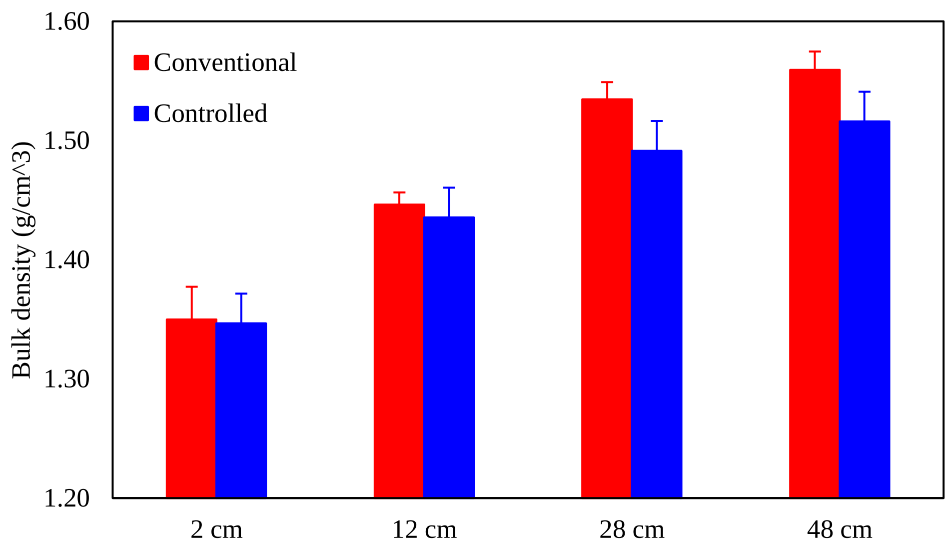

Figure 4.10 Mean dry bulk density at 2 cm, 12 cm, 28 cm, and 48 cm depths in the controlled and conventional drainage plots at South Dakota State University, Southeast Research Farm near Beresford, South Dakota.

4.9 Soil pH

The soil pH ranged from 6.6 to 8.0 with mean pH 7.30 in the conventional drainage plot, and from 6.9 to 7.9 with mean pH of 7.59 in the controlled drainage plot. Mean soil pH was consistently greater at four depths (0-10 cm, 10-20 cm, 20-30 cm and 30-45 cm) for the conventional drainage plot compared to the controlled drainage plot (Figure 4.11).Overall, mean soil pH of the controlled drainage plot was statistically significantly higher than pH of the conventional drainage plot with a difference of 0.29 ($p < 0.05$). Field research in Sweden and Minnesota also reported higher pH in controlled drainage plots compared to conventional drainage plots (Feser et al., 2010; Sanchez Valero et al., 2007). Higher soil pH in controlled drainage plots is likely due to the anoxic condition in created by higher water table in the soil profile (Sanchez Valero et al., 2007).

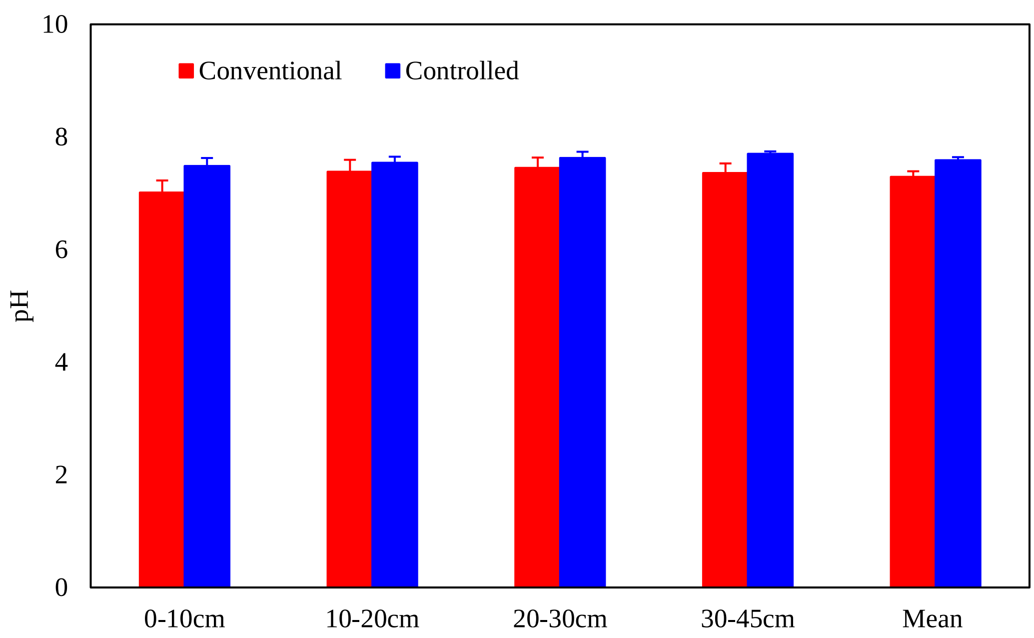

Figure 4.11 Mean soil pH of conventional and controlled drainage plot at South Dakota State University, Southeast Research Farm near Beresford, South Dakota.

4.10 Soil Moisture

Soil moisture content was collected continously at two separate locations (near plot outlet and middle of plot) in both controlled and conventional drainage plots. The descriptive statistics of the daily soil mositure content near the plot outlet is presented in Table 4.2. Daily soil moisture content was statistically significantly higher in the conventional drainage plot compared to the controlled drainage plot at 15 and 76 cm depths ($p < 0.05$), but statistically significantly higher in the controlled drainage plot at 105 cm depth ($p < 0.05$). This was not expected as conventional drainage remove more water from the soil profile, leading to lower moisture content compared to controlled drainage.

Table 4.2 Descriptive statistics of soil moisture content at the outlet of conventional and controlled drainage plots located at South Dakota State University, Southeast Research Farm near Beresford, South Dakota.

	Min		Mean		Max	
Depth	Conv.	Cont.	Conv.	Cont.	Conv.	Cont.
15 cm	0.13	0.12	0.26	0.24	0.43	0.41
45 cm	0.24	0.21	0.30	0.30	0.38	0.41
76 cm	0.30	0.29	0.32	0.31	0.53	0.45
105 cm	0.21	0.29	0.38	0.41	0.52	0.51

Conv: conventional drainage plot
Cont: controlled drainage plot

The seasonal variation of soil moisture content was not consistent between controlled and conventional drainage plots for measurements taken at all depths (Figure 4.12). There was no consistent seasonal trend in soil moisture observed at the four depths; however, the daily soil moisture content increased with increase in depth in both controlled and conventional drainage plot. The difference between the soil moisture content between controlled and conventional drainage was minimal at all four depths, except for 105 cm depth after June 2016. The large difference in soil moisture content between controlled and conventional drainage plot at 105 cm depth after June 2014 may likely be due to drainage of excess water in spring and high evapotranspiration demand of crop in the conventional drainage plot, leading to substantial decreases in soil moisture. The soil moisture content at shallower depths responded to precipitation events during dry preiods. For example, moisture content at 15 cm depth increased during June, July and August of 2016 after each precipitation event.

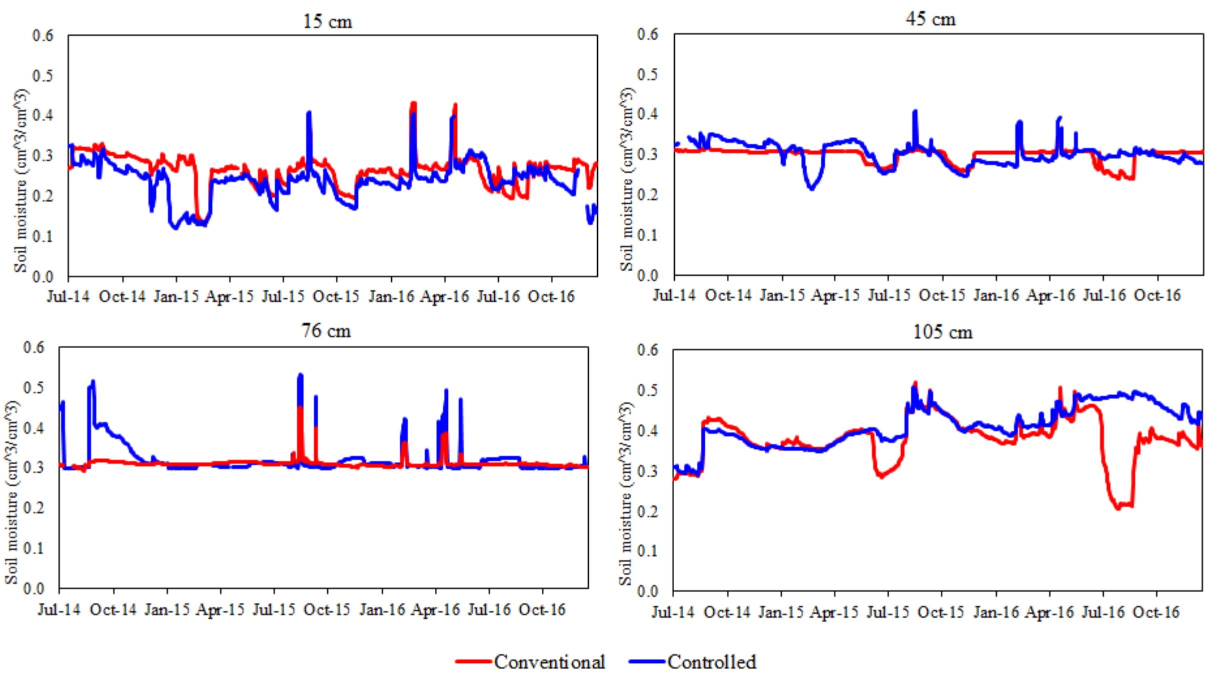

Figure 4.12 Daily soil moisture content at 15 cm, 45 cm, 76 cm and 105 cm depths near the outlet of conventional and controlled drainage plots located at South Dakota State University, Southeast Research Farm near Beresford, South Dakota.

The descripitive statistics of soil mositure content at middle of the plots are shown in Table 4.3. The difference in mean soil moisture content was statistically significantly higher in conventional drainage compared to controlled drainage at 10 cm, 40 cm, 60 cm and 100 cm depths, while controlled drainage has statistically singificantly higher soil moisture at 20 cm depth ($p < 0.05$). The pattern in soil moisture content at middle of the plots was not consistent with soil mositure near the plot outlets for respective depths.

Table 4.3 Descriptive statistics of soil moisture content at middle of conventional and controlled drainage plots located at South Dakota State University, Southeast Research Farm near Beresford, South Dakota.

	Min		Mean		Max	
Depth	Conv.	Cont.	Conv.	Cont.	Conv.	Cont.
10 cm	0.09	0.12	0.30	0.28	0.43	0.41
20 cm	0.07	0.14	0.32	0.36	0.43	0.47
40 cm	0.23	0.16	0.32	0.29	0.41	0.50
60 cm	0.38	0.26	0.46	0.35	0.64	0.49
100 cm	0.40	0.31	0.45	0.41	0.53	0.48

Conv: conventional drainage plot
Cont: controlled drainage plot

Similar to soil moisture content near plot outlets, seasonal variation in soil moisture content at middle of the plots was also not consistent in both controlled and conventional drainage plots (Figure 4.12).The difference in daily soil moisture content between controlled and conventional drainage plots was quite visible at all five depths while there was minimal difference in soil moisture content near plot outlets compared to middle of plots. The maximum difference in soil mositure content was measured at 60 cm depth while the minimum difference was measured at 10 cm depth.

There was also inconsistency in daily soil moisture content between the two locations (i.e. outlet and middle of plots) and their corresponding depths during the study period. For example, soil moisture content in the conventional drainage plot was higher at 15 cm depth near plot outlet, while controlled drainage has higher daily soil moisture content at 20 cm depth. In contrast to this study, a field study conducted in Iowa reported no difference in means of soil moiture content at 10 cm, 20 cm and 40 cm depth between controlled and conventional drainage plots (Schott et al., 2017). Researchers in Minnesota reported significantly higher soil moisture content between 0 and 120 cm depths in drained plots compared to undrained plots during growing season (Jin et al., 2003). Drainage management of the controlled drainage plot during the growing season is similar to no drainage condition. The study shows variabiltiy in soil moisture content near the outlet and middle of both drainage plots at all depths. Conventional drainage plot has higher soil moisture content compared to the controlled drainage plot at all depths for both locations (i.e. plot outlet and middle), except at 105 cm depth near the plot outlet and 20 cm depth in the midle of plots. These findings were not expected as the controlled drianage plot should hold more water in the soil profile and should subsequently have higher soil moisture content compared to the conventional drianage plot. Further monitoring and analysis are needed to better understand water fluxes in the study plots.

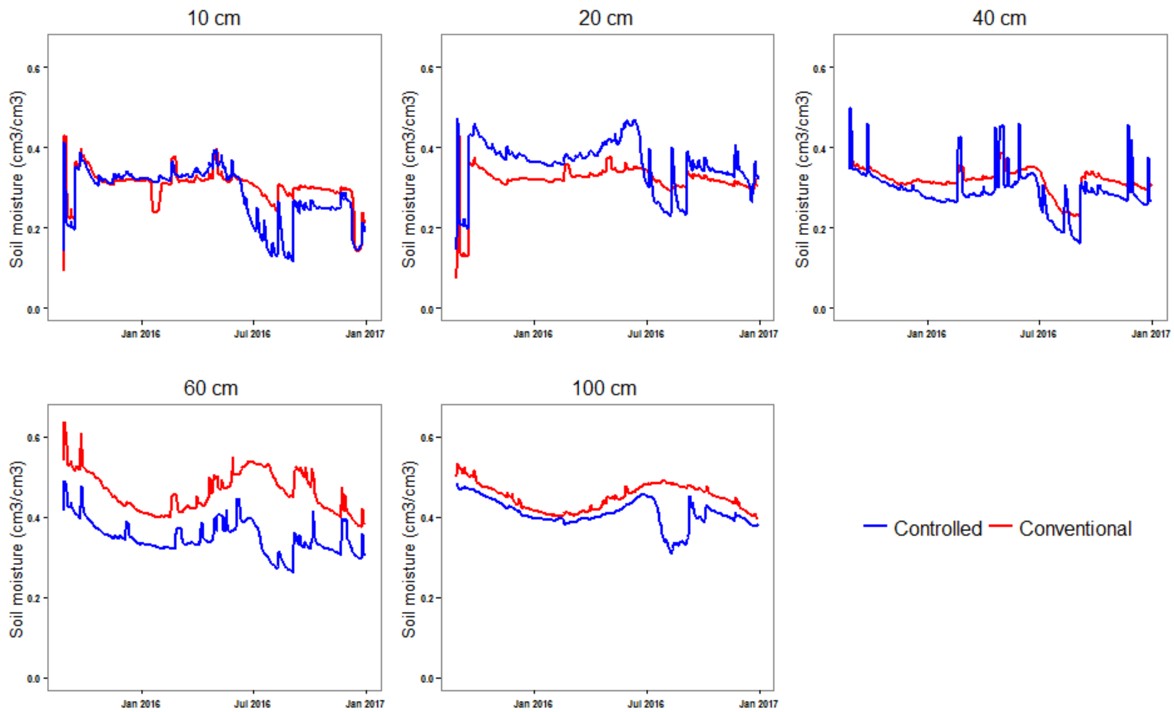

Figure 4.13 Daily soil moisture content at 10 cm, 20 cm, 40 cm, 60 cm, and 100 cm depths in middle of conventional and controlled drainage plots located at South Dakota State University, Southeast Research Farm near Beresford, South Dakota.

4.11 Soil Temperature

Similar to soil moisture content, soil temperature values were continously collected near outlet and middle of both controlled and conventional drainage plots. Figure 4.14 shows the soil temperature near plot outlets for both controlled and conventional drianage plots. The mean soil temperature ranged from 14.2°C to 14.5°C, from 15 cm to 105 cm depth, in the conventional drainage plot, and from 14.6°C to 14.5°C, from 15 cm to 105 cm depth, for the controlled drainage plot during the study period. The difference in mean soil temperature between controlled and conventional drainage plots were statistically not siginificant for all four depths (15 cm, 45 cm, 76 cm, 105 cm). Soil temperature showed consistent seasonal trend in both controlled and conventional drainage plots. Low soil temperature was measured during winter season, while high soil temperature was measured during summer season at both drainage plots. With increase in depth, the difference between highest and lowest seasonal soil temperature was reduced in both drainage plots. The largest variation in daily mean soil temperature was observed at 15 cm depth; but generally soil temperature decreased with increased depth. Soil temperature dropped below 0°C at 15 cm and 45 cm depth during winter season while soil temperature approached 30°C during summer at 15 cm depth.

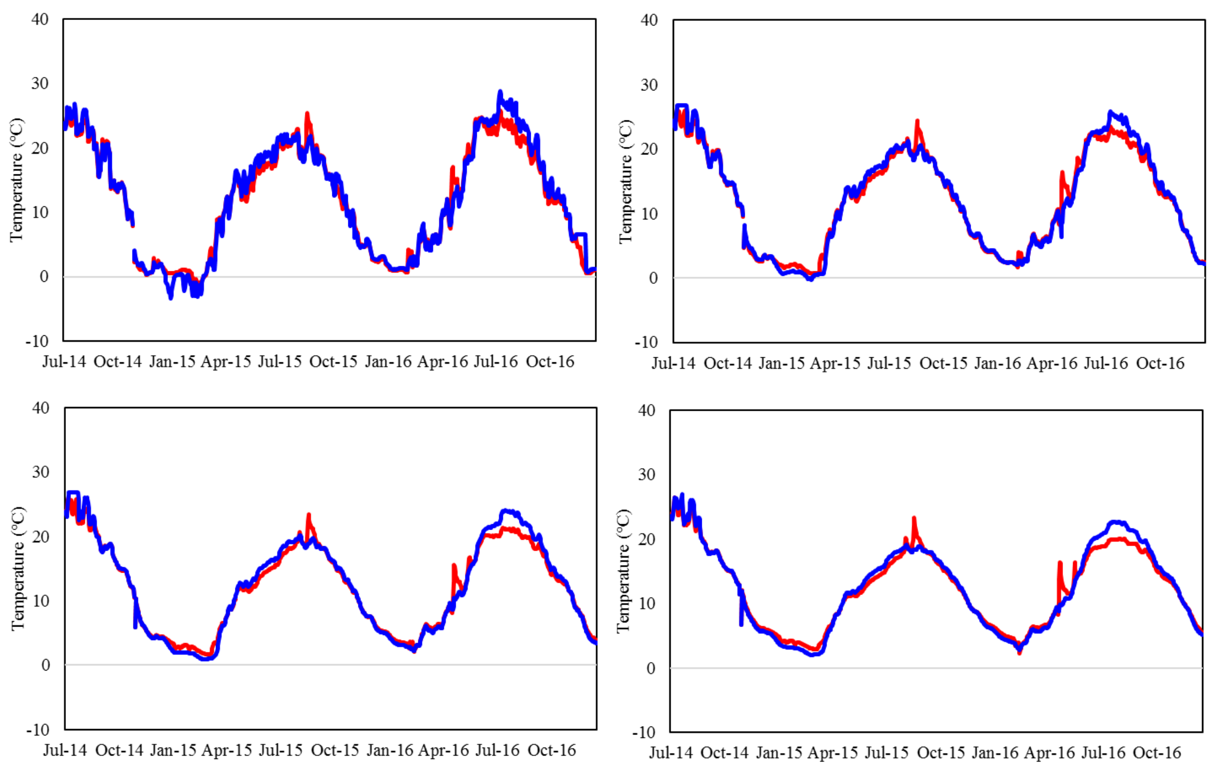

Figure 4.14 Soil temperature at 15, 45, 76,and 105 cm depths near the outlet of conventional and controlled drainage plots located at South Dakota State University, Southeast Research Farm near Beresford, South Dakota.

Soil temperature in middle of controlled and conventional drainage plots is presented in Figure 4.15. The mean soil temperature in the middle of the plot ranged from 11.9°C to 12.8°C, from 10 cm to 100 cm depth, in conventional drainage, and from 11.6°C to 12.5°C, from 10 cm to 100 cm depth, for the controlled drainage plot during study period. The difference in daily mean soil temperature between controlled and conventional drainage plots was statistically not siginificant for all five depths (10 cm, 20 cm, 40 cm, 60 cm and 100 cm). Soil temperature in middle of both plots exhibits seasonal trends similar to results near plot outlet. During winter season, the soil temperature dropped below 0°C, and increased to approximately 30°C at shallower depths during summer season for both controlled and conventional drainage plots. Daily fluctuation of soil temperature was prominent at 10, 20 and 40 cm depths. Fluctuation of daily soil temperature was minimum at at 60 and 100 cm depths. The difference in temperature between controlled and conventional drainage plots was minimal at all five depths.

This study showed no statistical significant difference in mean soil temperature between controlled and conventional drainage pratice ($p > 0.05$). Jin et al. (2008) assessed the influence of subsurface drainage on soil temperature at five depths and two drain spacings in two different field sites with two soil types (i.e. loam and silty clay loam). The results showed significantly higher soil temperature in drained plots compared to undrained plots during growing season, and the difference in soil temperature was highest at 30 to 60 cm depths. The results mentioned above are in contrast with findings from the SDSU Southeast Research Farm site as there was no statistical significant difference in soil temperature at all depths between the controlled and conventional drainage plots. Even though this study compared conventional to controlled drainage, controlled drainage in during most of the growing season exhibits reduced drainage intensity and leads to no drainage condition. Generally, lower soil moisture increases temperature in the soil profile (Al-Kayssi et al., 1990), which is a typical behavior in conventional drianage fields compared to controlled drainage fields. However, differences in soil texture in the study plots may have affected soil temperature patterns in the controlled and conventional drianage plots. This study shows similar soil temperature in both drainage plots, which may be due to the way the plots were setup. The adjacent drainage plots setup likely influences the lateral water movement, creating similar soil water charactersitics in both plots.

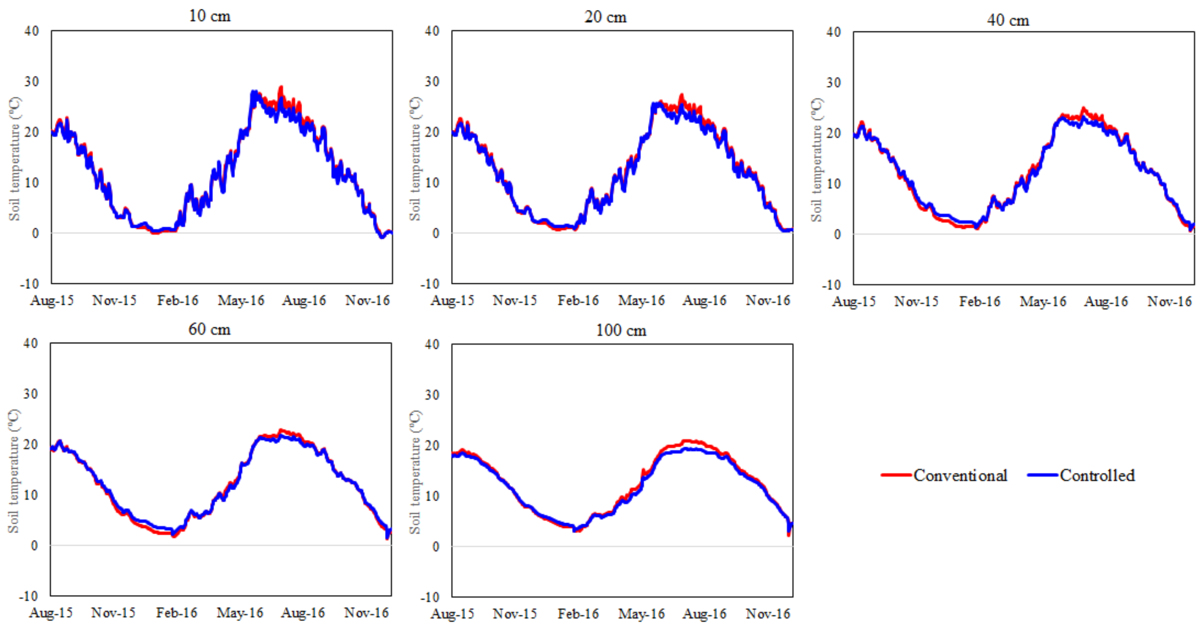

Figure 4.15 Soil temperature at 10 cm, 20 cm, 40 cm, 60 cm and 100 cm depths in middle of conventional and controlled drainage plots located at South Dakota State University, Southeast Research Farm near Beresford, South Dakota.

4.12 Soil Nitrate

Soil samples are collected in 2016 after harvesting corn to measure residual soil nitrate, which ranged from 2 to 42 mg/kg with a mean of 12.74 mg/kg in the conventional drainage plot, and from 7 to 78 mg/kg with a mean of 24.74 mg/kg in the controlled drainage plot (Figure 4.16). The mean residual nitrate content in all four depths (0-10 cm, 10-20 cm, 20-30 cm, and 30-45 cm) was statistically not significant ($p > 0.05$); however, overall mean residual soil nitrate content was statistically significantly higher in the controlled drainage plot compared to the conventional drainage plot ($p < 0.05$). Mean residual soil nitrate in the conventional drainage plot decreased with increase in soil sampling depth, while in the controlled drainage plot the residual soil nitrate did not show any pattern with increase in sampling depth.

Generally, residual soil nitrate tends to be lower in the soil surface (10 cm) compared to the deeper depths. This is likely due to greater soil organic content and plant cover residues at the soil surface (Jaynes et al., 2001). However, in this study the mean residual soil nitrate was highest near the soil surface but gradually decerases with increase in depth in the conventional drainage plot. For the controlled drainage plot, the mean residual soil nitrate was lower at soil surface and has inconsistent mean residual soil nitrate with increase in depth. A four-year study in Iowa reported significantly higher ($p < 0.05$) mean soil nitrate residual in conventional drainage plots compared to nitrate residual in controlled drainage plots with corn-soybean rotation (Jaynes, 2012). Wesstrom et al. (2001) also reported higher mineral nitrate content in late autumn soil samples for the conventional drainage practice compared to controlled drainage practice under potato and barley production. In contrast, results obstained in this study resulted in significantly higher soil nitrate residual in the controlled drainage plot compared to nitrate residual in the conventional drainage plot.

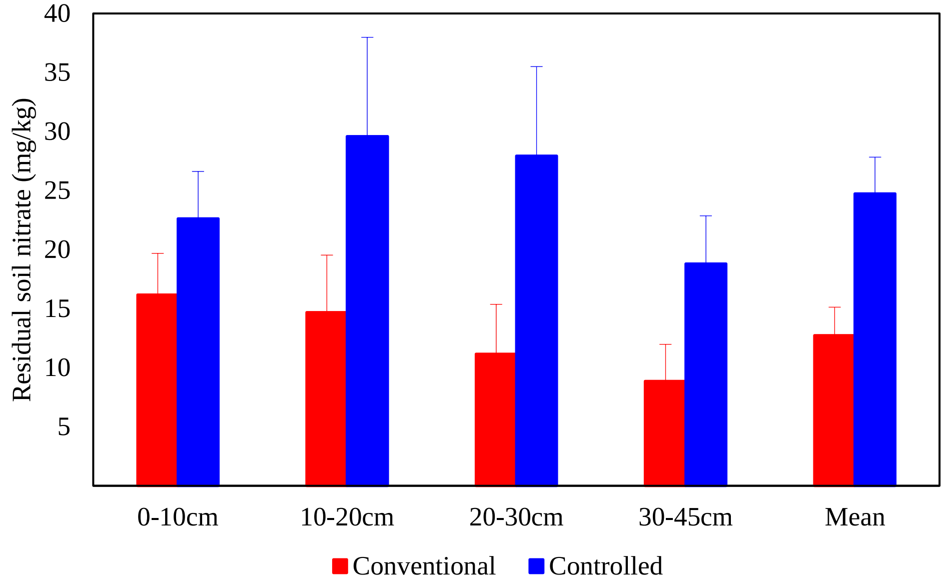

Figure 4.16 Residual soil nitrate content in the controlled and conventional drainage plots located at South Dakota State University, Southeast Research Farm near Beresford, South Dakota.

4.13 Soil Penetration Resistance

The soil penetration resistance in the conventional drainage plot ranged from 642 to 4147 KPa with a mean of 1526 KPa, and from 440 to 4587 KPa with a mean of 1488 KPa for the controlled drainage plot during the study period. The mean soil penetration reistance did not exhibit any specific pattern (Figure 4.17). Mean soil penetration resistance between controlled and conventional drainage was statistically not significant ($p > 0.05$). However, there was seasonal patterns in soil penetration resistance for both the controlled and conventional drainage plots. Soil penetration resistance was lower during spring and fall seasons when soil was relatively wetter due to precipitation and spring snow melt. Penetration reistance gradually increased during summer (i.e. June, July and August) when soil was drier due to crop evapotranspiration demands.

Soil penetration reistance depends also on precipitation amount and timing during the growing season (Kandel et al., 2013). For example, high precipitation in June 2014 resulted in low soil penetration resistance measurement.

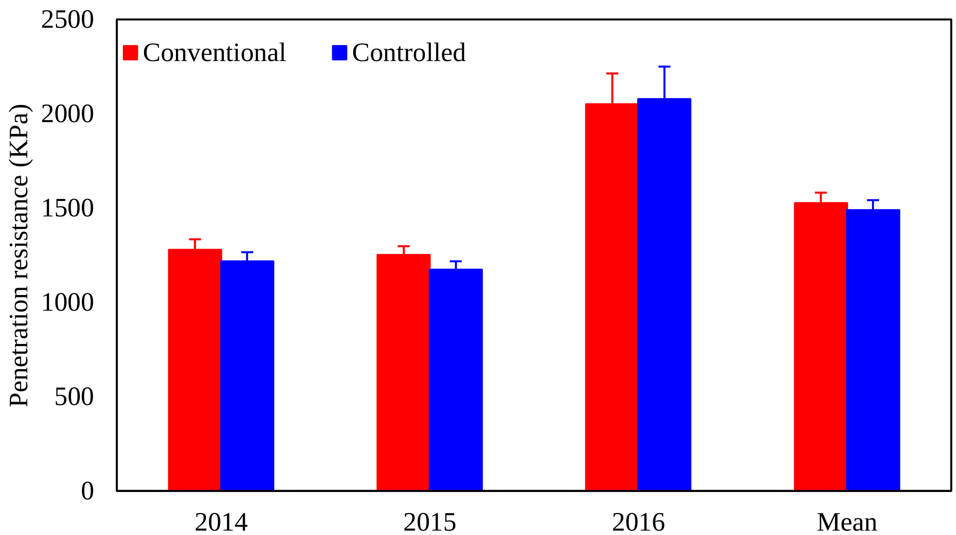

Figure 4.17 Annual soil penetration resistance in the controlled and conventional drainage plots located at South Dakota State University, Southeast Research Farm near Beresford, South Dakota.

4.14 Crop Yield

Soybean, Oats, and Corn were planted in 2014, 2015 and 2016, respectively. Crop yield in the conventional drainage plot were 3.6, 9.9 and 13.0 ton/ha, and they were 3.3, 10.4 and 11.9 ton/ha in the controlled drainage plot for 2014, 2015, and 2016, respectively. There were 7.6% and 9.2% reductions in soybean and corn yields in the controled drainage plot during 2014 and 2016, while 5.4% increase in oat yield was observed in the year 2015. Reduced corn yield was also reported for controlled drainage plots compared to conventional drainage plots in Iowa (Helmers et al., 2012). However, similar other studies reported no yield increase to 18% increase in corn yield(Ghane et al., 2012; Jaynes, 2012; Poole et al., 2011), no yield increase to 8% increase in soybean with controlled drainage compared to conventional drainage in the region (Cooke and Verma, 2012; Ghane et al., 2012; Jaynes, 2012). The inconsistency in crop yield examined in various studies discussed above is likely due to the fact that controlled drainage is mostly an environmetal practice for water quality protection.

4.15 Leaf Area Index

The descriptive statistics of LAI during the study period are presented in Table 4.4. The difference in mean LAI was statistically not significant ($p > 0.05$); however, the controlled drainage plot has slightly higher LAI compared to LAI from the conventional drainage plot during all three study years (2014 to 2016). The LAI measurement was within the range of 0 to 6.5 m^2/m^2 for corn and 0 to 5.5 m^2/m^2 for soybean irrigated fields in Nebraska (Nguy-Robertson et al., 2012). The LAI gradually increases with increase in growth stage of the crop. The LAI measured was low during tillering stage (early June) and reached maximum at maturity stage (mid-August). The LAI values recorded were not consistent with yield data in 2014 and 2016 when as the conventional drainage plot has higher yield than the controlled drainage plot. Generally, plot with higher LAI tends to produce more biomass and subsequently should produce more yield; but this was not the case in this study. Further study is needed to understand the relationship between crop yield and LAI in these controlled and conventional drainage plots.

Table 4.4 Descriptive statistics of leaf area index in controlled and conventional drainage plots located at South Dakota State University, Southeast Research Farm near Beresford, South Dakota.

	Min		Mean		Max	
Year	Conv.	Cont.	Conv.	Cont.	Conv.	Cont.
2014 (Soybean)	4.72	5.13	5.08	5.46	5.44	5.8
2015 (Oats)	3.95	4.49	4.89	5.13	5.67	5.97
2016 (Corn)	0.53	0.47	3.57	3.84	5.88	6.27

Conv: conventional drainage plot
Cont: controlled drainage plot

5 CHAPTER FIVE: CONCLUSIONS/STUDY LIMITATIONS, RECOMMENDATIONS FOR FUTURE WORK

5.1 Conculsions

This demostration field study assessed the impacts of drainage water management on field hydrology and water quality in eastern South Dakota. Two adjacent drainage plots (controlled drainage and conventional drainage) were compared for drain flow, nitrate and dissolved phosphorous concentration in drain water and monitoring wells, shallowwater table depth, soil nitrate, soil moisture and temperature, soil penetration resistance, crop yield and LAI with soybean, oats, and corn during 2014, 2015, and 2016, respectively.

The controlled drainage plot showed reduction in annual drain flow by 24% to 100% with an overall mean reduction of 58% compared to the conventional drainage plot. Mean daily water level at the outlet of the conventional drianage plot ranged from 14 to 31% of the total annual precipitation, while water level ranged from 24% to 92% of total annual precipitation for the controlled drainage plot. Mean nitrate concentrations in drain water increased from less than 4 mg/L in 2015 to greater than 12 mg/L in 2016 in both controlled and conventional drainage plots. Controlled drainage showed 21% to 89% less annual nitrate load with a mean of 55% compared to conventional drainage. Dissolved phosphrous concentrations in drain water were above 0.03 mg/L for both plots. Mean dissolved concentration for the conventional drainage plot was 0.048 mg/L and 0.081 mg/L for controlled drainage plot during 2016. Controlled drainage showed increase in annual dissolved phosphorous load by 35% compared to conventional drianage. The effect of controlled drainage was also observed in shallow groundwater table with the controlled drainage plot having higher water table (1098 mm) compared to the conventional drainage plot (1168 mm). Mean nitrate concentration in shallow groundwater samples from the conventional drainage plot was 19.4 mg/L and 13.6 mg/L from the controlled drainage. Mean dissolved phosphorous concentration from the conventional drainage plot was 0.257 mg/L and 0.091 mg/L from the controlled drainage plot.

Soil textural analysis categorized soil to somewhat poorly drained with 1.45 g/cm^3 bulk density in the controlled drainage plot to poorly drained with 1.47 g/cm^3 bulk density in the conventional drainage plot. Soil pH in both controlled and conventional drainage plots were basic. Soil moisture content near plot outlet and middle showed unexpected higher moisture content in the conventional drainage plot than in the controlled drainage plot. There was no difference in soil temperature near the outlet and middle of the plots; but soil temperature in the controlled drainage plot was slightly higher than soil temperature in the conventional drainage plot. Residual soil nitrate content in the conventional drainage plot decreased with increases in depth, while there was no patterns observed in residual soil nitrate in the controlled drainage plot. The residual soil nitrate content in the conventional drainage plot was significantly lower with a mean of 12.74 mg/kg than in the controlled drianage plot, which has a overall mean of 24.74 ($p < 0.05$). Although soil penetration resistance showed no statistical significant difference between the controlled and conventional drainage plots, penetration resistance was slightly higher in the conventional drainage plot compared to the controlled drainage plot.

Soybean and corn yields were 7.6% and 9.2% less in the controlled drainage plot compared to yields in the conventional drainage plot, while oats showed 5.4% increase in yield with controlled drainage. Leaf area measurement showed opposite trends compared to crop yields, except in the year 2015 with oat production.

While subsurface drainage gained attention in eastern South Dakota, there are several environmental concerns associated with it, especially nutrient losses to waterways. This demonstration study suggests that controlled drainage has the potential to addresss water quality concerns in eastern South Dakota. The data measured in this study will be added to the Transforming Drainage project (https://transformingdrainage.org/) to understand the economic and environmental benefits of controlled drainage to support crop production.

5.2 Study Limitations and Recommendations for Future Work

The challenges associated with the demonstration plots include:

- This demonstration study has adjacent drainage plots without guard subsurface drain between. This will likely affect field hydrological parameters as plots may experience lateral seepage from each other, depending on topogarphy, potentially affecting drain flow, shallow groundwater table, soil moisture, and associted nutrient concentrations.
- Drain flow measurement with decagon CTD sensors at the outlet of plots was not reliable under submerged conditions.

- Due to lack of resources, grab sampling was adpoted to collect drain water for nutrient analysis in this study. While this approach provides an idea of nutrient content in the drain water, it does not always capture nutrient content with repsect to flow contition.

Future work should consider exploring the following ideas:

- Long-term field studies must be performed with experimentally designed field plots to develop better understanding about the effects of controlled and conventional drainage on field hydrology, water quality, and crop yield.
- Better sampling schemes can be performed to understand the effects of nutrient losses on deep groundwater.
- Automatic water samplers such as ISCO samplers can be used for better nutrient load estimation with respect to the volume and timing of drain flow.
- Modeling can be used to evlauate the long-term impact of controlled and conventional drainage on field hydrology and water quality.

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